Research Article

Rubber Hands Feel the Touch of Light

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ABSTRACT—*Two experiments involving a total of 220 subjects are reported. The experiments document that "stroking" a false hand with the bright beam of light from a laser pointer can produce tactile and thermal sensations when the hand can be seen as one's own. Overall, 66% of subjects reported somatic sensations from the light. Felt hand location was recalibrated toward the location of the false hand for those subjects who felt the light. Moreover, the proprioceptive recalibration from the laser experience was comparable to that produced by actual coordinated brushing of the false hand and of the unseen real hand after 2 min of stimulation. The illusion may be experienced on one's real hand as well. The results are discussed in terms of multisensory integration.*

In the rubber-hand illusion (RHI; Botvinick & Cohen, 1998), one's hand is hidden behind an occluder, and a rubber hand is placed in view nearby in a similar orientation. If the hidden real hand and the visible rubber hand are brushed in synchrony (Fig. 1a), the felt touch (of the brush on the real hand) is experienced (rather jarringly) as being produced by the seen touch of the other brush on the rubber hand. Here we report a new perceptual illusion in which "stroking" the rubber hand with a laser light (Fig. 1b) produces thermal or tactile sensations in most observers despite the absence of any direct stimulation to their skin.

We interpret this touch-from-light illusion in terms of a multisensory-integration theory wherein perceptual signals of high certainty from one sense modality can produce perceptual consequences that influence the experience of a second modality (De Gelder & Bertelson, 2003; Driver & Spence, 2000; Ernst & Banks, 2002; Gibson, 1966; McGurk & MacDonald, 1976; Shimojo & Shams, 2001). For example, an insect crawling on the skin would not normally produce tactile sensations if the mechanical disturbances to the skin are below sensory threshold. Once the insect is seen, however, a vivid experience of tactile sensations could arise from the combination of the visual localization evidence with sensory noise from the tactile sensors (see Durgin, 2002). In the present case, sensory integration depends on the ease with which a rubber hand can be incorporated into the body schema or body image (Head et al., 1920; Schilder, 1938).

Illusory tactile sensations from seen touch have been reported in a patient with a dysfunctional tactile sensory system (Rorden, Heutink, Greenfield, & Robertson, 1999) and in a unique individual who experienced tactile sensations when seeing other people touched (Blakemore, Bristow, Bird, Frith, & Ward, 2005; see also Bradshaw & Mattingley, 2001), but no general phenomenon of touch from sight has been reported previously in normal populations. In order to document this phenomenon, we report two experiments in which we used an objective measure known to correlate with the RHI to support the subjective reports of our subjects—most of whom reported experiencing tactile or thermal sensations (or both) on their hand while watching a laser stroke a rubber hand. Specifically, we measured the change in proprioceptive localization of subjects' real hand toward the visual location of the rubber hand. A number of researchers have measured such localization errors for the standard RHI and have shown that they discriminate between coordinated and mismatched touch (Armel & Ramachandran, 2003; Botvinick & Cohen, 1998; Dunphy, Evans, Klostermann, & Durgin, 2005; Tsakiris & Haggard, 2005).

EXPERIMENT 1

Experiment 1 involved three main conditions, into which 60 subjects were divided equally. In the coordinated-touch (RHI) condition, subjects experienced coordinated brushing of the back of their own unseen hand and a visible rubber hand. In the laser condition, subjects simply observed a laser light (650 nm, 1.3 μW) playing over the rubber hand. In the mismatched-touch (control) condition, subjects experienced mismatched brushing of the real and rubber hands. This last condition is generally

