Journal of Experimental Psychology:
Human Perception and Performance
2015, Vol. 41, No. 1, 42–49

0096-1523/15/$12.00 http://dx.doi.org/10.1037/a0038514

Bodily Illusions Disrupt Tactile Sensations

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To accurately interpret tactile information, the brain needs to have an accurate representation of the body to which to refer the sensations. Despite this, body representation has only recently been incorporated into the study of tactile perception. Here, we investigate whether distortions of body representation affect tactile sensations. We perceptually altered the length of the arm and the width of the waist using a tendon vibration illusion and measured spatial acuity and sensitivity. Surprisingly, we found reduction in both tactile acuity and sensitivity thresholds when the arm or waist was perceptually altered, which indicates a general disruption of low-level tactile processing. We postulate that the disruptive changes correspond to the preliminary stage as the body representation starts to change and may give new insights into sensory processing in people with long-term or sudden abnormal body representation such as are found in eating disorders or following amputation.

Keywords: body representation, tactile acuity, tactile sensitivity, body distortion, body schema

We perceive tactile sensations with reference to a central body representation that is built up from multisensory experience. Visual, proprioceptive, and tactile information are integrated to provide direct and indirect cues about body size and shape (Serino & Haggard, 2010). The brain maintains but is also required to plastically adjust and update this internal body representation in response to changes in body shape during growth and development (Gallace & Spence, 2010). The consequences of altered body representation on sensory perception have frequently been used as an indirect way of examining the nature and extent of this plasticity (Serino & Haggard, 2010). Artificially altering body representation using various techniques may have serious consequences on many aspects of tactile perception. Surprisingly, the effects on fundamental sensations (as opposed to the perception that they can give rise to) such as tactile acuity and sensitivity are unknown.

Visually modifying the perceived size of the body, for example, by viewing the body through a magnifying lens, is known to impact tactile perception (Kennett, Taylor-Clarke, & Haggard, 2001), tactile distance perception (Taylor-Clarke, Jacobsen, & Haggard, 2004), tactile size perception (Longo & Sadibolova, 2013), haptic perception (Bruno & Bertamini, 2010), pain perception (Mancini, Longo, Kammers, & Haggard, 2011; Moseley, Parsons, & Spence, 2008), the perceived size of objects and their perceived distance from the observer (van der Hoort, Guterstam, & Ehrsson, 2011), the rubber hand illusion (Pavani & Zampini, 2007), and motor control, such as grasping (Marino, Stucchi, Nava, Haggard, & Maravita, 2010). Even noninformative vision can improve tactile perception by generally enhancing somatosensory processing (Haggard, Christakou, & Serino, 2007; Kennett et al., 2001; Longo, Pernigo, & Haggard, 2011). Together, these observations suggest that visually changing perceived body size can alter the mental representation of the body and that these changes affect tactile perception. Distorting perceived body size and shape visually (Bruno & Bertamini, 2010; Marino et al., 2010; Moseley et al., 2008; Taylor-Clarke et al., 2004), proprioceptively (de Vignemont, Ehrsson, & Haggard, 2005; Lackner, 1988; Longo, Kammers, Gorri, Tsakiris, & Haggard, 2009) or with cutaneous anesthesia (Gandevia & Phegan, 1999) provides further evidence of the complex relationship between tactile perception and the body representation to which it is referenced.

The well-known Pinocchio illusion (Lackner, 1988) is a proprioceptive illusion where vibration applied to the tendons of an arm while grasping the nose creates an illusory lengthening of the nose. Using a modification of this illusion, de Vignemont, Ehrsson, and Haggard (2005) created an illusory elongation of the finger and found that perceived tactile distances were altered. When the finger felt longer, stimuli were reported as farther apart compared with a control condition. Ehrsson et al. (2005) used functional magnetic resonance imaging (fMRI) to examine the neural correlates of similarly induced perceptual changes during the "waist-shrinking illusion," and showed that brain changes occur in the cortices lining the left postcentral sulcus and the anterior part of the intraparietal sulcus during such perceptual alterations of the size of the body. It seems that proprioceptively induced illusions may be manipulating a mechanism of body representation in the brain.

This article was published Online First December 8, 2014.

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This research was supported by a Discovery Grant to Laurence R. Harris from the Natural Sciences and Engineering Research Council (NSERC) of Canada. Sarah D'Amour held a scholarship from the NSERC CREATE program. Sarah D'Amour developed the study concept. All authors contributed to the study design. Sarah D'Amour performed the testing and data collection, and performed the data analysis and interpretation under the supervision of Laurence R. Harris, as well as drafting the manuscript. Laurence R. Harris and Lisa M. Pritchett provided critical revisions. All authors approved the final version of the manuscript for submission.

