Psychologically induced cooling of a specific body part caused by the illusory ownership of an artificial counterpart

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The sense of body ownership represents a fundamental aspect of our self-awareness, but is disrupted in many neurological, psychiatric, and psychological conditions that are also characterized by disruption of skin temperature regulation, sometimes in a single limb. We hypothesized that skin temperature in a specific limb could be disrupted by psychologically disrupting the sense of ownership of that limb. In six separate experiments, and by using an established protocol to induce the rubber hand illusion, we demonstrate that skin temperature of the real hand decreases when we take ownership of an artificial counterpart. The decrease in skin temperature is limb-specific: it does not occur in the unstimulated hand, nor in the ipsilateral foot. The effect is not evoked by tactile or visual input per se, nor by simultaneous tactile and visual input per se, nor by a shift in attention toward the experimental side or limb. In fact, taking ownership of an artificial hand slows tactile processing of information from the real hand, which is also observed in patients who demonstrate body disownership after stroke. These findings of psychologically induced limb-specific disruption of temperature regulation provide the first evidence that: taking ownership of an artificial body part has consequences for the real body part; that the awareness of our physical self and the physiological regulation of self are closely linked in a top-down manner; and that cognitive processes that disrupt the sense of body ownership may in turn disrupt temperature regulation in numerous states characterized by both.

Body ownership refers to the feeling that your body belongs to you and is constantly there (1, 2)—it constitutes a fundamental aspect of self-awareness. That our body is ours is often taken for granted, but disruption of this sense of body ownership is characteristic of numerous pathological conditions, for example stroke, schizophrenia, autism, epilepsy, neuropathic pain, anorexia nervosa, and bulimia. Many of these pathological conditions are also characterized by disruption of temperature regulation, which is attributed in a broad sense to disruption of or damage to structures subserving autonomic control, in the brain or the periphery (3–16) [supporting information (SI) Table S1]. That the effects are often confined to one side of the body or even to a single limb has only been explained in terms of peripheral or somatotopic-specific damage. No one has proposed that disruption of temperature regulation might be linked to disruption of body ownership. We hypothesized that, in healthy adults, temperature regulation in a specific limb could be disrupted by psychologically disrupting the sense of body ownership.

That body ownership can be disrupted psychologically in healthy volunteers has been demonstrated by out-of-body (17–19) and rubber hand (20) illusions. These sorts of illusions exploit the brain’s predilection for integrating congruent tactile, visual, and proprioceptive inputs. The most-studied of these illusions, the rubber hand illusion (RHI), is typically induced by brushing a person’s hand (hidden from view) while synchronously brushing a visible rubber hand. Many people perceive the touch as if it were actually coming from the rubber hand and a measurable shift in the perceived location of the experimental limb (toward the rubber one) is observed (20). In the RHI, it is as though the artificial body part is in some sense treated as being part of their own body. Brain imaging studies corroborate this observation: When one “takes ownership” of the rubber hand, threatening the rubber hand evokes cortical responses (that are commensurate in magnitude with the reported strength of the illusion and are consistent with the withdrawal of the hand from threat), in parietal, premotor, and insula areas (21, 22). Notably, these areas are also important in sympathetic control and temperature regulation (23)—the insula cortex has been labeled the “interoceptive cortex” (24).

Until now, no one has investigated the consequences, for the real body part, of taking ownership of an artificial counterpart. In six separate experiments, with six independent groups of healthy volunteers, we demonstrate that the RHI evokes a limb-specific decrease in the temperature of the participant’s own hand and a decrease in the weight given to tactile information from that hand. The magnitude of both effects correlates with the strength of the illusion (for a summary of experiments, see Table S2).

