Cognitive, Affective, & Behavioral Neuroscience
2004, 4 (2), 170-181

Mislocalizations of touch to a fake hand

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Observers can mislocalize a tactile target delivered to an unseen hand if a visible rubber glove is positioned next to a pair of distractor lights that flash in correlation with the tactile target (Pavani, Spence, & Driver, 2000). In the present study, we explored visual, tactile, and postural factors that influence this *fake hand effect*. Comparison with baseline conditions revealed that the fake hand effect was larger than a general spatial congruity effect but weaker than the effect obtained when tactile and visual stimuli were actually in the same locations (Experiment 1). Surprisingly, the effect did not depend on direct vision of the fake hand (Experiments 1 and 2), nor was it enhanced by congruent tactile information (Experiment 3). However, the fake hand effect was sensitive to the postural compatibility of the real and the fake hands (Experiment 4). These findings indicate that the available sensory information is used flexibly to incorporate the rubber glove into the body schema.

Touch is a proximal sense, in that we can directly make contact only with surfaces that are located on our body or can be reached by our limbs (Cholewiak & Collins, 1991). Yet our sense of touch is not limited to proximal stimuli. For example, tactile sensations can be transmitted through objects held in the hand; when an object such as a pen is held, our experience is of "feeling" the tip of the pen, rather than its immediate contact points with our hand (e.g., Iriki, Tanaka, & Iwamura, 1996; Maravita, Spence, Kennett, & Driver, 2002; Vaught, Simpson, & Ryder, 1968; Yamamoto & Kitazawa, 2001; see also Maravita & Iriki, 2004). In a recent laboratory study of this effect, Yamamoto and Kitazawa (2001) reported that accuracy in judging the temporal order of two successive stimuli delivered to the tips of hand-held sticks decreased when either the observer's hands or the sticks themselves were crossed (i.e., lay in contralateral space). However, when both the hands and the sticks were crossed (so that the tips of the sticks were again in ipsilateral space), accuracy recovered, thus suggesting that the tactile stimulus was felt at the tip of the tool.

The research reported in this article was funded by grants from the NSERC, the Michael Smith Foundation for Health Research, and Human Frontiers to A.K., an NSERC Discovery Grant to J.T.E., a Killiam Fellowship to S.S.-F., and awards from the NSERC, the UGF, and the Michael Smith Foundation for Health Research to E.L.A. This research was based on the doctoral dissertation of E.L.A. The authors are grateful to several undergraduate psychology students at the University of British Columbia for their help in collecting the data: T. Ailon, J. Braunstein, D. Cameron, A. Gandhi, J. Harrington, A. Inkster, R. Janssen, M. Jassel, and J. Scott. Correspondence may be addressed to E. L. Austen, School of Human Kinetics, University of British Columbia, Vancouver, BC, V6T 1Z1 Canada (e-mail: austen@interchange.ubc.ca).

Tactile sensations can also be attributed to distant objects via vision (e.g., Botvinick & Cohen, 1998; Nielsen, 1963; Pavani, Spence, & Driver, 2000; Rock & Harris, 1967). Botvinick and Cohen, for example, reported that the apparent location of one's unseen arm can be influenced by seeing brush strokes applied to a visible fake hand while feeling synchronous strokes on one's own arm. The self-report measure used to index this illusion, however, did not differentiate between the expectation biases that might be at play in this situation and the sensory integration effects that were claimed by the authors.

The aim of the present study was, first, to establish an expectation-free measure of visually altered tactile sensations and, second, to examine the nature of the visual, tactile, and postural interactions that are relevant when the experience of touch is influenced by visual signals. The measure we developed was adapted from an existing procedure that we call the *fake hand effect* (Pavani et al., 2000). We will first review its background, before describing the steps we took to alter it, and then will use it to study how vision, touch, and proprioception interact.

The fake-hand effect was first reported by Pavani et al. (2000), who had participants place their hands beneath a small stand (out of sight) while simultaneously holding foam cubes in each hand. Tactile vibrators were positioned under each index finger and thumb. The task was to indicate, as quickly as possible, whether a target tactile vibration was felt on the "top" (finger) or the "bottom" (thumb). A matching pair of foam cubes, which held distractor lights at the corresponding locations of the tactile vibrators, were positioned so that they either appeared to be held by a rubber glove (fake hand condition) or not (no fake hand condition). One of the visual distractors was always presented simultaneously with the tactile target. The location of the visual distractor (top vs. bottom) could be either spatially *congruent* or spatially *incongruent* with the location of the tactile vibration (top vs. bottom). Because the participants were instructed to respond only to the tactile vibrations in this experiment, any influence of the visual signals provided an indirect measure of visual interference.

The results showed first that the distractor lights interfered with the tactile spatial discrimination, so that the observers were generally slower and less accurate in localizing the target tactile vibration when the lights appeared in incongruent spatial locations than when they appeared in congruent locations (Pavani et al., 2000). This congruency effect (CE) was indexed by a difference in response times (RTs; i.e., incongruent RTs minus congruent RTs). It is important to note that this general spatial CE was present in both the fake hand and the no fake hand conditions. That is, in all conditions, the spatial location of the distractor lights interfered with the tactile location reports.

A second finding was that the CE in the fake hand condition (145 msec) was larger than that in the no fake hand condition (90 msec). That is, the CE increased simply by placing the pair of fake hands next to the distractor lights and in alignment with the observer's hands below. According to Pavani et al. (2000), the distractor lights captured the location of the tactile vibration, and this capture effect was enhanced by the presence of the aligned fake hands. This fake hand effect is larger than the general CE noted above and, therefore, provides indirect evidence of sensory integration when the fake hand is present and aligned with the observer's own unseen hands. However, this effect has yet to be compared with the sensory integration observed when the lights and the tactile vibrations occur in the same physical locations.

A third finding of interest was that the fake hand effect disappeared when the fake hands were oriented at right angles to the observer's arms (i.e., the CE dropped back to 85 msec), suggesting that attributing touch to an external object may require more than a mere temporal correlation between vision and touch. But this postural CE was also not explored further in that study.

Overview of Experiments

A serious limiting factor in the design used by Pavani et al. (2000) was that it did not include a control condition in which the tactile stimuli were delivered to the same location as the distractor lights. Comparison with this condition would permit the visual–tactile integration observed in the fake hand condition (i.e., increase in baseline CE due to the presence of the fake hand) to be compared directly with both (1) the general spatial CE (when no fake hand is present) and (2) the effect obtained when vision and touch are actually spatially congruent.

We therefore first replicated Pavani et al.'s (2000) design, while including a condition in which the observer's own hands (and tactile vibrators) were located in the position normally occupied by the fake hands (Experiment 1). We found that the CE in this real-hand baseline was larger overall than that in the fake hand condition. Thus, the referral of tactile sensations to a remote location is not identical to receiving the tactile stimuli at that location.

In Experiment 2, we examined the contribution of direct vision of the fake hand to the magnitude of the CEs. One surprising finding was that CEs were unaffected by whether the fake hands were directly visible or not. However, a second important finding was that the presence of one directly visible hand in the context of another hand that was covered had a strong influence on the CEs, so that the effects were larger on the side of the visible hand. This points to some flexibility in the extent to which the body schema incorporates the rubber glove, with direct visual support being stronger than visual imagery (memory).