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Although previous studies looking at tendon vibration illusions have provided insight into understanding the connection between tactile perception and the sense of our bodies, the results pertain only to one area of tactile perception and do not necessarily apply to more fundamental, elementary tactile sensations such as intensity, acuity, and location. Whether altering body representation using nonvisually induced changes affects tactile sensations is unknown. Here, we used a modification of the Pinocchio illusion to test whether altering perceived arm and waist size (see Figure 1) might affect tactile sensations. Experiments 1 and 2 investigated whether illusory elongation or shrinkage of the arm affected tactile acuity and sensitivity. Experiments 3 and 4 tested whether tactile acuity and sensitivity were affected during illusory expansion and shrinkage of the waist. Because tactile judgments are made with respect to the body, a change in tactile ability would be expected if the brain were not able to update and recalibrate body representation during such sudden modifications of perceived body size. The purpose of these experiments was to directly address whether altering perceived body size by nonvisual manipulations could affect tactile sensations. Because earlier studies have shown that bodily illusions can impact the tactile perception of objects, perceptually changing the size of the body would be expected to cause a disruption in body representation, which might in turn affect elementary tactile sensations such as acuity and sensitivity. Altering perceived body size in either direction (extending or shrinking) was expected to cause a reduction of tactile acuity and tactile sensitivity.