Results

The RHI was elicited by using the standard experimental protocol (20). In Experiment 1, we compared skin temperature of the experimental hand during the RHI to that when the rubber hand was removed and the participant’s own unseen hand was no longer stimulated. The mean ± SEM skin temperature of the experimental hand was 0.27 ± 0.11°C lower during the RHI trials than during the control trials [t(10) = −2.34, P = 0.041 (Fig. S1)]. Experiment 2 investigated whether the decrease in skin temperature might reflect a body-wide sympathetic response, for example, because of increased general arousal. The unstimulated hand was now hidden from view, and the experimental hand was brushed, during both the RHI and control trials. Skin temperature recordings from the experimental hand corroborated the results of the previous study (mean ± SEM...
RHI than during the control conditions at the hand (mean ± SEM decrease = 0.82 ± 0.21°C; Fig. 1C) but not at the foot (0.08 ± 0.12°C; F(5, 35) = 14.94, P = 0.001; Fig. 1B). The RHI (Fig. 1A) preceded the decrease in skin temperature of the experimental hand (Fig. 1B), which shows that the RHI does not result from the drop in skin temperature, which might have been expected according to the somatic marker hypothesis (27).

Experiment 5 assessed skin temperature while participants watched one of their hands being stroked while their other hand was hidden behind an occluding screen. This experiment did not involve the RHI (the rubber hand was removed from the table), and was different from the asynchronous stroking condition of Experiment 3, because in that condition participants saw a hand being stroked and felt their own hand being stroked, although the timing of the strokes was not matched. No differences between conditions, nor hands, nor any interaction, were observed, which shows that the decrease in skin temperature is not evoked simply by simultaneously seeing and feeling one’s own hand being stroked. That is, it is not simply a result of synchronous visual and tactile input, but depends on a simultaneous induction of the illusion of ownership over an artificial counterpart.

Perhaps the decrease in skin temperature results from a shift in attention toward the limb concerned. The final experiment used an established protocol to investigate this issue, by interrogating the processing of tactile information during the RHI. Participants made temporal order judgments (TOJs) concerning pairs of tactile stimuli, one applied to the index finger of either hand, at a range of interstimulus intervals. The outcome of the TOJ task is the point of subjective simultaneity (PSS), which provides a measure of the relative weighting given by the brain to tactile input from either limb. The TOJ task was undertaken during three conditions: RHI, asynchronous stroking and control (the rubber hand was on the table to the right of the participant, but was not stroked). During the RHI trials, the tactile stimulus had to be applied to the experimental hand before an identical stimulus was applied to the other hand, in order for the two stimuli to be perceived as simultaneous (PSS = 11.0 ± 1.2 ms), which means less weight was given to processing tactile information from the experimental hand. The PSS was greater during the RHI trials than during the control trials (1.9 ± 0.2 ms) (ANOVA main effect [F(2, 28) = 10.22, P < 0.005; post hoc P < 0.01 for both; Fig. 2). The vividness of the RHI was positively related with the PSS (r = 0.64, P < 0.001; Fig. 1D).

RHI was more vivid, so too is the decrease in skin temperature on the real hand. (Fig. 1C) Hand skin temperature, and mean foot skin temperature (broken line) during control (Ctl) and RHI conditions. (D) Vividness of the RHI and point of subjective simultaneity (PSS). PSS to the right means that the brain is prioritizing tactile input from the opposite side over identical tactile input from the experimental hand. *, significant difference at P < 0.02.

The vividness of the RHI was positively related with the PSS (F = 41.11, P < 0.001; Fig. 1B). The decrease in skin temperature results from a shift in attention toward the limb concerned. The final experiment used an established protocol to investigate this issue, by interrogating the processing of tactile information during the RHI. Participants made temporal order judgments (TOJs) concerning pairs of tactile stimuli, one applied to the index finger of either hand, at a range of interstimulus intervals. The outcome of the TOJ task is the point of subjective simultaneity (PSS), which provides a measure of the relative weighting given by the brain to tactile input from either limb. The TOJ task was undertaken during three conditions: RHI, asynchronous stroking and control (the rubber hand was on the table to the right of the participant, but was not stroked). During the RHI trials, the tactile stimulus had to be applied to the experimental hand before an identical stimulus was applied to the other hand, in order for the two stimuli to be perceived as simultaneous (PSS = 11.0 ± 1.2 ms), which means less weight was given to processing tactile information from the experimental hand. The PSS was greater during the RHI trials than during the control trials (1.9 ± 0.2 ms) (ANOVA main effect [F(2, 28) = 10.22, P < 0.005; post hoc P < 0.01 for both; Fig. 2). The vividness of the RHI was positively related with the PSS (r = 0.64, P < 0.001; Fig. 1D).
Discussion