In Experiment 3, we tested whether the discrepancy between the quantitative results obtained in the present experiment and the subjective reports collected by Pavani et al. (2000) could be accounted for by the fact that the observers did not wear gloves in the present experiments but wore them in Pavani et al.'s task. We showed that the CEs were not influenced by the addition of tactile information congruent with the visible rubber gloves. If the fake hand effect relied on the quality of the tactile experience, wearing the gloves would have modified the CEs. That they were unaffected by the additional tactile information emphasizes further that the fake hand effect is based on a more general interaction between vision and touch than on any one modality in particular.

In Experiment 4, we examined the influence of corresponding postures between the real and the fake hands more systematically than Pavani et al. (2000) did, by maintaining the general orientation of the arm (straight ahead) while manipulating rotation around the elbow (either supine or prone vs. mixed). The results showed that strong CEs depended on the correspondence between the rotational postures even though the two were still aligned in orientation.

EXPERIMENT 1

A general spatial CE was reported by Pavani et al. (2000) even in the baseline condition, where there was no fake hand. For example, visual signals from "upper" locations proved to be an advantage when the tactile discrimination also involved a signal from an "upper" location and were a disadvantage when the tactile signal was from a "lower" location. We refer to this as a *general* CE, because it occurred regardless of the specific locations of the signals along the horizontal meridian.

In addition, Pavani et al. (2000) reported an increase in the CE that was linked to the spatial location of a visible rubber glove. The CE was now larger if the glove was present on the same side as the hand where the tactile discrimination was required. We refer to this as the *fake hand effect*, because it is an index of visual–tactile integration that can be uniquely attributed to the presence of the rubber glove.

The primary goal of Experiment 1 was to consider the fake hand effect in the context of a new condition, the *real hand baseline*, in which the tactile target occurred in the locations normally occupied by the fake hand. If tactile vibrations in the fake hand effect are being fully attributed to the glove locations, the CE should be similar in magnitude in the fake hand and the real hand baseline conditions. In addition to this primary question, three additional questions were considered in Experiment 1.

Are Response Patterns Similar for a Visible Glove and a Real Hand?

Regardless of the absolute CE in the fake hand versus real hand baseline conditions, it is important to know whether these two conditions are influenced in similar ways by factors relevant to visual–tactile integration. If they are, it will strengthen our confidence in the fake hand effect as an index of visual–tactile integration. For instance, previous research has indicated that tactile target processing is disrupted more by near than by far distractors (Driver & Grossenbacher, 1996; Macaluso, Frith, & Driver, 2000; Soto-Faraco, Ronald, & Spence, in press), even when other factors are controlled (e.g., distance of distractor from eye or ear; see, e.g., Driver & Spence, 1994; Spence, Ranson, & Driver, 2000). By measuring the CE at multiple target–distractor horizontal separations, it is possible to determine whether the pattern generated in the presence of the fake hand (fake hand condition) is more similar to the case in which the observer's own hand is at the location specified by vision (i.e., real hand baseline condition) or at the location specified only by proprioception (i.e., no fake hand condition).

Is the Fake Hand Effect Influenced by the Observer's Viewing His or Her Own Arm?

Previous research has suggested that vision of a limb can significantly influence the perception of unseen tactile stimuli delivered to the limb (di Pellegrino & Frassinetti, 2000; Kennett, Taylor-Clarke, & Haggard, 2001; Làdavas, Farnè, Zeloni, & di Pellegrino, 2000; Pierson, Bradshaw, Meyer, Howard, & Bradshaw, 1991), even when the view is given by a monitor and the observer sees his or her own limb indirectly (Tipper et al., 1998; Tipper et al., 2001). On the other hand, there is some evidence to suggest that viewing the space above the hidden limb might be sufficient to benefit target localization (Newport, Hindle, & Jackson, 2001). Given these two possibilities, it is important to determine whether the CE in the no fake hand and real hand baseline conditions is affected by the visibility of the real limb. To assess this question, the observers' limbs in these two conditions were visible on half of the trials and were hidden from view on the remaining trials.

Is a Direct View of the Glove Necessary for Tactile Attribution?

Thus far, the fake hand effect has been tested only under conditions in which the fake hand was in complete view of the observers. The question remained as to whether the fake hand effect would persist when the observers knew that the fake hand was present but were no longer permitted to see it directly. To test this, the visibility of the fake hand was manipulated so that, on half of the trials in which it was present, it was visible, and on the remaining trials, it was hidden from view under a black cloth. It was expected that if a direct view of the fake hand is necessary for tactile attribution, a larger CE should be obtained when the fake hand was visible than when it was hidden.

Method

Participants. Forty-two undergraduate observers from the University of British Columbia psychology participant pool participated in a 45-min experimental session in return for partial course credit. All had normal or corrected-to-normal vision. All the observers were naive as to the purpose of the experiment and were fully debriefed upon completion.

Procedure. The task of the observers was to make a speeded forced choice tactile localization judgment. The target was a tactile vibration applied to either the finger or the thumb of the observer's right hand. Location responses were made via two foot pedals, one positioned under the toes of the right foot, and the other under the heel. At rest, both pedals were depressed.[1] To indicate that the tactile vibration location was at the finger, the observers released the pedal under their toes briefly and then rested. To indicate that the tactile vibration location was at the thumb, they briefly released the pedal under their heel and then rested. The observers were instructed to ignore the simultaneous onset of a distractor light-emitting diode (LED) while maintaining center fixation and attending to the target tactile vibration. The observers took short breaks between each experimental block of trials.

Apparatus. Figure 1 includes illustrations of the basic experimental setup for each of the three conditions, including samples of the visibility manipulation: visible (Figure 1A) and hidden (Figure 1B). Also included in Figure 1 is an example of each of the three target–distractor separations (none, small, and large). A chinrest was centered on a table. It was used to stabilize the position of the observer's head at a distance of 47 cm from a red central fixation LED. Cardboard boundaries were constructed and secured on the left and right sides of the chinrest and were used to maintain the position of the observer's forearms.

The two target tactile vibrators were Oticon-A bone conduction vibrators of 100 Ω. They were positioned in the upper and lower left-hand corners of a foam cube. A TENMA function generator was used to deliver each tactile target. To mask the sound of the vibrators, white noise was played through a pair of headphones worn by the observers. Two yellow distractor LEDs were positioned in the upper and lower right-hand corners of a second foam cube, which was placed on top of a tall strip of foam running horizontally from the back of one set of forearm boundaries to the other.

The fake hand, used at different points during the experiment, was constructed using a right-handed pink soft rubber dishwashing glove stuffed with cotton batting. When the fake hand was present, it rested on a sheet of black foam-core board that was positioned over the top of the forearm boundaries. Note that whenever the fake hand was present, this meant that the observer's own hands were under the foam-core board and, thus, out of sight.

The observers made their responses by releasing one of two foot pedals as quickly and as accurately as possible. When they localized the tactile vibration to their fingers, the observers were instructed to release the pedal under the toes, and when they localized the tactile vibration to their thumbs, they were instructed to release the pedal under the heel.