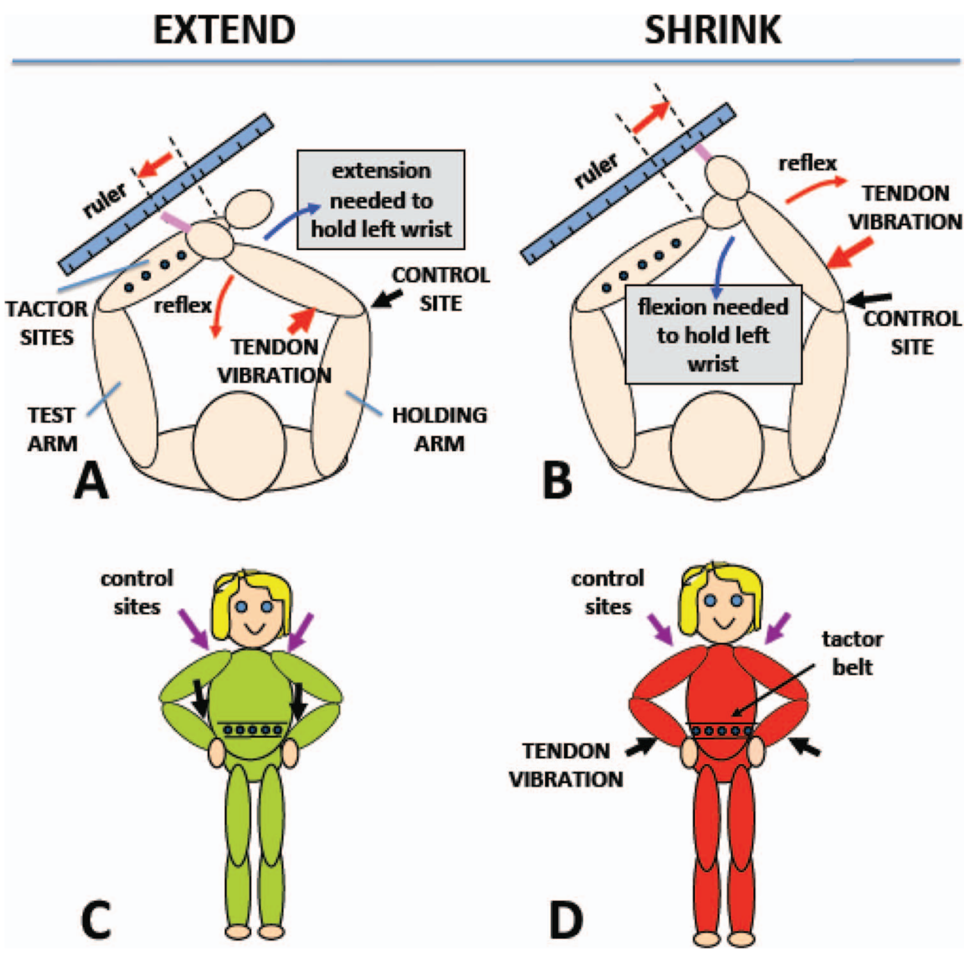

Figure 1. How the arms and waist were perceptually altered. (A, B). *How the Pinocchio illusion was implemented on the arm* Stimulating the biceps tendon (A) caused the right arm to flex reflexively. When the right arm held the left arm's wrist it caused the left arm to feel extended. The reverse applied after stimulating the triceps tendon (B). There were five tactors positioned along the arm, which were used for the acuity experiment. Two of them (midarm and closest-to-the-wrist) were also used for the sensitivity experiments. Control vibration was applied to a point on the right forearm near the bony elbow. The ruler used to assess misperception of the position of the right arm is also shown (C, D). *How the Pinocchio illusion was implemented on the waist*. Vibrating the wrist flexor tendons of both arms simultaneously (C) made the waist feel it was expanding. Vibrating the wrist flexor tendons (D) had the opposite effect. There were five tactors positioned along a belt, which were used for the acuity experiment. Three of them (1, 3, and 5) were used for the sensitivity experiments. Control vibration was applied to the two shoulders.

Experiments 1 and 2: Arm Acuity and Sensitivity

Materials and Method

Participants. Fifteen participants took part in Experiment 1 (nine females, mean age 29.6 years). Fifteen volunteers participated in Experiment 2 (nine females, mean age 28.8 years). All participants gave written informed consent. All studies were approved by the York University Research Ethics Board and were performed in accordance with the Treaty of Helsinki. Minimum sample size was determined a priori for each experiment, on the basis of statistical power analysis. Prior experiments that used tendon vibration illusions (Craske, 1977; de Vignemont et al., 2005; Ehrsson et al., 2005; Fuentes, Gomi, & Haggard, 2012) indicated that having a final sample size of 10 subjects generally leads to sufficient power but often a larger sample size is required because many participants do not experience the illusion and cannot be included in data analysis. To account for potential removal of participants, we determined that the ideal number of participants to run before stopping data collection would be 15.

Stimuli. Tactile stimuli were 50 ms bursts of 250 Hz vibration of variable intensity generated by a 64bit sound card powered by a PC computer played through C2 tactors (Engineering Acoustics, California). The tactors were 1.17" diameter and 0.30" thick. Only a small central cylinder (0.34") within the tactor actually vibrates. Five tactors, with the centers separated by 3 cm, were mounted on a Velcro strap that was fastened along the dorsal surface of the left arm by a tensor wrap. Any slight differences between the tactors or the tension applied by the strap holding them to the arm were rendered immaterial because the data collected were compared between the control and the tendon vibration conditions. The array was positioned with the central tactor midway between the wrist and the elbow.

Procedure. Blindfolded participants were seated in a chair and comfortably rested their left forearm, with the tactor array attached, on a cushion that was placed on a table. A strap lightly held the left arm in a relaxed position. The right elbow rested on an armrest arranged as a pivot to allow the right arm to reach the left wrist.

Experimental design. For each of the two experiments, three conditions were tested; perceptually elongating and shortening the arm, as well as a control condition in which arm length was not perceptually altered. The three conditions were presented in blocks of 20 trials with the order in which the blocks were presented counterbalanced across participants. The sequence was repeated for each participant until all trials were complete. Continuous vibration was applied throughout each block at the tendon or control site, with each block taking between 90 and 110 s with a 1-min gap between each block.

Experiment 1: Tactile acuity. To measure tactile acuity on the arm we used the method of constant stimuli with a two-alternative forced choice (2AFC) design. Each trial consisted of two intervals—one interval containing a single vibrotactile stimulus and one interval containing two simultaneous vibrotactile stimuli. The intervals were delineated by three auditory beeps (250 Hz, 0.1 ms). Tactors in the two-tactor interval were spatially separated by one to four tactor separations (3, 6, 9, or 12 cm). For separations of 3, 6, or 9 cm, the pair of tactors to stimulate was chosen at random from the available combinations. Intensity was always suprathreshold but was manipulated to assure that vibration intensity could not be a reliable indicator for which interval contained two vibrotactile stimuli. For intervals containing two stimulations, the intensity was 5%, 7.5%, or 10% of maximum intensity for both tactors in the pair. For intervals containing one vibrotactile stimulus, the intensity was independently chosen from 10%, 15%, or 20% of maximum.

