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RESEARCH ARTICLE

Vibrotactile masking through the body

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Abstract Touches on one hand or forearm can affect tactile sensitivity at contralateral locations on the opposite side of the body. These interactions suggest an intimate connection between the two sides of the body. Here, we explore the effect of masking not across the body but through the body by measuring the effect of a masking stimulus on the back on the tactile sensitivity of the corresponding point on the front. Tactile sensitivity was measured on each side of the stomach, while vibrotactile masking stimulation was applied to one side of the front and to points on the back including the point directly behind the test point on the front. Results were compared to sensitivity, while vibrotactile stimulation was applied to a control site on the shoulder. A reduction in sensitivity of about .8 dB was found that required the masking stimulus to be within about 2 cm of the corresponding point on the back.

Keywords Long-range tactile masking · Somatosensory sensitivity · Tactile detection thresholds · Body representation · Flat body hypothesis

Introduction

Somatosensory information about the body surface is split into two in the brain with each hemisphere receiving information from only one-half of the body (Penfield and Boldrey 1937). The two representations are connected through callosal pathways, so that even by area 5 many of the cells receive inputs from both sides (Manzoni et al. 1980, 1989). Even by this stage of processing the body-in-the-brain is treated as an integrated whole. However, this arrangement does not help us understand how the "flat map" in the cortex is turned into a useable representation of a three-dimensional body. Research investigating the representation of touch has tended to focus on the fingers and hands, with relatively few studies examining the whole body (but see Cholewiak et al. 2004; van Erp 2008). Here, we look for interactions between the front and back of the body to look for evidence of how the three-dimensional shape of the body is represented.

An important way to study the tactile sense is through the use of masking in which the sensitivity at one location is affected by vibration applied at a remote site. Traditionally, long-range tactile masking effects have been studied using the fingers, hands and arms, where masking has been found to occur between mirror-symmetric points across the body (Sherrick 1964; Braun et al. 2005; D'Amour and Harris 2014). Long-range reciprocally inhibitory pathways have been demonstrated between cortical tactile maps of the two halves of the body (Reed et al. 2011) which may be the neurophysiological explanation of these long-range interactive effects. However, the mobile limbs may be a special case and concentrating on these body parts ignores the body as a whole. Few studies have explored tactile masking using more extensive areas of the body (e.g., Alliusi et al. 1965; Geldard and Sherrick 1965; Craig 1966).

One reason that the limbs might be a special case, apart from their obvious motility, is that they fall within the visual field. Recent evidence (Tipper et al. 2001; Harrar and Harris 2010; Pritchett and Harris 2011) has suggested, counterintuitively, that tactile location may be coded at least partially in visual coordinates. However, we can never completely see our entire body and many regions, for example the back can never be seen. How then might the

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back be represented? Are we to postulate different coding systems for different parts of the body? Or might unseen parts of the body be somehow linked to corresponding visible areas?

To investigate the brain's representation of invisible body parts, we explored whether long-range interactions could be found between the visible front and the invisible back of the body. Having found evidence of through-the-body masking, we then measured the spatial tuning of the effect.

Methods

Participants

Ten participants took part in Experiment 1 (nine females, mean age 21.1 years, SD = 2.1 years) and 14 individuals participated in Experiment 2 (eight females, mean age 19.9 years, SD = 2.8 years). They were recruited from the York University Participant Pool and received credit for taking part in the experiments. All experiments were approved by the York Ethics board, and all participants signed informed consent forms. All experiments were performed in accordance with the Treaty of Helsinki.

Stimuli

Detection stimulus

Tactile stimuli were 100 ms bursts of 250 Hz vibration of variable intensity controlled by a 64-bit sound card powered by a PC computer played through C2 tactors (Audio Research, California). Two tactors were mounted on a belt worn around the waist. The tactors were positioned 12 cm on each side of the midline and 3 cm below the navel.