Stimuli. To produce a visual distractor, one of the two LEDs was flashed three times for a duration of 50 msec each time, with each flash separated by a 50-msec interstimulus interval (ISI). To produce the tactile target, three 50-msec 200-Hz sine-wave signals separated by 50-msec ISIs were sent from one of the two tactile vibrators. The target and the distractor were always presented simultaneously. Target and distractor locations were random, with the constraint that each location was selected from equally often. Whenever the observers made an error in response (including a failure to provide a response),

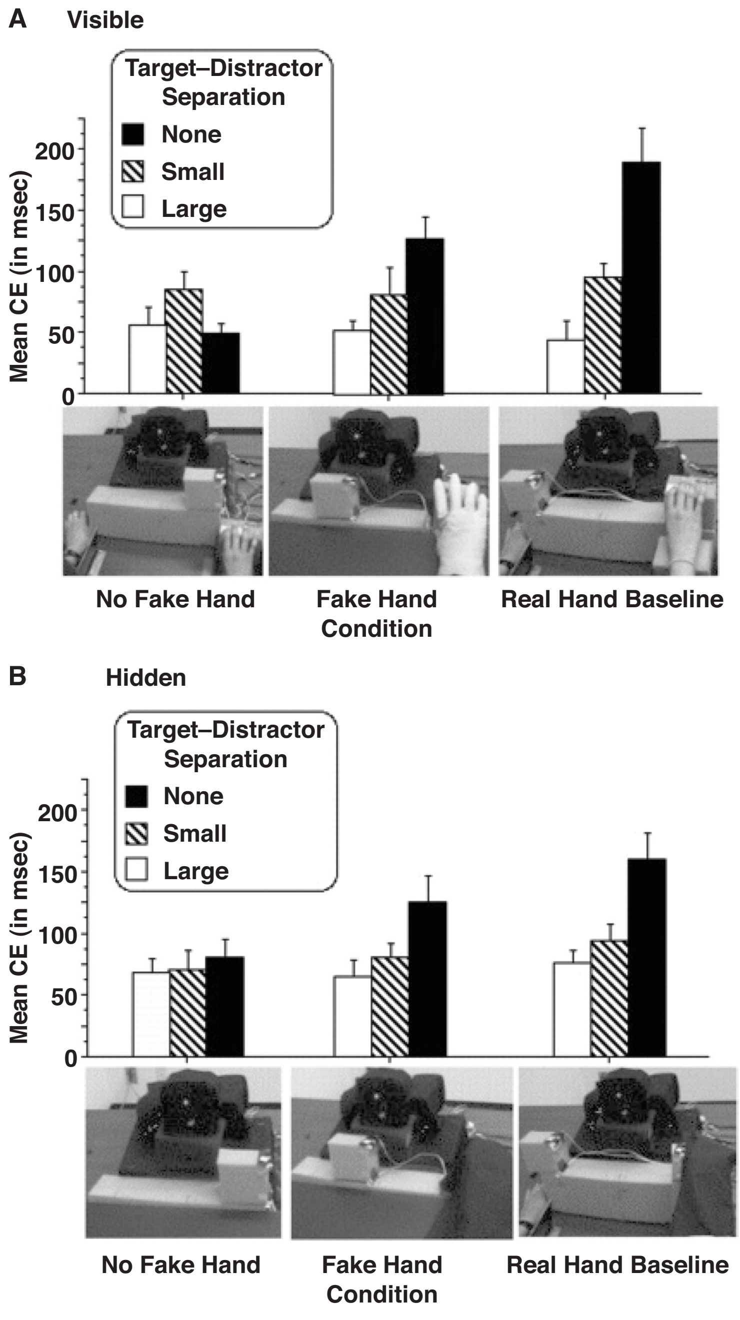

Figure 1. Mean response time congruency effect (CE, in milliseconds) for Experiment 1 as a function of condition (no fake hand, fake hand, or real hand baseline) and target–distractor separation (none, small, or large) for (A) visible and (B) hidden limbs. Error bars are ±1 standard error of the mean.

a yellow LED positioned 2 cm below the fixation LED was flashed six times for 50 msec each time (50 msec between each flash).

Design. Each observer completed two practice blocks of 15 trials at the beginning of the experiment. In the first practice block, only tactile stimuli were presented (i.e., no distractor lights). The second practice block consisted of both visual and tactile stimuli. Following the practice blocks, the observers participated in six experimental blocks of 96 trials (576 trials in total). Correct RTs and mean percentages of errors were recorded.

The observers were randomly assigned to one of three conditions: no fake hand ($n = 14$), fake hand ($n = 14$), or real hand baseline ($n = 14$). In all three conditions, the observer held the vibrator cube between the index finger and the thumb of the right hand. The no fake hand and fake hand conditions were similar to those tested by Pavani et al. (2000), wherein the observer's right hand was always below the position of the distractor cube. In the fake hand condition, a sheet of foam-core board was spread over the top of the forearm boundaries, thus hiding the observer's hands below, and the fake hand was positioned on top of the foam-core board on the right-hand side. Note that this positioning of the fake hand meant that it was always aligned vertically with the observer's hand, below, and it was aligned horizontally with the distractor cube. A foam cube was positioned between the index finger and the thumb of the fake hand to enhance the similarities with the observer's hand. On trials in which the distractor cube was positioned beside the fake hand, the fake index finger rested next to the upper distractor light, and the fake thumb rested next to the lower distractor light. The real hand baseline condition was the key comparative condition introduced in the present study. It was similar to the no fake hand condition, with the one exception that the height of the observer's hand was raised to the level of the distractor cube by having the observer rest the arm on a thick strip of foam.

Three within-subjects factors were manipulated: *congruency* of target–distractor locations, horizontal *separation* between the distractor cube and the target cube, and the *visibility* of the observer's hand or of the fake hand (when present). Each of these factors will be described in turn below.

Target–distractor locations were either congruent or incongruent (congruency factor). Congruent trials, in this case, consisted of an upper LED paired with a top–finger vibration or a lower LED paired with a bottom–thumb vibration. Incongruent trials, in contrast, consisted of an upper LED paired with a bottom–thumb vibration or a lower LED paired with a top–finger vibration. Each target–distractor pair occurred equally often in each block.

The horizontal separation between the LED distractor cube and the target tactile vibration cube was manipulated by moving the distractor cube in a leftward direction away from the tactile vibration cube. There were three possible separations: none (0 cm apart, distractor cube at right), small (15 cm apart, distractor cube at center), or large (30 cm apart, distractor cube at far left). Note that within any condition, the position of the target tactile vibration cube remained constant, in that it remained on the right side. Thus, the distractor cube was always to the left of the target cube, and only the position of the distractor cube was altered. This meant that when the fake hand was present, it remained on the right side above the location of the observer's hand, below, and the distractor lights were beside the fake hand, a small distance away, or a larger distance away.

The visibility of the observer's limbs in the no fake hand and real hand baseline conditions and the visibility of the fake hand in the fake hand condition were manipulated so that they were visible on half of the trials and hidden on the remaining trials. The sheet of foam-core board was used to hide the observer's hand in the no fake hand condition, whereas a black cloth was used to hide the fake hand and the observer's hand in the remaining two conditions.

The two within-subjects factors, separation (three levels) and visibility (two levels), were blocked, resulting in six blocks in total. The order of blocks was randomized. Condition (three levels) was a between-subjects factor.