Participants identified which interval contained two simultaneous vibrotactile stimuli and reported their response using foot pedals (Yahama FC5), where the left foot was lifted to report the first interval or the right was lifted to indicate the second interval. Each of the four tactor separations was presented 20 times for each of the three conditions for a total of 240 trials. The experiment was divided into 12 blocks, four for each of the three conditions.

Experiment 2: Tactile sensitivity. Tactile detection thresholds were measured under the three conditions for two tactors on the array (middle of the left arm and close to the left wrist). A QUEST adaptive staircase procedure (Watson & Pelli, 1983) was used with a 2AFC design to obtain a detection threshold estimate at each touch location. The QUEST algorithm assumes the observer's psychometric function follows a Weibull distribution and adaptively determines the next line length to be presented on the basis of the participant's response to the previous trials. As the experiment goes on, knowledge on the observer's psychometric accumulates. Each trial consisted of two intervals—one interval containing a vibrotactile stimulus and one interval containing nothing—delineated by auditory beeps as for the acuity experiment. Stimuli were presented in two intervals of 1,050 ms, each separated by beeps of 100 ms. Participants identified whether the first or second interval contained the vibrotactile stimulus and responded using the foot pedals, left for the first interval, right for the second. Their response determined the intensity of the next stimulus according to the QUEST. There were three blocks per condition (for a total of 9 blocks) with 20 trials per block (total of 20×9 trials) corresponding to 30 trials for each tactor and condition.

Tendon vibration. Illusory changes in the perceived length of the left arm were induced by vibrating the tendons of the right arm (Hitachi Magic Wand, Japan) while participants held their left wrist with their right hand (Figure 1 a and 1b). Biceps vibration created the perception that the left arm was elongating whereas triceps vibration caused illusory shortening of the left arm. In the control condition, vibration was applied was applied away from the tendons over bone approximately an inch down from the medial epicondyle of the humerus (de Vignemont et al., 2005). The frequency of vibration was ~83 Hz (device set on "low") and the skin surface vibrated was about 1 cm^2. The vibrator was held in place by the experimenter and continuous vibration was applied throughout the blocks of trials.

Effectiveness of the illusion. To assess the effectiveness of the illusion, the perceived position of the right arm was assessed at the beginning of each block. Blindfolded participants were asked to place their right index finger on the perceived location of their left wrist. Where they first touched was recorded using a ruler laid parallel to the left arm. The perceived position was measured four times for each condition in Experiment 1 and three times for each condition for Experiment 2. These measurements were taken at the beginning of the experiment and after completing one set of all three conditions. Errors in reaching with the right arm indicated that tendon vibration was effective in eliciting a distorted perception of the position of the right arm. When the right arm grasped the left arm's wrist this misperception is interpreted as a change in arm length of the left arm. As an additional test, after the end of each experimental block participants were asked to report if their left arm felt longer, shorter, or of regular length.

These two measures were used to assess whether participants had experienced the illusion and if they should be included in the analysis. Using the averages of the measurements, participants who reliably experienced the illusion were considered as those who (a) over- or underestimated the position their right arm during the tendon vibration conditions, (b) reached for their left wrist accurately during the control and no-vibration measurements, (c) verbally reported feeling a longer or shorter arm during the appropriate tendon vibration condition, and (d) verbally reported feeling no change in arm length during the control and no-vibration conditions. Only participants who met these criteria were included in the analysis (Experiment 1: $n = 13$; Experiment 2: $n = 15$).

For Experiment 1, during biceps tendon vibration participants misperceived the position of their right arm by 5.15 cm ($SE = 1.08$) compared with the control condition, and by −6.70 cm ($SE = 0.51$) when vibration was applied to the triceps tendons. For Experiment 2, during biceps tendon vibration the position of their right arm was misperceived by 3.33 cm ($SE = 0.37$) and during biceps tendon vibration by −2.48 cm ($SE = 0.39$) compared with the control condition.

Data analysis. The number of correct responses was expressed as a fraction of the total number of trials and plotted as a function of stimulus separation (Experiment 1, acuity) or intensity (Experiment 2, sensitivity). Data were fitted with a cumulative Gaussian psychometric function (Eq. 1) using the curve fitting toolbox in MATLAB (version 2012a).

$$y = 0.50 + 0.50/(1 + \exp(-(x - x_0)/b)) \quad (1)$$

where x_o is the 75% threshold, b is the *SD* and x is the stimulus separation or intensity for Experiments 1 and 2, respectively.