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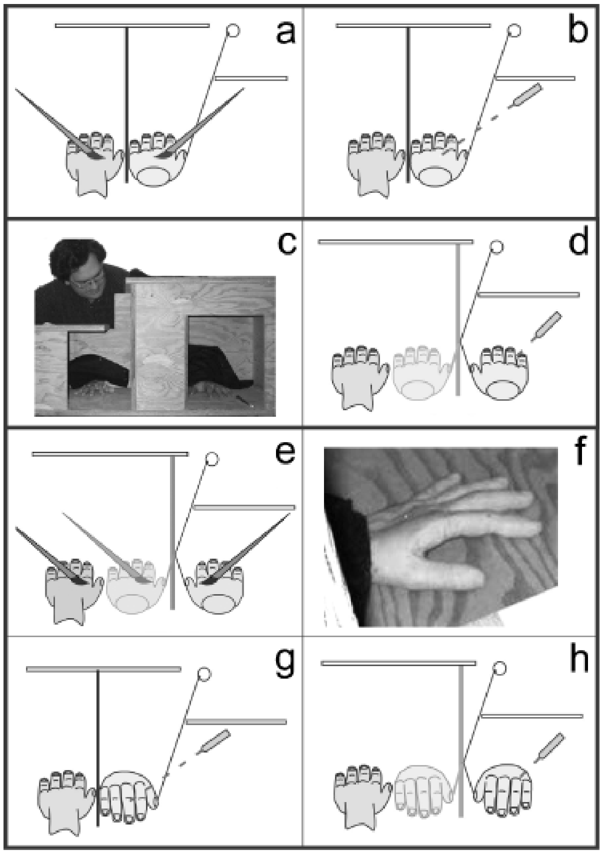

Fig. 1. Illustrations of the apparatus used. Each of the panels (except c and f) shows the subject's line of sight (from the ''eyeball'' at the upper right) down into the box that was used to hide the subject's real hand (shown with wrist) and replace it visually with a false hand. In the rubber-hand illusion (a), the unseen real hand and the visible rubber hand are brushed in synchrony; the felt touch from the real hand is experienced as originating from the seen touch on the rubber hand. In the new phenomenon reported here (b), the unseen hand is not stimulated, yet most people report precisely localized thermal or tactile sensations arising from watching a laser ''stroke'' the rubber hand. Watching one's real hand stroked with a laser light can produce similar sensations. In Experiment 1, a mirror box (c) was used to display the rubber hand while occluding the subject's real hand. The apparent position of the false hand (as reflected in the mirror) is depicted in (d) and in (e) using a grayed hand outline to the right of the real hand. The subject's view of the rubber hand in the mirror is shown in (f); a black felt sleeve concealed the cutoff wrist. In Experiment 2, the real hand was occluded either by a wall placed in the box (a, b, and g) or by a mirror that provided a view of the rubber hand (d, e, and h). Conflict was provided in the laser conditions of Experiment 2 by inverting the false hand front to back (g and h). In the brush conditions (a and e), conflict was achieved by mismatched brushing of the real and false hands.

found to block the effects of ownership (such as mislocalization) associated with the RHI. All subjects viewed the rubber hand in a visual location offset 15 cm toward the midline from their real hand. The rubber hand was viewed via a mirror box (Fig. 1c). Figures 1d and 1e show schematic illustrations of how the mirror concealed the real hand. Figure 1f shows the view of the rubber hand in the mirror. For half the subjects in each condition, the mirrored scene also included a visible occluder (a small box) just beyond the rubber hand in a visual location containing the location of their own hand.

We measured felt position of the hidden real hand both before and after 2 min of the experimental manipulation: Subjects used their right index finger to indicate, on the underside of the apparatus, the felt location of their left thumb, which was recorded to the nearest 5 mm. Following the final measurement, they filled out a short questionnaire concerning their experience (e.g., whether they felt ownership of the false hand). For those in the laser condition, the questionnaire included a question about whether they had felt the light and a follow-up question asking them to describe the sensations if they had reported any.

Seventeen of the 20 subjects (85%) in the laser condition (8 for whom the visible occluder was present and 9 for whom it was not) reported that they had felt the touch of the laser on their skin. Eleven of these reported that it felt "warm" or "hot," and 7 described feeling tactile pressure (4 used the term "tingly"). (Two subjects reported both thermal and tactile sensations, and 1 declined to describe the sensations.) In response to a final question on the questionnaire concerning what subjects found most surprising about the experiment, 15 reported that feeling the light was most surprising (others discussed felt ownership of the rubber hand).