Results and Discussion

On each trial, target localization RTs and mean percentages of errors were recorded.[2] Correct mean RT CE and error CE were then computed for each condition by finding the difference between the incongruent and the congruent means. Since RT CE was the main measure of interest (e.g., objective measure of tactile attribution), it will be the focus of all the analyses and discussions reported. Mean error CE will be reported only where significant. Since, in all cases, either there were no significant effects in error CE, or the same pattern of data was found across conditions in both RT CE and error CE (e.g., the larger RT CE paired with the larger error CE), speed–accuracy tradeoffs were not a concern.

In addition to these main analyses of the CE, identical analyses were computed using the mean correct RT and the mean percentage of error data. This was done to ensure that the pattern of results for the CE, which are difference scores, was similar to that for the direct scores. Since these results were always consistent with the RT and error CE analyses, they will not be reported here.

Both RT CE and error CE were subjected to analyses of variance (ANOVAs) involving within-subjects factors of separation (none, small, or large) and visibility (visible or hidden) and the between-subjects factor of condition (no fake hand, fake hand, or real hand baseline). Significant three-way interactions were followed up using simple interaction effects, whereas significant two-way interactions were followed up using simple effects testing. Significant main effects were followed up using least significant difference (LSD) tests. The results are considered below with regard to the four questions raised in the introduction to Experiment 1.

Tactile attribution. As is pictured in Figure 1, when the limbs were visible and there was no separation between the targets and the distractors (see the solid black bars in Figure 1A), there were significant differences in the magnitude of the CE across the three conditions [$F(2,39) = 12.75$, $MS_e = 5,371$, $p < .001$]. The CE was largest for the real hand baseline condition (189 msec), smaller for the fake hand condition (128 msec), and smallest for the no fake hand condition (50 msec). All the paired comparisons were significant at $p < .05$. This suggests that although tactile targets were mislocalized toward the fake hand when it was present, the felt location of touch was different when vision alone indicated that the tactile vibrations were beside the distractor lights (fake hand condition), as compared with when vision and proprioception indicated a spatial alignment between the targets and the distractors (real hand baseline condition). This is an important new finding, since it indicates that the attribution of touch to the fake hand is less compelling than the observer's subjective reports would lead one to believe.

Response patterns for a fake versus a real hand. Overall, the CE decreased with increasing target–distractor separation in the fake hand and the real hand baseline conditions, but not in the no fake hand condition. The condition × separation interaction was significant when the limbs were visible [$F(4,78) = 7.99$, $MS_e = 2,984$, $p < .01$]. For the real hand baseline condition, the CE was largest when there was no target–distractor separation (189 msec), it decreased for the small separation (95 msec), and it decreased even further for the large separation (44 msec; all ps $< .05$). Similarly, for the fake hand condition, the CE tended to be larger when there was no separation (128 msec) than when there was either a small separation (82 msec; $p < .06$) or a large separation (52 cm; $p < .05$), but the comparison between the CEs at the latter two separations did not reach significance ($p > .05$). In contrast, for the no fake hand condition, the CE was larger at the small separation (85 msec) than when there was no separation (50 msec; $p < .05$). The comparisons with the large separation (56 msec) did not reach significance (p values $>$

.05). These results are consistent with the idea that the fake hand is similar to a real hand for observers, although the effect is not as compelling as when the observer's own hand is in the location of the glove.

It is interesting to note that in the fake hand and the real hand baseline conditions, the CE was largest overall when there was no target–distractor separation, despite the fact that at the small separation, the distractor lights were located at the center of gaze. If seeing the distractors were the key factor, one would expect that it would be at this location that the lights would have the greatest impact on target localization responses. That they had their greatest impact when they were next to the target vibrations and away from the center of gaze indicates that it is the spatial proximity between the targets and the distractors that is of most importance. This target–distractor separation effect is consistent with earlier reports suggesting that the greater the discrepancy in information within the visual and proprioceptive sources, the less evidence there is for visual bias (Over, 1966; see Welch & Warren, 1986).

Given that the separation pattern above was not observed in the no fake hand condition, it is likely that the vertical separation between targets and distractors was sufficient to weaken the magnitude of the CE. In fact, it was only in this condition that the CE tended to be higher at the center of gaze (small separation) than when there was no separation between the targets and the distractors. Furthermore, since the separation effect was present in the fake hand condition, it suggests that the fake hand must have successfully bridged the vertical target–distractor separation that was apparent in the no fake hand condition.

When mean error CE was used as the dependent variable, only the main effect of separation was significant [$F(2,78) = 6.98$, $MS_e = 41$, $p < .01$]. LSD testing revealed that the CE was larger when there was no target–distractor separation (7%) than for either the small (4%) or the large (4%) separations ($ps < .01$), which were not significantly different from one another ($p > .20$).

CE for a visible versus a hidden hand. Hiding either the real or the fake hand from view had very little impact on the CE, in comparison with when the hand was visible (compare Figure 1B with Figure 1A). The exception to this is for the no target–distractor separation (see the solid black bars in Figure 1), where the condition × visibility interaction approached significance [$F(2,39) = 3.05$, $MS_e = 2{,}108$, $p < .06$; remaining $Fs < 1$]. The CE was larger in the no fake hand condition when the observer's hand was hidden (81 msec; see Figure 1B) than when it was visible [50 msec; see Figure 1A; $F(1,13) = 4.54$, $MS_e = 1{,}494$, $p < .055$; all remaining p values $> .05$]. Since this effect of visibility was limited to the no fake hand condition, it seems likely that making the observer's hand visible in this case emphasized the vertical separation between the tactile vibrations and the distractor lights, thereby reducing the CE.

The finding of a fake hand effect even when the fake hand was covered with a cloth is somewhat of a surprise, since it suggests that directly seeing the hand is not critical for tactile attributions. It also suggests that knowing that the fake hand is present and having partial visual information to reinforce that is sufficient to influence responses. We examined this finding with a more stringent test of visibility in Experiment 2.

EXPERIMENT 2

In order to confirm that the fake hand effect persists without visibility of the fake hand, we introduced two different manipulations in the context of the original experimental design used by Pavani et al. (2000). First, a box was used to cover the glove, instead of a cloth, in order to eliminate information about the shape of the covered hand. If a placeholder is sufficient to remind the observer of the fake hand's presence, the CE obtained when the hand is hidden under the box will be like that found with the cloth in Experiment 1. In contrast, if the placeholder is not sufficient, the CE should be smaller when the glove is hidden under the box.

Second, we tested a condition in which one glove was hidden and a second glove was in view. We reasoned that vision of only one limb might introduce a perceptual competition between the visible and the hidden limbs and that tactile attributions would be influenced by this competition. That is, the more detailed visual information might carry more weight than partial visual information when both were available.

Vibrotactile stimulators were now held in both the left and the right hands, and in the fake hand condition, a fake hand was positioned above each of the observer's hands. In the no fake hand condition, the fake hands were absent, and only the distractor lights and the central feedback cube were visible. With this design, it was possible to present tactile targets and visual distractors to either the right or the left side of space. Most important, it was possible to manipulate the visibility of both fake hands or the visibility of just a single fake hand. For example, hiding one of the fake hands meant that the other fake hand was visible. This tested the hypothesis that a visual reminder of the fake hand (without vision of the fake hand itself) is sufficient for tactile mislocalization.