For Experiment 2, "standard thresholds" were measured in the presence of control vibration applied to the nontendon site. Detection thresholds were converted to decibels relative to this standard threshold using:

$$dB = 10 \times \log 10\,(\text{threshold}/\text{standard threshold}) \quad (2)$$

The statistical analysis comprised of repeated measures analysis of variances (ANOVAs). For all tests, α was set at $p < .05$. All multiple comparisons were made using Bonferroni correction.

Results

Experiment 1: Tactile acuity on a perceptually distorted arm. Figure 2a shows the mean tactile acuity thresholds for the three conditions: elongation, shortening, and control. A three-way (control, elongation, and shorten conditions) repeated measures ANOVA with a Greenhouse-Geisser correction determined that mean acuity thresholds differed significantly between conditions, $F(1.17, 14.06) = 5.85$, $p = .026$, $\eta_\rho^2 = .33$. Planned comparisons were conducted to determine if altering the perceived size of the arm impacted tactile acuity. Significant differences in acuity thresholds between the control condition and both of the tendon vibration conditions were revealed (elongation: $t(12) = -6.33$, $p < .001$; shorten: $t(12) = -2.8$, $p = .016$). Participants had higher thresholds (the stimuli had to be further apart to be distinguished) both while the arm was perceptually elongated (MD = 1.27 cm, $SE = .20$) and shortened (MD = 1.27 cm, $SE = .45$).

Experiment 2: Tactile sensitivity on a perceptually distorted arm. The elevation in detection thresholds for the elongation and shorten conditions relative to the control condition are shown in Figure 2b. A 2 (touch location) × 3 (control, elongation, and shorten conditions) repeated measures ANOVA was conducted to examine whether tactile sensitivity was affected when arm length was perceptually altered. The control condition was 0 dB by definition. There was a significant main effect of touch location, $F(1, 14) = 5.39$, $p = .036$, $\eta_\rho^2 = .28$, as well as of condition, $F(2, 28) = 8.52$, $p = .001$, $\eta_\rho^2 = .38$. A significant interaction between touch location and condition was also found, $F(2, 28) = 2.19$, $p = .049$, $\eta_\rho^2 = .19$, revealing that the effect of condition on tactile sensitivity depended on location. This interaction was investigated further by evaluating the simple effects of condition separately for each touch location. Simple-effects analyses showed that only detection thresholds for the touch located closest to the wrist were increased when the arm was perceptually extended (MD = 1.46, $SE = .408$, $p = .009$) or shortened (MD = 1.51, $SE = .406$, $p = .007$). All comparisons between conditions were not significant for the midarm touch location.

Experiments 3 and 4: Waist Acuity and Sensitivity

Materials and Method

Participants. Sixteen participants took part in Experiment 3 (12 females, mean age 22.5 years). Fifteen volunteers participated in Experiment 4 (10 females, mean age 24.4 years). All participants gave written informed consent. All studies were approved by the York University Research Ethics Board and were performed in accordance with the Treaty of Helsinki. The same rules that were used in Experiments 1 and 2 applied for determining sample size and when to stop data collection.

Stimuli.

Tactile. Tactile stimuli were the same as for Experiments 1 and 2. Five tactors, separated by 3 cm, were mounted on a belt that was worn around the waist with the central tactor positioned 3 cm below the navel.

Procedure. Blindfolded participants stood with their arms akimbo with the palms of their hands in contact with their waist and with the tactor belt fastened around their waist (Figure 1 c and 1d).

Experimental design. Participants were tested under three conditions—when the waist was perceptually expanded or shrunk, and during control vibration. The three conditions were presented in blocks of 20 trials in a counterbalanced order across participants and the order was repeated for each participant until trials were complete. Continuous vibration was applied throughout each block, with each block lasting between 90 and 110 s with a 1-min gap between blocks.

Experiment 3: Tactile acuity. The experimental design was identical to Experiment 1 except for location of the vibrotactile stimuli and response method. Because participants were required