These six experiments yield important new findings. First, they uphold our hypothesis that temperature regulation can be disrupted in healthy volunteers by psychologically disrupting the sense of body ownership. This is the first empirical evidence that the taking ownership of a rubber hand is accompanied by a significant drop in skin temperature for the real hand. Second, we observed that this effect is not limited to the limb being touched on the rubber hand, but extends to the ipsilateral foot. Third, the effect is not evoked by tactile or visual input per se, nor by simultaneous tactile and visual input per se, nor by a shift in attention toward the experimental side or limb. That the illusion-induced drop in skin temperature was confined to a single limb also provides the first evidence of cortically mediated local changes in homeostatic control.

Disruption of both body ownership and temperature regulation are characteristic of numerous clinical states (Table S2). Notably, the disruption of body ownership and temperature regulation can be confined to one side of the body or to a single limb (6, 8). The magnitude of the effect reported here was similar to that observed in some states, for example schizophrenia, but smaller than that reported in neuropathic pain states such as complex regional pain syndrome (1–2°C). Notably, only participants with a particularly vivid RHI were evaluated (Experiment 4), the magnitude of the temperature drop approached that (0.8 ± 0.2°C). One might expect a smaller effect in healthy volunteers undergoing a perceptual illusion than in patients with neurological dysfunction, because there is a fundamental difference in the change in body ownership involved: For the RHI, participants invariably know the rubber hand is not actually theirs, even though it feels like it. Patients, however, can have the absolute conviction that the limb they see protruding from their trunk is not their own limb but that of an "imposter."

Our findings build on a range of neuroimaging and psychophysiological studies that have shown that the taking ownership of an artificial body part engages homeostatic processes similar to those engaged by real body parts (28, 29). However, the current results provide further evidence of healthy human participants of limb-specific changes in temperature regulation and the first evidence that such a localized effect on body temperature can be evoked via a cognitive illusion. Moreover, the psychological induction of an illusory body part decreases the weighting given to tactile information from the real limb.

The vividness of the RHI was positively related with the PSS. Remarkably, this type of shift in PSS, away from the concerned limb, has been demonstrated in neurological disorders associated with limb disownership, for example unilateral spatial neglect after stroke. In such conditions, the shift in PSS is thought to reflect defective deployment of spatial attention (30) or damage to the neural systems that subserve higher order representation of body and space (31). In other words, the shift in PSS away from the experimental limb implies a functional disownership of that limb. Although decreased skin temperature can reduce receptor sensitivity and nerve conduction velocity (32), the magnitude of the drop in temperature that occurred during the RHI is far too small to explain the PSS effect (33).

These findings have implications for our understanding of self-awareness. First, these findings show that the conscious sense of our physical self, and the physiological regulation of our physical self, are linked. In fact, our results suggest that the conscious sense of our physical self may actually contribute to its homeostatic regulation. This finding is particularly important because temperature dysregulation in pathological conditions has only ever been attributed to damage or dysfunction of autonomic networks in the central nervous system before. The current results suggest that higher order cognitive processing...
being stroked while their other hand remained out of sight. The left and right experimental condition involved the participant watching one of their hands. Experiments 1, 2, 3, or 4. This experiment did not involve the RHI.

**Experiment 2. Participants and methods.** Eleven (six female) right-handed volunteers (mean ± SD age = 26 ± 4 years) participated. None had participated in Experiment 1. The protocol was identical to that used in Experiment 1, with the following exceptions: The participants’ skin temperature was now recorded from identical sites on both hands, which were hidden from the participant’s view during both conditions. The experimental hand was once again struck in synchrony with the rubber hand in both conditions.