Method

The method was identical to that in Experiment 1, with the following exceptions.

Participants. Thirteen undergraduate students participated in a 1-h experimental session for partial course credit.

Apparatus. The observers laid their arms on the surface of a table (within arm boundaries on either side) and underneath a smaller stand, where they held a foam cube in each hand. Each foam cube contained a pair of tactile vibrators. On the surface of the smaller stand, two foam cubes were positioned so that one was aligned above each tactile foam cube, held below. These visible cubes each held pairs of distractor lights. In four of the five conditions, a pair of fake hands was positioned so as to appear to "hold" the distractor lights on their respective sides. To hide either or both of the fake hands, a box cover was placed over the top of the hand. In doing so, hand shape information was eliminated. On the remaining block, the fake hands were absent.

Stimuli. There were now four possible target locations and four possible distractor light locations. The locations were randomly selected, with the constraint that all the locations were selected from equally often and that there were equal numbers of congruent and incongruent trials and equal numbers of same- and opposite-side target–distractor presentations.

Design. The observers participated in three training sessions of 15 trials each, followed by five experimental blocks of 96 trials. All factors were run as within-subjects factors. The observers participated in five randomly ordered fake hand conditions: no fake hand, both visible, both hidden, left-hand hidden, and right-hand hidden. Note that in all the conditions, the observer's hands were always underneath the small stand, below the level of the distractor lights. In the no fake hand condition, there were no fake hands on the stand; only the distractor light cubes and the feedback cube in the center were visible. In the remaining conditions, both fake hands were present and were positioned so as to appear to "hold" the distractor lights. In the both visible condition, both fake hands were in view, whereas in the both hidden condition, both fake hands were hidden beneath box covers. In the left-hand hidden and right-hand hidden conditions, the left or the right fake hand, respectively, was hidden from view underneath a box cover, while the remaining hand was visible.

Results and Discussion

Mean RT CE and mean error CE were again the dependent measures of interest, and the analyses followed the pattern established in Experiment 1. All the factors were within subjects and included condition (no fake hand, visible, hidden, left-hand hidden, or right-hand hidden) and target–distractor side (same or opposite).

Both fake hands visible versus hidden. When both fake hands were hidden from view, using box covers, the CE was of the same magnitude as when both fake hands were visible (see Figure 2). The main effect of condition was significant only when the targets and the distractors were presented to the same side of fixation [$F(2,50) = 5.44$, $MS_e = 10{,}422$, $p < .05$]. The CE was smaller in the no fake hands condition (77 msec) than in either the both visible (169 msec) or the both hidden (137 msec) condition ($ps < .05$). The CE in the latter two conditions did not differ significantly from one another ($p > .20$). These results suggest that when observers are aware of the presence of the fake hands but are unable to see them directly, they continue to mislocalize tactile targets to them. This means that the fake hand effect can be elicited by partial visual information that simply reminds observers that the fake hands are present.

Error CE was larger when the targets and the distractors were presented to the same side (6.1%) versus the opposite side (1.8%) of fixation [$F(1,25) = 9.03$, $MS_e = 79$, $p < .01$]. No other effects were significant (Fs < 1).

One visible versus one hidden fake hand. The main finding here was that the CE was significantly larger for same-side targets and distractors when they were presented on the side of the visible fake hand (182 msec), as compared with the side of the hidden fake hand [106 msec; $F(1,25) = 7.33$, $MS_e = 10{,}278$, $p < .05$; see Figure 2A]. This finding suggests that when there is potential for competition between a visible and a hidden hand, observers will weight the visual information more heavily, so that full visual cues influence tactile localizations more than do partial cues. This is an important finding, since it indicates flexibility in the observer's usage of the visual information that is available when there is a discrepancy between the seen and the felt limb locations. In the absence of any other visual information, observers will respond to a hidden limb as though it were visible, but they will fail to do so when there is more salient visual information available.

Error CE for same-side target–distractor presentations tended to be larger for targets presented to the visible

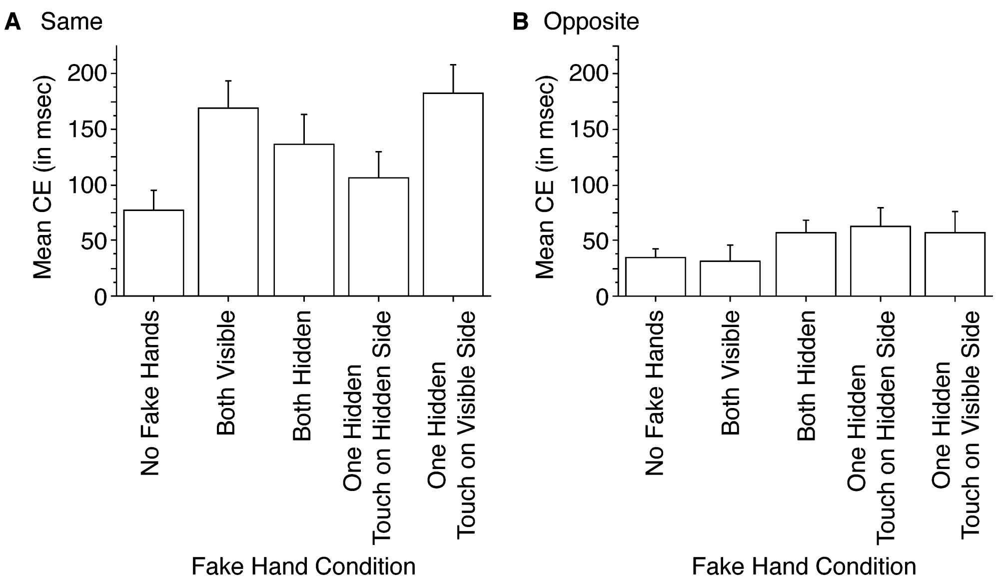

Figure 2. Mean response time congruency effect (CE, in milliseconds) for Experiment 2 as a function of fake hand condition (no fake hands; both visible; both hidden; one hidden, touch on hidden side; or one visible, touch on visible side) for (A) same and (B) opposite target–distractor presentations. Error bars are ±1 standard error of the mean.

(12%) versus the hidden (7%) fake hand [$F(1,25) = 3.07$, $MS_e = 111$, $p < .10$]. With opposite-side target–distractor presentations, error CE tended to be larger when the targets were presented to the hidden hand (6%) than when they were presented to the visible hand [2%; $F(1,25) = 3.26$, $MS_e = 59$, $p < .10$]. This last result, although not significant in the RT CE, is still consistent with the pattern observed there.

Experiments 1 and 2 confirm previous findings that tactile targets can be mislocalized toward a fake hand. The novel contribution of these experiments is that tactile targets are not mislocalized to the extent that the experience replicates the one observers have when they hold their own hands in the same location as the fake hands. This places a serious qualification on the subjective reports collected by Pavani et al. (2000), indicating that observers feel "as if the rubber hands were my hands," or "as if I was feeling the tactile vibration in the location where I saw the rubber hands," or even that it "seemed as if the lights were near to my real hands" (p. 357). In particular, the present results indicate that the experience is only 70% of its full possible strength.[3]

One possible explanation for this discrepancy in the results obtained using qualitative (subjective reports) versus quantitative measures (CE in RT) is that the observers tested in Experiments 1 and 2 did not wear gloves on their hands to match the fake hands, whereas the observers tested in Pavani et al. (2000) did. That is, it may be that feeling the soft rubber on their hands, as well as seeing the soft rubber fake hands, enhanced the experience of tactile mislocalizations. Experiment 3 was designed to test whether the fake hand effect was any stronger when the observers could feel the rubber material on their own hands.