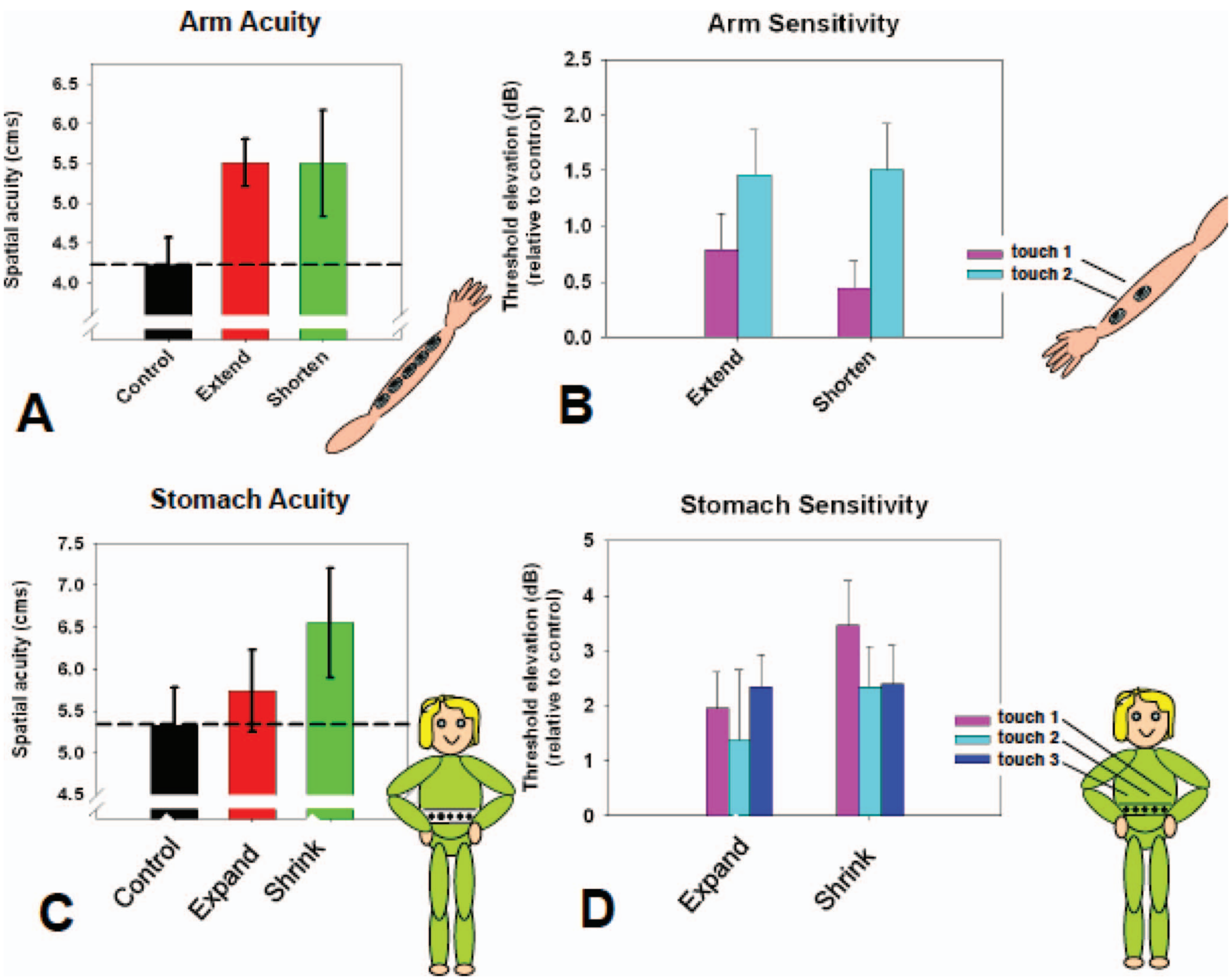

Figure 2. The effect of expanding or shrinking a body part on tactile sensations. Tactile spatial acuity (A, C) and sensitivity (B, D) of the arm (A, B) and stomach (C, D) for each of the three conditions. Spatial acuity thresholds are plotted in cm for the control, extend, and shorten conditions. The dashed horizontal lines represent the acuity on the arm (A) and stomach (C) under control conditions. The elevation in detection thresholds are given in decibels relative to detection thresholds measured under control conditions (elbow, B or shoulders, D). Detection thresholds are shown for two points on the forearm and three on the waist as indicated in the inserts. Error bars represent *SE*s.

to stand throughout the experiment, the experimenter recorded their verbal responses as to whether the two vibrotactile stimuli were in the first or second period.

Experiment 4: Tactile sensitivity. Tactile detection thresholds were measured at three locations on the torso (6 cm to the left of the midline, on the midline, and 6 cm to the right). The experimental design was the same as for Experiment 2 except for location of the vibrotactile stimuli and that responses were given verbally as for Experiment 3. There were three blocks per condition with a total of 24 trials per block (24 trials for each tactor).

Tendon vibration. A variation of the Pinocchio illusion was used to create illusory changes in waist size. Vibration was applied to the tendons of either both wrist extensors (producing an illusory shrinking of the waist) or both flexor muscles (producing an illusory expansion of the waist). In the control condition, vibration was applied to both shoulders. The vibrators and vibration properties were the same as in Experiments 1 and 2. The vibrators were held in place by means of two adjustable stands to maintain a constant position and pressure.

