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In your skin? Somatosensory cortex is purposely recruited to situate but not simulate vicarious touch

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A B S T R A C T

Previous studies of vicarious touch suggest that we automatically simulate observed touch experiences in our own body representation including primary and secondary somatosensory cortex (SCx). However, whether these early sensory areas are activated in a reflexive manner and the extent with which such SCx activations represent touch qualities, like texture, remains unclear. We measured event-related potentials (ERPs) of SCx's hierarchical processing stages, which map onto successive somatosensory ERP components, to investigate the timing of vicarious touch effects. In the first experiment, participants ($n = 43$) merely observed touch or no-touch to a hand; in the second, participants saw different touch textures (soft foam and hard rubber) either touching a hand (other-directed) or they were instructed that the touch was self-directed and to feel the touch. Each touch sequence was followed by a go/no-go task. We probed SCx activity and isolated SCx vicarious touch activations from visual carry over effects. We found that vicarious touch conditions (touch versus no-touch and soft versus hard) did not modulate early sensory ERP components (i.e. P50, N80); but we found effects on behavioural responses to the subsequent go/no-go stimulus consistent with post-perceptual effects. When comparing other- with self-directed touch conditions, we found that early and mid-latency components (i.e. P50, N80, P100, N140) were modulated consistent with early SCx activations. Importantly, these early sensory activations were not modulated by touch texture. Therefore, SCx is purposely recruited when participants are instructed to attend to touch; but such activation only situates, rather than fully simulates, the seen tactile experience in SCx.

1. Introduction

Observing another person being touched briefly by an object has been reported to automatically elicit processing in the observer's somatosensory cortex (SCx) (Keysers et al., 2010; Gallese and Ebisch, 2013). Support for this comes from fMRI studies that have shown that secondary SCx is activated when observing touch (Keysers et al., 2004), several others have even implicated activation of primary SCx (Kuehn et al., 2013, 2014, 2018; Schaefer et al., 2009, Schaefer et al., 2013). Such an increased activity in early, sensory SCx during vicarious touch has been suggested to allow for internally simulating others' tactile perceptions and has been argued to play a key role in social interactions (Keysers and Gazzola, 2009, 2014). Likewise, theories of embodied cognition have proposed that ongoing cognition is grounded in modality specific simulations (Damasio, 1989; Barsalou, 1999). However, in contrast to the theory of embodied simulation (Gallese, 2005; Gallese

and Ebisch, 2013) which proposes a full simulation of the tactile experience as if experiencing the touch on one's skin, theories of embodied cognition have suggested that such modality specific modulations may not be complete (Barsalou et al., 2003, 2005) suggesting neural activations which fall short of a full simulation of the tactile experience. Importantly, while previous studies have compared touch with no-touch observations, these have not investigated the effects of touch qualities. Touch perception is highly sensitive to surface texture which is encoded by neuronal populations in primary SCx (Lieber and Bensmaia, 2019). Understanding the extent to which SCx simulation of other's touch experiences also involves touch quality, like texture, would show whether such simulations fully match the neural processing of touch including texture (Gallese, 2005; Gallese and Ebisch, 2013), or merely situates it within the specific relevant modality (Barsalou et al., 2003, 2005) with no differentiation in activation patterns between different touch qualities. Furthermore, a more recent study has even questioned whether

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previously reported primary and secondary SCx engagement rather reflects posterior parietal cortex activity (Chan and Baker; 2015). Thus, SCx engagement in vicarious touch and whether such engagement reflects stages of early sensory touch processing or post-perceptual processes related to memorizing and appraising the observed touch is still not clear.

In contrast to fMRI, event-related potentials (ERP) allow investigation of the unfolding of successive stages of neural processing of sensory information on a millisecond time scale. Somatosensory processing is very hierarchical with successive early somatosensory components (i.e. P50, N80, P100) that are elicited by an onset of a tactile stimulus reflecting different anatomical and functional processing stages from primary (i.e. P50 and in part N80), to secondary (P100 and N140), to higher order SCx (Vibel et al., 2023). However, involvement of SCx in vicarious touch is not readily observable in ERPs. Yet, it can be revealed by probing SCx activity (c.f. Galvez-Pol et al., 2020, 2021). Importantly, previous ERP studies of vicarious touch (Adler and Gillmeister, 2019; Adler et al., 2016; Rigato et al., 2019) have not accounted for any contamination of the probed somatosensory ERPs by ongoing visual activity and may have also been affected by visuospatial congruency effects (e.g. Igarashi et al., 2004; Pavani et al., 2000; Sambo and Forster, 2009). Thus, while previous ERP studies have reported modulation of primary SCx (i.e. P50) and the Late Positive Complex (LPC) when observing touch, possible confounding variables may have impacted their findings.