Masking stimulus

The masking stimulus was provided by a Magic Wand vibrator (Hitachi, Japan) applied to the skin. The head of this vibrator is spherical with a diameter of about 4 cm. It was applied lightly to the skin making a contact zone of about 1 cm^2. Masking vibration was 83 Hz with the device set on "low." In Experiment 1, the masking stimulus was applied to one of the four sites on the body: on the front (on the left side of the stomach about 3 cm above the left tactor), on the back (directly behind the left tactor) and at control sites on both shoulders. These sites are shown in Fig. 1a–c. For Experiment 2, the masking stimulus was applied at one of seven sites equally spaced around the left side of the trunk and up the back on the left side as shown in the insets of Fig. 1e, f. These masking sites were (1) on the front (on the left side of the stomach 2 cm to the left of the left tactor), (2) on the side (on the left side of the trunk), (3) half way between the side and the back position, (4) on the back (directly behind the left tactor), (5) mid back (half way up the back on the left side), (6) top back (near the top of the back on the left side) and (7) control (on the back of the left shoulder). The masking vibrator was held in place by an adjustable stand and was left on throughout the duration of each experimental block (<2 min).

Procedure

Blindfolded participants stood for the duration of each block. The experimenter arranged the adjustable stand to apply the masking stimulus to the pre-chosen body site and left it running in place while a block of trials was run. Using a two alternative forced choice (2AFC) paradigm, participants were presented with two 1 s periods marked by three beeps (5, 3 and 5 kHz; duration 100 ms) and identified in which period the touch was present. Stimulus intensity was controlled by a QUEST psychometric procedure (Watson and Pelli 1983) running in MATLAB (version 2011b) on a PC. Participants verbally reported the period in which the stimulus was thought to occur.

Experimental design

For Experiment 1, tactile detection thresholds for the two tactors on each side of the stomach were measured in the presence of the masking vibration at one of the four sites shown in Fig. 1a–c. Each combination had 30 trials per tactor. Trials were divided into three blocks per condition with 20 trials per block (of a total of 12 blocks). Each block took less than 2 min.

For Experiment 2, tactile detection thresholds on the left side of the stomach were measured in the presence of masking vibration at one of the seven sites shown in Fig. 1e, f. Each condition had 40 trials. Trials were divided into two blocks per condition with 20 trials per block (for a total of 14 blocks). Each block took less than 2 min.

The sets of blocks for each experiment were run in a counterbalanced order, chosen for each subject using a Latin square, repeated as required.

Data analysis

The QUEST program returned an estimate of the threshold value. To visualize and confirm this, the participant's decision (correct or incorrect, 1 or 0) was plotted against the log (intensity) used for each trial and fitted with a