Effectiveness of the illusion. To assess the effectiveness of the illusion, the measurement of perceived waist size was assessed at the end of each block. Directly after vibration was stopped, participants (still blindfolded) were asked to indicate the waist size felt during the previous block by holding out their hands, palms facing inward. The distance between the hands was measured using a tape measure. Illusory waist size was measured four times for each condition in Experiment 3 and three times for each condition for Experiment 4. Perceived waist size was also measured when no vibration was present (four times in Experiment 3 and three times in Experiment 4) both at the beginning of the experiment and after completing one set of all three conditions. Discrepancies between estimates with and without tendon vibration indicated that tendon vibration effectively experienced changes in their perceived waist size. Participants were also asked at the end of each block to report if their waist felt like it had expanded, shrunk, or was unaffected.

As for Experiments 1 and 2, these two measures were then used to assess whether participants had experienced the illusions and if they should be included in the analysis. Only subjects who reliably experienced the illusions based on these two measures were included in the analysis (Experiment 3: $n = 14$; Experiment 4: $n = 13$).

The difference between measurements of perceived waist size reported in the illusion conditions and the control conditions was calculated. For Experiment 3, during the expand condition, participants perceived their waist to be expanded (increased by 6.92 cm, $SE = 1.69$) compared with the control condition. Waist size was perceived as smaller (decreased by −4.22 cm, $SE = 0.92$) in the shrink condition than in the control condition. For Experiment 4, waist size was perceived as expanded during the expand condition (increased by 7.16 cm, $SE = 2.15$) and shrunken during the shrink condition (decreased by −5.52 cm, $SE = 1.09$) compared with the control condition.

Data analysis. As for Experiments 1 and 2 except one-tailed *p* values were used for the planned comparisons.

Results

Experiment 3: Tactile acuity on a perceptually distorted waist. Two-point discrimination thresholds are plotted for each condition in Figure 2c. To determine if altering the perceived size of the waist impacted tactile acuity, a three-way (control, expand, and shrink conditions) repeated measures ANOVA was performed. The results show that there was a significant effect of condition, $F(1.27, 16.53) = 6.58$, $p = .015$, $\eta_p^2 = .34$, (Greenhouse-Geisser correction applied). Planned comparisons showed that thresholds were significantly increased when waist size was altered compared with the control condition. Thresholds increased from 5.34 cm ± .45 both when the waist was perceptually expanded (increased to 5.74 cm ± .49, $t(13) = -2.17$, $p = .0245$) and when the waist was shrunk (increased to 6.55 cm ± .65, $t(13) = -3.39$, $p = .0025$).

Experiment 4: Tactile sensitivity on a perceptually distorted waist. The elevations in tactile thresholds while the waist was perceptually made to feel expanded or shrunk are plotted in decibels relative to the control condition in Figure 2d.

A 3 (touch locations—left, right, and center) × 3 (control, expand, and shrink conditions) repeated measures ANOVA was conducted to examine whether altering the perceived size of the waist affected tactile sensitivity. A significant main effect was found for condition, $F(2, 24) = 10.56$, $p = .001$, $\eta_p^2 = .47$, indicating that distorting the perceived width of the waist using tendon vibration did affect sensitivity. There was no difference between touch locations, $F(2, 24) = .37$, $p = .696$, $\eta_p^2 = .03$ and no interaction between condition and touch location, $F(4, 48) = .92$, $p = .458$, $\eta_p^2 = .07$, that is, all locations were affected equally. Pairwise comparisons between conditions revealed that thresholds were significantly increased both in the shrink condition (MD = 2.47 dB, $SE = .60$, $p = .002$) and the expand condition (MD = 1.45 dB, $SE = .583$, $p = .042$) relative to the control condition.

General Discussion

The aim of our experiments was to investigate the role that body representation plays in tactile sensation. We used bodily illusions to perceptually alter body size and tested the impact that changes in perceived size had on tactile acuity and sensitivity. We found that illusory changes in body size caused degradation of tactile acuity and sensitivity for both the arm and the waist, demonstrating for the first time that elementary tactile sensations can be influenced by perceived body size changes in healthy individuals. Interestingly, we found a reduction of tactile performance for both illusory enlargement and shrinkage. These results provide evidence of how essential body representation is for tactile perception by showing how distorting body size, even for just 90 s, can influence the ability to perceive tactile sensations. We used vibrotactile stimuli at 250 Hz. Such stimuli would stimulate both slow and rapidly adapting mechanoreceptors in the skin (Gescheider, Wright, & Verrillo, 2009). It was not our aim to isolate one or other type of mechanoreceptor. Future experiments will use a range of frequencies to obtain a more detailed analysis of the effects we report.