EXPERIMENT 3

The main question addressed in the present experiment was whether a tactile sensory experience, in addition to a visual one, could influence the magnitude of the fake hand effect. That is, can the experience of feeling soft rubber on one's hands at the same time as seeing the soft rubber of the fake hands enhance the fake hand effect. To test this, the observers wore a pair of soft rubber kitchen gloves on their hands that matched those used to construct the fake hands. The prediction was that if the feel of rubber on one's hands increases tactile attribution to the fake hands, the CE would be larger when the observers wore a pair of soft rubber gloves than when their hands remained bare.

Method

The method was identical to that in Experiment 2, with the following exceptions.

Participants. Fourteen undergraduate students participated in a 45-min experimental session in return for partial course credit.

Apparatus. The observers laid their arms on the surface of a table (within arm boundaries on either side) and underneath a smaller stand, holding one foam cube containing a pair of tactile vibrators as described in Experiment 1. A black cloth was draped over the surface of the stand, obstructing a view of the observers' hands. An additional foam cube was aligned above each of the observers' hands, below. This pair of cubes held pairs of distractor LEDs. Again, these were as described in Experiment 1. On half of the experimental blocks, the observers were required to wear a pair of pink soft rubber kitchen gloves (a variety of sizes was available). As well, the observers wore a pair of thin disposable glove liners inside the kitchen gloves for sanitary purposes.

Design. The observers participated in three training sessions of 15 trials each, followed by eight experimental blocks of 96 trials. In addition to the within-subjects factors of condition (no fake hand or fake hand), congruency (congruent or incongruent), and distractor side (same or opposite), there was an additional within-subjects factor referred to as *gloves* (none or rubber). Half of the observers wore the gloves for the first four blocks and took them off for the remaining blocks, whereas the other half of the observers did the opposite.

Results and Discussion

The main finding was that mean RT CE was the same magnitude in the fake hand condition whether the observers experienced the feel of soft rubber on their hands or not, as is shown in Figure 3. That is, none of the main effects or interactions involving the gloves factor reached significance ($ps > .05$). The CE was larger overall in the fake hand condition (94 msec) than in the no fake hand condition [59 msec; $F(1,13) = 10.77$, $MS_e = 3{,}143$, $p < .01$]. And as was expected, the CE was larger overall when the target and distractor were presented on the same side of fixation (100 msec; see Figure 3A) versus the opposite side [53 msec; see Figure 3B; $F(1,13) = 16.93$, $MS_e = 3{,}692$, $p < .01$].

When error CE was the dependent measure, the condition × distractor side interaction was significant only when the observers did not wear gloves [$F(1,13) = 8.26$, $MS_e = 18$, $p < .05$]. This was such that when the targets and the distractors were presented on the same side, error CE was larger overall in the fake hand condition (12%) than in the no fake hand condition [4%; $F(1,13) = 4.82$, $MS_e = 97$, $p < .05$]. When the targets and the distractors were presented on the opposite side, the simple main effect of condition did not reach significance ($F < 1$).

These findings suggest that the fake hand effect is not influenced by the experience of a feeling of rubber that matches the visual information about the hands. Nor is it necessary to have a perfect match in either the texture or the visual material of the fake hands and the real hands.[4] But one can also ask whether wearing gloves weakened the tactile signal overall. This possibility is ruled out by the observation that the speed and accuracy of detection of the target tactile vibrations were not affected by whether the observers wore gloves or not, thus suggesting that the tactile signal was unchanged by the gloves.[5] Could it be the case that once the observers had worn the gloves for the first four blocks, the effect persisted for the remaining blocks after they had been removed? Again, this possibility was ruled out by the finding that the effects were larger, if anything, when the observers wore the gloves in the second half of the experiment (i.e., positive carryover from gloves to no gloves is not an issue).[6]

EXPERIMENT 4

We have shown that the fake hand effect is obtained when vision gives only *placeholder* information about the

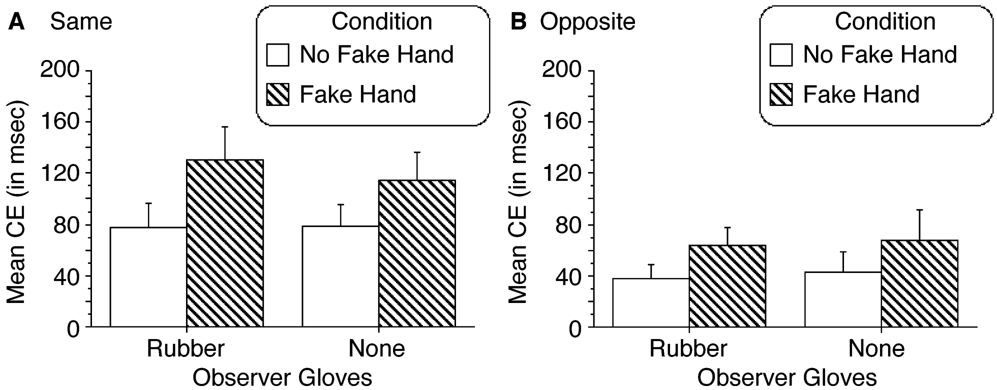

Figure 3. Mean response time congruency effect (CE, in milliseconds) for Experiment 3 as a function of condition (no fake hand or fake hand) and observer gloves (rubber or none) for (A) same- and (B) opposite-side target–distractor presentations. Error bars are ±1 standard error of the mean.

location of the glove (Experiments 1 and 2) and that it does not depend on the "feel" of the hand being congruent with the feel of a glove (Experiment 3). A question that remains then is whether the glove is actually incorporated into the mental representation of the body (the body schema) or whether the glove serves only as an external object that contributes to spatial interference effects, as many other studies have already shown for vision and touch independently (e.g., Driver & Grossenbacher, 1996; Soto-Faraco et al., in press). This can be tested by systematically manipulating the postural relations between the visible glove and the observer's hidden arm.

Pavani et al. (2000) showed that the fake hand effect "is specific to the case in which the rubber hand is aligned so as to look plausibly like the participant's own hand" (p. 356). The manipulation in that study involved either keeping the glove aligned with the observer's hand, below, or turning the gloves by 90º so that they were misaligned with the observer's arms (i.e., perpendicular to the real arm). But note that this manipulation involved changes in both visual alignment and posture. That is, when the gloves were aligned with the observer's hands, both the dominant visual position of the glove and its posture matched the observer's arm. When the glove and the arm were misaligned, both the dominant visual position and the posture mismatched the observer's arm. This makes it difficult to determine whether visual position or postural compatibility is the critical factor. If the fake hand effect is an index of how strongly the glove is incorporated into one's body schema, postural compatibility should be the critical factor.

Alternatively, if the fake hand effect remains strong when visual alignment is maintained but there is a postural mismatch (e.g., fake hands in a prone posture, real hands in a supine posture), it would suggest that the gloves are not being incorporated into the body schema. Instead, this result would be consistent with the fake hand effect's being another instance of a more general spatial interference effect (e.g., Driver & Grossenbacher, 1996).