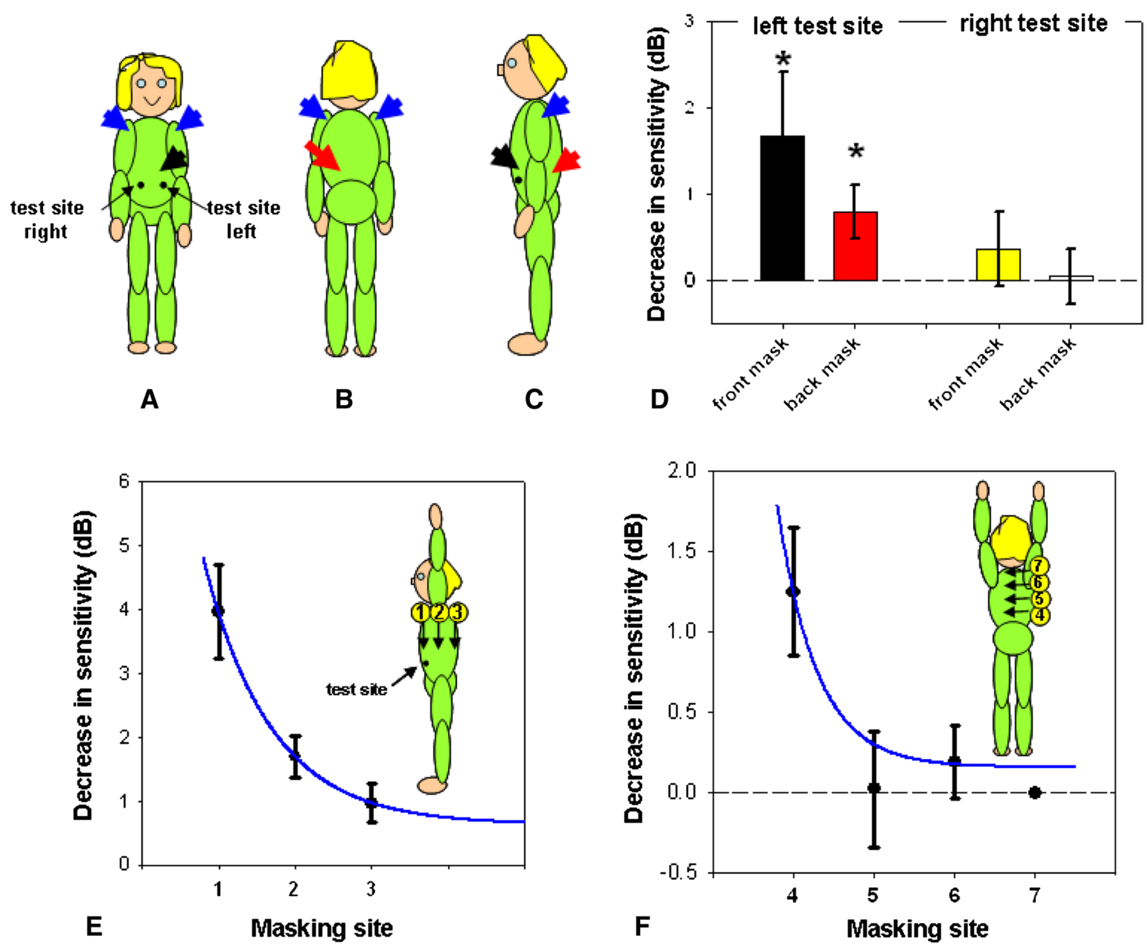

Fig. 1 Experiment 1: **a–c** The sites where masking vibration was applied: *black arrow* near the left test site on the front, *red arrow* on the corresponding point of the back. *Blue arrows* indicate the sites of vibration used as a control condition. Masking stimuli caused a significant increase in thresholds relative to control (*asterisks* correspond to $p < .05$) when applied either near the test site on the front (*black bar* in **d**) or at the corresponding point on the back (*red bar* in **d**). No effect was found at the test site on the side of the body contralateral to the masking sites (*yellow bars* in **d**). *Error bars* are SEs. Experiment 2: The masking effects when the masking stimulus was applied to sites on the front (**e**) or sites on the back (**f**) (masking sites shown numbered in the *insets*). Standard error bars are shown (location 7 was the control relative to which other data were expressed and therefore has a standard error of 0). Exponentials are plotted through the data points (color figure online)

cumulative Gaussian (Eq. 1) using the curve fitting toolbox in MATLAB.

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

where x_o is the 75 % threshold value, x is the log (intensity) tested and b is the standard deviation.

Detection thresholds were converted to decibels relative to the threshold measured when the control vibration was applied to the control sites using:

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

Results for Experiment 1 were not affected by which control was used and so only data relative to the right shoulder control are reported for that experiment. Statistical analyses were conducted using these threshold increases in dB.

Results

Experiment 1

All thresholds were expressed as increases in decibels relative to the thresholds measured in the control condition and are shown in Fig. 1d. Paired sample t tests were conducted to determine whether tactile detection thresholds were significantly increased when the masking stimulus was applied to the front and to the back compared to the control (right shoulder). All p values are reported as one-tailed values. Thresholds for the left tactor were significantly increased by a masking stimulus on the front 3 cm from the left testing site, $t(9) = 2.489$, $p = .0175$ by $1.71 \pm .69$ dB, and most importantly for this study, were also increased when the masking stimulus was on the corresponding point on the left side of the back, $t(9) = 3.748$, $p = .0025$ by $.83 \pm .22$ dB. Significant differences were found between the left and right tactor locations when the masking stimulus was on the left side of the front, $t(9) = 2.183$, $p = .0285$ (with a $1.69 \pm .78$ dB increase in the left relative to the right) and when the masking stimulus was on the left side of the back, $t(9) = 3.063$, $p = .0065$ (with a $1.12 \pm .37$ dB increase in the left relative to the right). Thus, we report an effect of masking through the body in which detection thresholds on the ipsilateral side of the stomach were increased when a masking stimulus was applied to the back. Experiment 2 investigated the spatial tuning of this effect.