Average ratings of felt ownership of the false hand (on a scale from 1 through 7) were much higher following coordinated touching (5.2 ± 0.3) than following mismatched touching (3.4 ± 0.3), $t(38) = 3.78$, $p_{rep} = .99$, $d = 1.20$. Ownership judgments were also higher in the laser condition (excluding the 3 subjects who did not report feeling the laser; 4.5 ± 0.4) than in the mismatched-touch condition, $t(35) = 2.20$, $p_{rep} = .93$, $d = 0.72$. Although all subjects indicated that they were fully aware that they were observing a rubber hand, 70% (28) of those in the experimental conditions (12/20 in the laser condition and 16/20 in the coordinated-touch condition) nonetheless reported feeling that the rubber hand was their own hand (rating of at least 5). Moreover, 93% of these (26) reported that they experienced this feeling immediately or almost immediately.

In most instances, subjective reports in the laser condition did not differ from those in the coordinated-touch condition. The one exception is that subjects in the coordinated-touch condition gave a higher rating to the idea that they had been confused about the location of their real hand during the experiment (4.3 ± 0.4 vs. 3.1 ± 0.3), $t(38) = 2.42$, $p_{rep} = .95$, $d = 0.77$. This finding suggests that real tactile stimulation more saliently activated conflicting proprioceptive position sensing than the laser light did.

Figure 2 shows the mean error in felt hand location (toward the false hand location) in each condition. Posttest errors were analyzed using pretest errors as a covariate. Prior studies not using a mirror have found no positive shift following mismatched-touch conditions (Armel & Ramachandran, 2003; Botvinick & Cohen, 1998). Although there is normally an initial bias in intermanual localization (11.6 ± 3.4 mm in this ex-

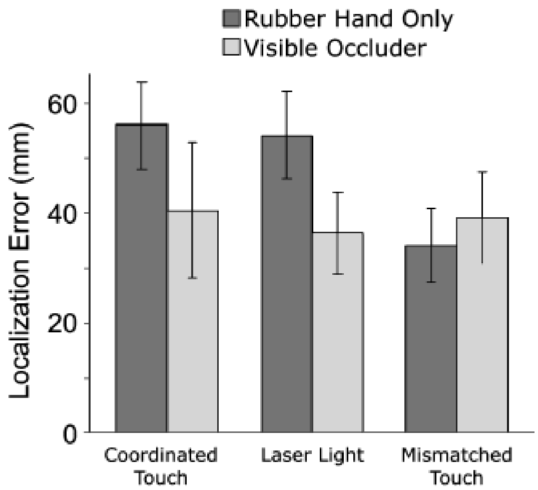

Fig. 2. Recalibration results of Experiment 1. Average shift in felt position of the hidden hand is plotted as a function of occluder presence/absence and type of stimulation. Standard errors of the means are shown.

periment), the average posttest error in our mismatched-touch condition (36.6 ± 5.2 mm) was substantially larger than the pretest error, $t(19) = 4.79$, $p_{rep} = .99$, $d = 1.02$. An analysis excluding these control data showed that error was reliably greater when no visible occluder was provided than when an occluder was shown in the mirror, $F(1, 32) = 5.80$, $p_{rep} = .95$, $\eta^2 = .093$. The effect of the visible occluder suggests that using the mirror apparatus facilitated the spatial realignment of felt position toward seen position because the mirror's own status as an occluder was camouflaged by the depicted scene (Dunphy et al., 2005; see also Holmes, Crozier, & Spence, 2004; Holmes & Spence, 2005).

EXPERIMENT 2

To better compare localization errors from the touched-by-light effect and the classic RHI, we conducted a second experiment that included conditions with a normal occluder. A total of 160 students participated. None had previous experience of the RHI or the touched-by-light effect. The subjects were divided equally among eight conditions defined by the factorial combination of stimulation (laser or brushes), occluder (mirror or wall) and conflict (absent or present). Conflict was achieved in the touch conditions by mismatched brushing of the real and false hands, as in Experiment 1. In the laser conditions, conflict was established by inverting the false hand, because misorientation of the rubber hand is known to reduce the sense of ownership (Ehrsson, Spence, & Passingham, 2005; Pavani, Spence, & Driver, 2000). The inversion preserved the relative positions of the various digits (thumb to the right), but reversed their orientation. The four laser conditions are depicted in Figures 1b, 1d, 1g, and 1h. The brush conditions are depicted in Figures 1a and 1e.