In order to test the contributions of postural matches between the fake and the real hands to the fake hand effect, the alignment of the gloves and the hands was held constant in Experiment 4 (both were always pointing in the direction of the distractor lights), but their relative postures were varied. The postures of the gloves and the hands either matched (both prone or both supine) or mismatched (one prone, the other supine).

Method

The method was identical to that in Experiment 3, with the following exceptions.

Participants. Twenty-eight participants received partial course credit for their participation in the 45-min experimental session.

Details. The observers participated in three practice blocks of 15 trials. There were six experimental blocks of 96 trials, for a total of 576 trials. The observers were randomly assigned to one of two observer hand orientations: prone or supine. In the prone position, the observers rested the finger on the top tactile vibrator and the thumb on the bottom tactile vibrator, as before. In the supine position, the observers adopted the reverse position (i.e., rested the finger on the bottom tactile vibrator and the thumb on the top tactile vibrator). All the remaining factors were within subjects and included fake hand condition (no fake hand, prone, or supine) and distractor side (same or opposite). Note that for a prone fake hand, the finger of the fake hand rested next to the upper distractor light, and the thumb rested next to the lower distractor light, as before. For a supine fake hand, the finger was next to the lower distractor light, and the thumb was next to the upper distractor light.

On two blocks of trials, the orientation of the fake hands was consistent with that of the observer's hands (e.g., observer's hands prone, fake hands prone). On another two blocks, the orientation of the fake hands was inconsistent with that of the observer's hands (e.g., observer's hands prone, fake hands supine). On the remaining blocks, the fake hands were absent.

Procedure. The observers in the prone condition were instructed to respond by using a toe lift when they localized the tactile vibration to the finger (top digit) and to respond with a heel lift when they localized the tactile vibration to the thumb (bottom digit). In contrast, the observers in the supine condition were given the reverse instructions—to respond with a toe lift when the tactile vibration was localized to the thumb (top digit), and to respond with a heel lift when the tactile vibration was localized to the finger (bottom digit). It was important to give these instructions to the observers in the supine condition, in order to hold constant the mapping of spatial location to response across different limb orientations. It meant that a tactile vibration on the top digit was always paired with a toe lift response, and a tactile vibration on the bottom digit was always paired with a heel lift response.

Results

Mixed design ANOVAs were computed using observer hand orientation (prone or supine) as a between-subjects factor and fake hand condition (no fake hand, prone, or supine) and distractor side (same or opposite) as within-subjects factors. The main finding was that the fake hand effect occurred only when the posture of the gloves was consistent with the arm posture of the observer, as is shown in Figure 4. When the observer's hands were prone, the main effect of fake hand condition was significant [$F(2,26) = 5.14$, $MS_e = 1{,}280$, $p < .05$], where the CE was largest when the fake hands were prone (94 msec), rather than supine (72 msec) or absent (64 msec; ps $< .05$). When the observer's hands were supine, the main effect of fake hand condition was again significant [$F(2,26) = 3.80$, $MS_e = 2{,}874$, $p < .05$], but in this case, the CE was largest overall when the fake hands were supine (95 msec), as compared with prone (55 msec; $p < .05$).

It is important to note that whenever the orientations of the real and the fake hands were inconsistent, the CE was not significantly different from when there were no fake hands (ps $> .10$). This indicates that the fake hand effect depends on the postural compatibility of the visible glove and the unseen arm of the observer. We interpret this as strong evidence that the visible glove is being incorporated into the body schema of the observer.

When error CE was the dependent measure, only the main effect of distractor side was significant [$F(1,26) = 22.68$, $MS_e = 3$, $p < .01$]. Overall, the CE was larger for same side (6.8%) than for opposite side (3.0%) presentations of the targets and the distractors.

GENERAL DISCUSSION

Recent studies of visual–tactile integration have reported that vision of a rubber glove can influence tactile experience, so that vibrations delivered to an unseen limb are attributed to positions in space that closely correspond to the location of a visible rubber glove (Botvinick & Cohen, 1998; Pavani et al., 2000). The first goal of the present study was to measure this *fake hand effect* in the context of two important control conditions: no fake hand present and actual hands placed in the location of the rubber glove. Comparing the fake hand effect with performance in these two conditions indicated that it reached only 70% of its potential strength—that is, it was less compelling than the experience of having one's hands in the same locations as the visible gloves.

A second goal was to examine the influence of vision of the rubber glove on the fake hand effect. Experiment 1 indicated that direct vision of the glove was not necessary; it was sufficient to know simply that the glove was present under a cloth. This finding was replicated in Experiment 2, where the cover used to occlude the glove was a box and, therefore, no longer permitted even the shape of the glove to be seen.

Experiment 2 also revealed an important interaction in the influence of vision on the fake hand effect. Although the fake hand effect persisted when both gloves were present but covered from direct view, it was weaker when the hidden glove corresponded to the hand that was touched and a visible glove lay above the nontouched hand. This suggests that observers are reassigning perceptual weights to different sources of information, depending on the larger context of task-relevant visible and tactile stimuli. When they are given direct visual information about one hand location and only indirect visual information about the other, the visible location contributes more to the interaction with touch.

Experiment 3 tested whether the fake hand effect was influenced by the tactile experience of the observer's feeling the gloves on his or her own hand. It was not; the fake

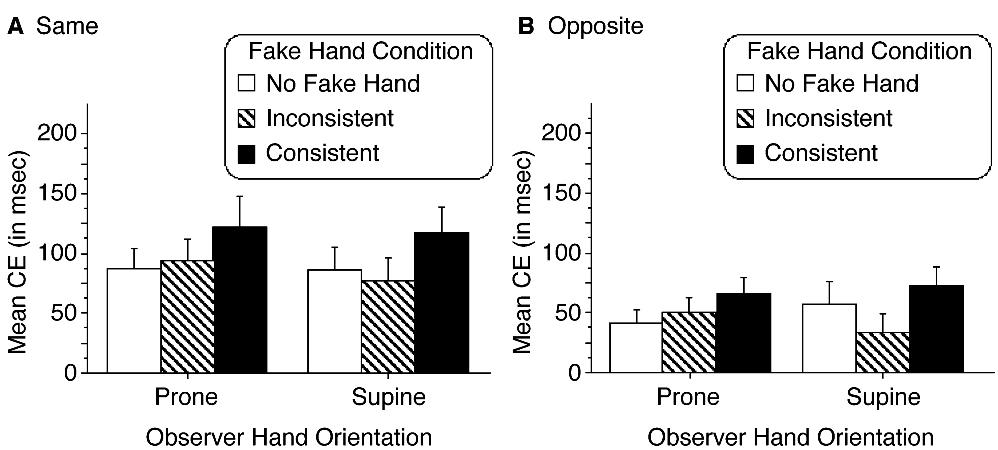

Figure 4. Mean response time congruency effect (CE, in milliseconds) for Experiment 4 as a function of fake hand condition (no fake hand, inconsistent, or consistent) and observer hand orientation (prone or supine) for (A) same and (B) opposite target–distractor presentations. Error bars are ±1 standard error of the mean.

hand effect was similar in size to that in Experiments 1 and 2. This means that only visual information about the glove was contributing to the fake hand effect.