Experiment 2

Threshold increases for the tactor on the left side of the stomach were expressed as dB increases relative when thresholds were measured in the presence of masking vibration applied to the control site on the back of the left shoulder. A repeated measures ANOVA was conducted on conditions in which the masking stimulus was applied to the three sites spaced around the waist (sites 1, 2 and 3, see Fig. 1e) and a significant effect of condition, $F(2, 26) = 14.70$, $p < .001$, $\eta_\rho^2 = .531$ was found. Bonferroni corrected post hoc tests revealed that the threshold for the front condition (site 1) was significantly increased relative to both the side (site 2, $2.269 \pm .670$ dB, $p = .015$) and back half (site 3, $2.997 \pm .631$ dB, $p = .001$) conditions. An exponential was fitted through these three threshold increases (see Fig. 1e) and showed a fall off with a space constant of 1.21 tactor spacings.

A repeated measures ANOVA was also conducted on the four back conditions (sites 4–7; back, mid back, top back and control, see Fig. 1f). The control condition was of course, by definition, 0. A significant effect of condition was found, $F(3, 39) = 4.696$, $p = .007$, $\eta_\rho^2 = .265$. Post hoc tests showed that the back condition was significantly increased from the control condition (site 4, $1.245 \pm .398$ dB, $p = .048$). An exponential was fitted through these four threshold increases (see Fig. 1f) and showed a fall off with a space constant of .63 tactor spacings.

Discussion

For the first time, we have demonstrated tactile masking through the body in which vibration on the back increases tactile thresholds at the corresponding point on the front. We further demonstrated that through-the-body masking, like contralateral masking (D'Amour and Harris 2014), is spatially tuned. By varying the location of the masking stimulus with respect to the corresponding point on the back (Fig. 1f), we showed a spatial constant of .63 tactor spacings which is around 2 cm (more precise estimates cannot be given because tactor spacings varied from person to person and our masking stimulus was quite large relative to these distances). Our study reveals a special relationship between the front and the back of the torso that may provide insight into how the body might be represented in the brain.

No contralateral masking on the trunk

Interestingly, thresholds were only increased when the masking stimulus was applied to the same side of the body as the test stimulus (Fig. 1d). This is in contrast to the cross-body masking effects that have been shown between the hands and arms (Halliday and Mingay 1961; Sherrick 1964; Bird 1964; Braun et al. 2005; Tamè et al. 2011; D'Amour and Harris 2014). This could be due to the different nature of the trunk in comparison with the fingers, hands, and arms and may be connected to the motility of the limbs.

The representation of the body in the brain

Localizing stimuli in space requires a three-dimensional representation of the body. How might this be achieved? For tactile stimuli felt on the hand and limbs, it requires knowledge of limb location in space and, although proprioceptors in the joints and muscles contribute to this assessment, limb location in space is most reliably provided by the visual system (Graziano 1999; Fuentes and Bastian 2010). Visual coding also seems to be important for locating touch applied to the front of the torso (Pritchett et al. 2012) but how might the location in space of points on the back be known? We postulate that the back may be "pinned" to the front with some kind of special connection that is revealed by the present through-the-body masking. Under this "flat body hypothesis," the location of points on the back would be coded at some level in terms of the location of the corresponding point on the front. Support for this idea comes from the observation that when asked to identify tactile patterns on the back of the torso or on the back of the head, participants make errors consistent with the patterns being perceived as if pressed through the body, or viewed from behind (Allen and Rudy 1970; Duke 1966; Natsoulas and Dumanoski 1964; Parsons and Shimojo 1987). Such a coding mechanism might be economical as a coding system for representing a complex three-dimensional structure in two-dimensional cortical maps. Any potential front–back confusion may be acceptable for a part of the body where tactile pattern recognition is not of primary importance.

The present study using a simple technique provides an unexpected result that modifies and challenges our understanding of how the three-dimensional body is represented in the brain.

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