Two white plaster hands were cast from an adult female. The greater opacity and paleness of the white plaster hands rendered their surface less skinlike (e.g., the laser light did not appear to penetrate the surface as it did with real or rubber skin). Questionnaires were used to assess subjective experience in the laser conditions (but not the touch conditions). Given the responses in Experiment 1, we followed the rating question about whether the light had been felt with separate boxes that subjects could check to indicate the experience of "warm" and "tingly" sensations (reporting one did not exclude reporting the other). In all conditions, we measured felt position of the real hand as in Experiment 1. As before, the experimental manipulation (either brushing the real and false hands or playing the laser over the false hand) lasted 2 min.

We discuss the laser condition primarily. Twenty-five subjects reported only thermal sensations (including one who reported "cold" sensations), 16 reported only tactile sensations, 8 reported both, and 31 reported neither. Reports of thermal sensations and reports of tactile sensations were statistically independent. For purposes of further analysis, the 48 subjects who checked off at least one of the two boxes and the 1 who wrote in "cold" were classified as having felt the light. This group constituted 61% of the laser subjects overall, and 70% of those who saw the plaster hand in the forward orientation (neither frequency nor ratings of feeling the light differed reliably by hand orientation or occluder).

Figure 3 (top panel) shows ratings of felt ownership of the plaster hand in the laser conditions as a function of occluder type and hand orientation, split according to whether or not participants reported a specific sensation of feeling the light. Because the relationship between ownership and having felt the light differed as a function of hand orientation, $F(1, 72) = 4.37$, $p_{rep} = .93$, $\eta^2 = .045$, we conducted a separate analysis for each hand orientation. As is clear from Figure 3, subjects who saw a correctly oriented plaster hand were more positive in their judgments of ownership if they felt the light than if they did not, $F(1, 36) = 18.16$, $p_{rep} = .99$, $\eta^2 = .316$. This relationship was not found for subjects who saw a misoriented hand.

An analysis of localization errors in the laser condition (Fig. 3, bottom panel), with pretest errors as a covariate, showed that there were larger errors when the plaster hand was hidden by a mirror than when it was hidden by a wall, $F(1, 64) = 8.60$, $p_{rep} = .98$, $\eta^2 = .076$. More important, subjects who felt the light demonstrated larger errors than those who did not, $F(1, 64) = 7.36$, $p_{rep} = .97$, $\eta^2 = .065$, an effect that was independent of hand orientation. Indeed, hand orientation did not have a reliable effect on localization. A possible implication of this result is that although a misoriented hand tended to block a sense of whole-hand ownership—among subjects who felt the light, ratings of ownership were lower when the hand was misoriented than when the hand was oriented correctly, $F(1, 45) = 9.38$, $p_{rep} = .98$, $\eta^2 = .164$—it did not block the development of local correspondences between visual and tactile receptive fields. Because shifts in felt position can be local to a single finger in the RHI (Tsakiris & Haggard, 2005), momentary and very local