Why might tactile performance get worse independent of the direction of change in perceived body size unlike pain thresholds, which some studies have shown to depend on the direction of body distortion (Mancini et al., 2011; Moseley et al., 2008, but see Diers, Zieglgänsberger, Trojan, Drevensek, Erhardt-Raum, & Flor, 2013; Ramachandran, Brang, & McGeoch, 2009)? We postulate that manipulations of perceived body size initiate a disruption in the body representation. It is a consequence of the initiation of such a change that we postulate may underlie our results. Putting the representation of the body into a state of flux would upset tactile perception that requires an accurate body representation to which touch sensations can be related. Altering body representation would lead to less reliability in this mapping process and thus add noise to all aspects of tactile perception. The reduction in acuity and sensitivity that we observe would then correspond to this noisy, temporarily unreliable body representation in the early stages of changing itself. Plasticity of body representation has been shown to occur in cases of amputation (Ramachandran & Hirstein, 1998) and brain-damaged patients (Sposito, Bolognini, Vallar, Posteraro, & Maravita, 2010) but these changes can often take months or years after injury to fully consolidate (Ramachandran & Hirstein, 1998).

Following changes in the perceived length of the arm, thresholds were elevated more for the site nearest the wrist (independent of the direction of the illusion, Figure 2b). If this were to do with distance from the wrist grip, the control condition (that vibrated the bones of the right arm) would be expected to produce at least as much mechanical vibration. We have no explanation for the variation between sites on the forearm but the greater effects found near the wrist might indicate that the perceived length of the arm was not distorted evenly. Possibly the part nearest the wrist was perceptually lengthened more than the part nearer the elbow. More detailed experiments would be needed to explore this possibility.

Asymmetry

Changes in tactile perception of objects pressed against the skin have been reported only for increases in perceived body size, with no corresponding effects reported in response to perceptual shrinking (de Vignemont et al., 2005). The explanation usually suggested (e.g., de Vignemont et al., 2005) for this asymmetry is that our bodies are more capable of enlarging, for example during normal growth, than shrinking and that only perceptually enlarging body parts can influence body representation. However, we found changes in tactile sensations following both perceptual expanding and shrinking. This supports our general disruption model that we postulate to occur whenever body representation is altered in either direction. Improvements in tactile perception are found when additional information is provided, such as vision (Bruno & Bertamini, 2010; Marino et al., 2010; Moseley et al., 2008; Taylor-Clarke et al., 2004), multisensory information (Pavani & Zampini, 2007), or training (Moseley & Wiech, 2009; Wong, Peters, & Goldreich, 2013), so it makes sense that decreased tactile performance would occur when information is removed or interfered with. Support for this line of thought comes from the case of pain. Distorted body representations and correspondingly decreased tactile acuity has been observed in individuals who suffer from pain disorders such as complex regional pain syndrome (Moseley, 2005), phantom limb pain (Flor, Nikolajsen, & Staehelin Jensen, 2006), and chronic back pain (Moseley, 2008).

Comparison With Clinical Distortions of Body Size

Patients suffering from Anorexia Nervosa have well known, long-term distortions of the size of their bodies (Cash & Deagle, 1997). These patients misperceive tactile distances (Keizer et al., 2011) and have increased two point discrimination thresholds (Keizer et al., 2012) consistent with our thesis that such elementary tactile abilities depend on perceived body size. However, Anorexia Nervosa patients show lowered (more sensitive) tactile detection thresholds (Keizer et al., 2012) unlike the effects reported here that showed consistent increases. This reflects a difference between short-term and long-term distortions of perceived body size. Whether longer-term induced changes in perceived body size in healthy individuals will eventually evoke increases in tactile sensitivity is the subject of ongoing investigations.

Conclusions

Changes in the perceived size of the body send the brain's body representation into turmoil. This turmoil is revealed by degradation in tactile acuity and sensitivity. Plasticity in the internal representation of the body is a vital part of coping with changing body size during development or pregnancy. Failures to respond adaptively to such changes may underlie phantom limb pain and body-image-related related disorders.

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Received May 8, 2014
Revision received October 1, 2014
Accepted October 6, 2014 ■