**Analysis.** A repeated-measures ANOVA with first factor, condition (RHI, control); second factor, hand (experimental, opposite). There was no main effect of condition [F(1, 10) = 2.215, P = 0.168] or hand [F(1, 10) = 2.229, P = 0.166].

**Experiment 3. Participants and methods.** Ten (seven female) right-handed volunteers (mean ± SD age = 28 ± 6 years) participated. None had participated in Experiments 1 or 2. The protocol used to induce the RHI was identical to that reported in Experiment 1. However, the control condition in Experiment 3 now involved the asynchronous brushing of the rubber hand and the real hand.

**Analysis.** A repeated-measures ANOVA with first factor, condition (RHI, control); second factor, hand (experimental, opposite). There was no main effect of condition [F(1, 9) = 1.237, P = 0.295] or of hand [F(1, 9) = 1.826, P = 0.210].

**Relating the vividness of the RHI to the magnitude of limb-specific temperature change.** The skin temperature during each RHI trial was subtracted from the mean skin temperature during both control trials to provide a measure of the temperature change for each trial, for each participant. This variable was calculated for Experiments 1–3. Participants rated the vividness of the RHI on a 10-point numerical rating scale (from zero, “not at all vivid,” to 10, “completely vivid”). This variable was calculated for Experiments 1–3. The data were entered into a linear regression to relate the vividness rating of the RHI to the magnitude of the change in skin temperature of the participant’s experimental hand. The vividness score was the independent variable and temperature change the dependent variable.

**Experiment 4. Participants and methods.** Eight (four female) right-handed volunteers (mean ± SD age = 27 ± 6 years) participated. Four participants had participated in Experiment 2, but none had participated in Experiment 1 or 3. Participants were excluded if they reported vividness of the RHI as “not at all vivid,” to 10, “completely vivid.” This variable was calculated for Experiments 1–3. The data were entered into a linear regression to relate the vividness rating of the RHI to the magnitude of the change in skin temperature of the participant’s experimental hand. The vividness score was the independent variable and temperature change the dependent variable.

**Analysis.** Average skin temperature during each epoch was analyzed by using a repeated measures ANOVA with first factor, time (6 epochs); second factor, site (hand, foot). This analysis revealed a significant main effect of Site [F(1, 7) = 32.599, P = 0.001] and a main effect of time [F(5, 35) = 25.872, P < 0.001], driven by the interaction between these two factors [F(5, 35) = 14.942, P < 0.001].

**Experiment 5. Participants and methods.** Ten (five female) right-handed volunteers (mean ± SD age = 26 ± 5 years) participated. None had participated in Experiments 1, 2, 3, or 4. This experiment did not involve the RHI. The experimental condition involved the participant watching one of their hands being stroked while their other hand remained out of sight. The left and right hands were tested in a random order.

**Analysis.** A repeated measures ANOVA with first factor, condition (control, asynchronous stroking, and synchronous stroking (RHI)). In the control condition, a rubber hand was present on the right of the participant, but was not stroked. A tactile vibrator identical to that attached to each index finger was also attached to the index finger of the rubber hand.

**Analysis.** The point of subjective simultaneity (PSS) and the just noticeable difference (JND) were calculated for each participant and were the primary outcome variables (see Shore et al. (36) for methods used to psychometrically fit data to extract the PSS and JND measures). Participants rated the vividness of the RHI after each block of TOJ trials.

**Did Participants Notice the Change in Their Skin Temperature?** When the data collection was completed, each participant was asked whether they had noticed any change in the temperature of either arm, or throughout the rest of their body, during the course of the experiment. Across Experiments 1–6 (excluding Experiment 5), 17% of the participants responded in the affirmative. They all reported that their experimental arm felt cooler during the RHI, but subsequent analysis revealed that the mean change in their skin temperature was no different from that of the remainder of the participants (n.s.).

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