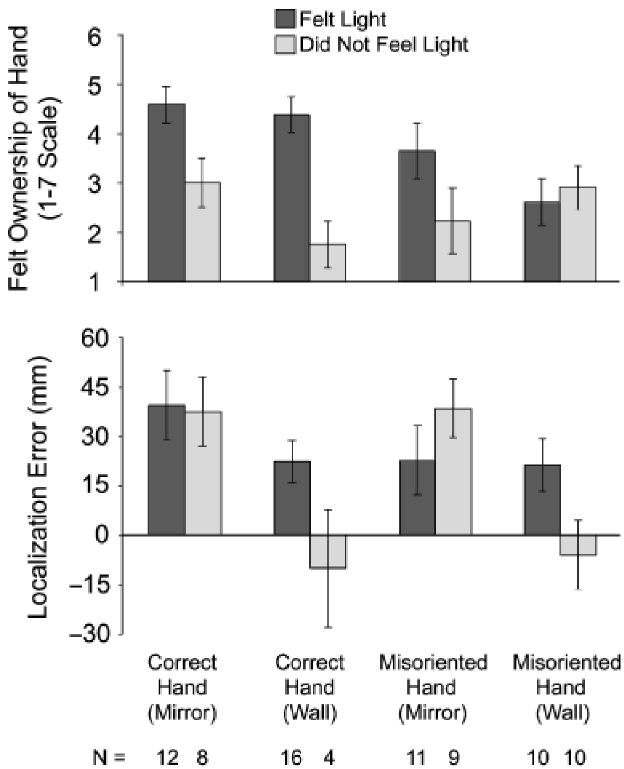

Fig. 3. ''Ownership'' ratings (top panel) and recalibration results (bottom panel) from the laser conditions of Experiment 2. Ownership ratings and average shift in felt position of the hidden hand are plotted as a function of type of occluder (mirror or wall), orientation of the plaster hand (correct or inverted orientation), and whether or not the subject felt the light. Standard errors of the means are shown. The labels at the bottom indicate the number of people in each cell.

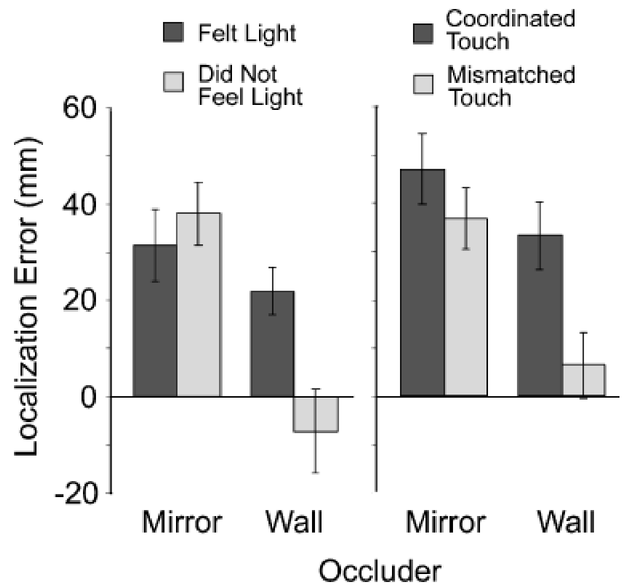

Fig. 4. Similarities of errors in felt position for the brush and laser conditions in Experiment 2. For the laser condition (left), localization error is plotted as a function of type of occluder (mirror or wall) and whether or not the subject felt the light. For the touch conditions (right), localization error is plotted as a function of type of occluder and whether or not brushing of the real and false hands was coordinated. Standard errors of the means are shown.

experiences of (illusory) correspondence may have produced both the somatic sensations and shifts in felt position.

Figure 4 shows localization error in the laser condition collapsed across hand orientation and replotted alongside corresponding data from subjects in the brush-stroke condition. Like the laser data, the brush data suggest that use of the mirror itself produced a shift, $F(1, 72) = 4.22$, $p_{rep} = .92$, $\eta^2 = .039$. Moreover, there was a clear effect of conflict (i.e., mismatched, rather than coordinated, touching), $F(1, 72) = 7.74$, $p_{rep} = .99$, $\eta^2 = .072$. In the figure, there is an obvious correspondence between localization errors from the RHI and from the laser effect: Subjects who reported feeling the light showed a localization error pattern similar to that of subjects who experienced coordinated touch, and the pattern for subjects who did not report feeling the laser resembled the localization pattern for subjects who experienced mismatched touch. These data support the idea that the effect of feeling the laser is quite similar to the effect of coordinated touch.

GENERAL DISCUSSION

Overall, two thirds of our 100 laser subjects readily reported thermal or tactile sensations from seeing a laser light stroke a rubber or plaster hand positioned near their own unseen hand. This finding represents an important new phenomenon concerning the integration of vision with the somatic senses. We have used recalibration of proprioceptive position sensing to corroborate the subjective reports of our subjects. Just as subjects who experienced coordinated touch in the brush conditions showed greater proprioceptive shift than those exposed to mismatched brushing, subjects who reported feeling somatic sensations from the laser light showed greater proprioceptive shift than those who did not.