In Experiment 4, the postural compatibility between the visible glove and the unseen arm was examined, without any confounding differences in the alignment or visual position of the gloves, as in Pavani et al. (2000). The results showed that postural compatibility was critical. When the posture of the gloves was inconsistent with that of the observer's arms, the fake hand effect disappeared. We take this as evidence that observers were incorporating the glove into their body schema in these experiments.

Overall, the results of the present study suggest that the human body schema is flexible enough to incorporate a disembodied rubber glove, provided that certain conditions are met. These include seeing the glove being placed into position beneath a cover and seeing a postural compatibility between the glove and the observer's own arm. The results also indicate that the extent to which the glove is incorporated into the body schema can be influenced quite subtly by the larger context of visible objects. Most striking, when both a fully visible glove and a hidden glove are presented as surrogates for the two unseen arms of the observer, it is the glove that is visible that determines the pattern of results.

Finally, all of these results must be interpreted against the background of the initial finding presented in Experiment 1—namely, that the visual integration indexed by the fake hand effect is not as strong as the visual integration that is observed when touch and vision correspond to the same body locations. This finding makes it clear that the prosthetic experience of the glove in the fake hand effect does not fully mimic the experience of an intact body. But at the same time, this way of indexing the fake hand effect will make it possible in future studies to determine what is needed to achieve a complete prosthetic experience.

Questions That Remain

Does the fake hand effect generalize to nonhand objects? Measures were taken in the present study to construct the fake hand so that it was undeniably hand-like. For example, the digits of the soft rubber glove were stuffed with cotton batting to make it appear as realistic as possible. But is it critical that the visual object next to the distractor lights was a hand? Perhaps there are critical properties of the fake hand that led to the tactile mislocalizations. If so, there is a chance that these properties can also be found in nonhand objects. The question thus remains as to what it is about the presence of the fake hand that leads to tactile mislocalizations.

If it is the case that the fake hand effect depends on the realistic construction of the hand, one might expect that the effect would be enhanced if a more realistic hand were used (e.g., a mannequin hand). This possibility, however, is negated by the present finding that the fake hand effect persisted even when the fake hands were no longer directly visible (Experiments 1 and 2) or even when they were replaced by costume alien hands (see note 4), although it could be the case that the visual cues available were sufficient to allow the observers to maintain a mental image of the hand.

Another possibility to consider is that the positioning of the finger and thumb of the fake hand helped to highlight the two distinct locations of the distractor lights and that this, in turn, influenced tactile mislocalizations. If so, it is likely that any visual object that highlighted the difference in locations would produce the same results. Imagine that word labels, such as *top light* and *bottom light*, were assigned to the distractor light locations. Would these manipulations lead to tactile mislocalizations? Although this is a possibility, the present findings of a fake hand effect when the digits of the fake hand were no longer visible suggest that drawing visual attention to the locations may not be a critical factor.[7]

Is an imagined hand sufficient for the fake hand effect? In the fake hand conditions of the present study, the observers always saw the fake hand as it was put in position and, thus, always saw it before it was hidden from view. The current thinking on the fake hand effect is that the available visual information is critical for producing the effect. Could it be the case, however, that simply imagining the presence of a fake hand next to the distractor lights would be sufficient for the effect in the absence of any visual cues to its presence? This might require, for example, comparing the effect across two groups, where one only imagined that the fake hand was present and the other actually saw the fake hand.[8] Note that the results of the visibility manipulation in the present study cannot distinguish between whether the partial visual cues to the fake hand's presence were critical or whether, when the fake hand was hidden, the observers were relying on a mental image of the hand.

Is the fake hand effect multisensory or multi-informational? Related to the previous question is the possibility that the fake hand effect is the result of integrating all the available visual and tactile information. According to Pavani et al. (2000), for example, the distractor lights captured the location of the tactile vibrations, and this was enhanced by the presence of the fake hand. One might ask, however, whether it was necessary that the distractors were visual (i.e., different modality than the target modality). Another way to think about this is to ask whether the fake hand effect is a product of presenting information in more than one modality (e.g., visual and tactile) or simply the product of presenting multiple sources of information. To test this, one could test whether an additional source of tactile information leads to the same result.

Is the fake hand effect observed in a dynamic task? What we currently know of the fake hand effect is based on a task in which the observer's arms remain stationary (i.e., a passive task). In most real-life situations, however, the position of the arms will change over time as one acts on objects in their surrounding environment. Thus, an important next step in this line of research will be to see whether the effect is present or strengthened in an active goal-directed task in which, for example, observers are required to reach and grasp a visible object (see Holmes, Calvert, & Spence, 2004). Knowing what happens to the fake hand effect under these conditions will have important implications for a variety of real-world scenarios, including telesurgery, where the surgeon's visual and tactile workspaces are separated in space.

Conclusion

The present findings indicate that touch on an unseen limb can be referred to a visible rubber glove, provided that certain conditions are met that support the incorporation of the glove into an observer's body schema. This includes (1) seeing the glove being placed into a position that corresponds plausibly to the location of the observer's own limb and (2) positioning the glove so that it is compatible in posture with the observer's limb. The fake hand effect documented under these conditions is best described as a weighted combination of sensory inputs, where weights are assigned flexibly to make best use of the available visual, tactile, and postural information.

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NOTES

1. This took little to no effort on the observer's part. The mere weight of the observer's foot at rest was all that was required to depress the pedals. Similarly, little effort was needed to release the pedal. The toes or heel had to be raised just enough so that the pedal was no longer completely depressed. Note that this did not require the toes or the heel to clear the pedal.

2. It should be noted that for all of the experiments, the observers were excluded if either their average RT was longer than 1,200 msec or they had fewer than 75% correct responses in any experimental condition.

3. This estimation came from dividing the largest CE in the fake hand condition (128 msec) from that in the real hand baseline condition (189 msec) and multiplying by 100.

4. This idea was further confirmed in an additional experiment in which the fake hand effect was obtained for same-side target distractor presentations when the rubber gloves were replaced by a pair of green alien costume gloves that had a visibly rough texture [fake hand (110 msec) vs. no fake hand [67 msec; $F(1,13) = 10.93$, $p < .01$].

5. Analyses using mean correct RT and mean errors as dependent variables revealed that the main effect of observer gloves was not significant in either analysis, nor did this factor interact with any of the other factors ($ps > .05$).

6. When glove order was included as a factor, the main effect was significant: The CE tended to be smaller when the gloves were worn in the first half of the experiment (50 msec) than when they were worn in the second half [112 msec; $F(1,12) = 6.21$, $p < .05$]. The glove order × condition interaction did not reach significance [$F(1,12) = 3.5$, $p > .05$].

7. Consistent with the proposal concerning differences in location, one could argue that the box cover led to the fake hand effect because it, too, had a well-defined top and bottom. But since the same results were found with the cloth cover, which had a less-defined shape, this possibility seems unlikely.

8. In such an experiment, the group participating in the imagined fake hand condition would always have to participate in the no fake hand condition first, since the instructions to imagine a fake hand might interfere with the results of the no fake hand condition were it to come first.

(Manuscript received October 31, 2003;
revision accepted for publication April 26, 2004.)