The experience of illusory somatosensory sensation may exist on a continuum with normal empathy in that people may feel the sensations seen to be experienced by others. Blakemore et al. (2005) found heightened somatosensory activity in a female subject who reported feeling tactile sensations when seeing other people touched. Keysers et al. (2004) found that viewing movies of actual touching activated secondary motor cortex. Our experiments document that many people report feeling things they can actually only see on a body surface that has become incorporated into their body schema.

Tactile discriminations are more precise when gaze is directed at the felt location (Newport, Raab, & Jackson, 2002), even when visual information is blocked by a shutter during the crucial moment of contact (Kennett, Taylor-Clarke, & Haggard, 2001). This result suggests intermodal coordination in the cortical coding of body-relative location, a coordination that might be due to gaze-based recruitment of populations of bimodal neurons (Graziano & Botvinick, 2002; Ladavas & Farne, 2004; Rizzolatti, Scandolara, Matelli, & Gentilucci, 1981).

However, the alignment of visual and somatic information can occur in body-surface reference frames as well (Tipper et al., 2001). Our data suggest that correlated (or illusory) bimodal perceptions may cause proprioceptive mislocalization rather than the other way around, because the use of a mirror increased mislocalization without increasing the likelihood of feeling the light.[1] Once the brain, encouraged by the correlation, incorporates the false hand into the body schema, conflict between spatial signals from proprioception and from vision probably stimulates the recalibration of felt position.

The thermal sensations our subjects reported are of interest in their own right. We have observed for ourselves that using a bluish laser on the rubber hand (and directly on our own hands) produces a different (cooler) thermal sensation than the red laser used in these experiments. It is unclear what role visual cognition may play in interpreting the somatic senses; it is known that thermal perception is spatially captured by the location of tactile sensations (Green, 1978, 2004). Although the heat energy of a laser pointer shone on a real hand is perhaps vaguely detectable,[2] the localized thermal sensations obtained in conjunction with vision (e.g., when viewing laser light on one's own hand) seem quite clear and distinct by contrast. These illusory effects seem easiest to initially establish under conditions of high luminance contrast (e.g., with the hand in shadow), but, once established, the effects generalize to less intense visual stimulation.

The perceived body is a kind of "user illusion" that facilitates interactions with the immediate environment (e.g., Dennett, 1991). The body-/self-referencing of certain kinds of experience may require attributing these perceptions to specific somatic modalities. Although visual attention can recruit bimodal cortical units to code a specific part of the body surface with increased precision, sensory-integration theory predicts that visual input might itself be experienced as tactile input. Consider the possible advantage of "feeling" an insect that one easily sees, but cannot readily feel, crawling on one's skin. If body-referenced action is required, then proprioceptive (somatic) localization may be quite useful.

[1]To verify the dissociation between the effect of the mirror on shift and on feeling the light, we conducted an additional analysis. For subjects in the laser conditions, there was reliably more shift in the mirror condition than in the wall condition even when ratings of feeling the light were used as a covariate, $F(1, 64) = 4.59$, $p_{\text{rep}} = .93$, $\eta^2 = .245$. This finding illustrates that the mirror had a role in producing shift independent of the additional effects of feeling the light illustrated in Figure 4 (e.g., for those in the wall condition). Note that the mirror did not reliably increase the frequency of reports of feeling the light. Indeed, the effect of the mirror on ratings of having felt the light actually trended in the opposite direction.

[2]The heat of the laser pointer used in these experiments was not reliably detectable on the back of the hand under our laboratory conditions. Twelve subjects each performed 56 trials (3 s in duration) to attempt to discriminate by feel whether the laser was shown on their hand or not. Overall, they were correct 52.7% of the time, a percentage that does not differ from chance. The average d' (0.14) was not different from 0, $t(11) = 1.63$, $p_{\text{rep}} = .86$, $d = 0.98$.

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