To diminish any congruency issues and probe SCx activity, in the current study tactile probes were delivered on half of the trials to both hands and were completely task irrelevant. Probing SCx activity allowed us to dissociate somatosensory activations from visual carry over effects and investigate modulations of early sensory components (see Galvez-Pol et al., 2020, 2021). We therefore analysed ERPs in response to tactile probes (i.e. visuotactile ERPs) and after visual carry over effects were subtracted out (i.e. VEP-free SEPs). In the first experiment, participants saw touch on a hand or touch was prevented by a transparent screen placed in front of the hand (i.e. no-touch). In the second experiment, participants saw two different touch textures, soft foam and hard rubber, touch a hand. In addition to these other-directed touch trials, participants were instructed that the observed touch was self-directed and to 'feel' the seen touch. This condition allowed us to directly contrast mere observation of touch effects with touch observation effects involving self-engagement with the visual stimuli. Each touch sequence was followed by a go or no-go stimulus (e.g. Galang et al., 2017) to reveal any vicarious touch effects on post-perceptual, cognitive and motor processes.

2. Materials and method

2.1. Participants

Fifty paid volunteers participated in a single 3-h session. Three participants were excluded based on below overall 85 % accuracy level in the go/no-go tasks. Four participants were excluded during visual inspection of the neurophysiological data due to not showing discernible somatosensory components (P45, N80, P100, N140) elicited by the task-irrelevant tactile stimulation. The remaining 43 participants' (18 males), aged between 18 and 55 years ($M = 29.19$, SD $= 10.60$) data was used for analysis. All participants had normal or corrected vision, two were ambidextrous and four were left-handed. All participants gave informed consent before participation. The study was approved by City, University of London, Psychology Research Ethics Committee. The study is also detailed on the Open Science Framework (10.17605/OSF. IO/GP4AU)

2.2. Experimental design

2.2.1. Experiment 1: touch and no-touch

Stimuli of the first vicarious touch experiment consisted of sequences of images displayed to induced apparent motion perception while allowing to precisely mark the timing of an object touching the skin in the concurrent EEG recordings (see Fig. 1). Those images were frames extracted from videos recorded specifically for this study. The videos showed a bare Caucasian, young adult, female, right hand centred in a black background, where an object (stick with rubber tip) would appear from the top left corner to touch the right index finger and go back. All stimuli were from an egocentric view, i.e., placed as if it were the viewer's own hand. Before the start of the experiments, participants were shown the screen and the stick with the rubber and foam tips. They were prompted to feel the touch tips. The image sequence of experiment 1 always showed a stick with a rubber tip touching a hand (i.e. touch condition), and on half of the trials the hand was protected by a transparent screen (i.e. no-touch condition) with matched visual and kinetic properties of the touch condition but with the screen present (Fig. 1b). To probe somatosensory activity, we presented tactile probes (5 ms) through small solenoids attached to the top of the right and left index fingers. Tactile probes were randomly delivered on half of all trials and conditions, simultaneous with the onset of the touch image. Each touch sequence was followed by the presentation of a rectangle (6.5 × 5.5 cm) which was either orange or purple (go/no-go task). Participants were instructed to press with both thumbs the space bar if the colour indicated a go trial (80 % of trials) and withhold the response to the colour that was associated with a no-go trial (20 % of trials). The assignment of colour and response was counterbalanced across participants. At the end of the first experiment participants were asked to rate on a scale from 1 (= not at all) to 5 (= extremely) the similarity in physical appearance of their hand and the hand on the screen. Participants also completed the Interpersonal Reactivity Index (IRI) to collect self-report measures of empathy (Davis, 1983) and the embodiment scale (ES) by Longo et al. (2008). For the latter the wording of questions was changed to fit the experiment, in particular references to 'rubber hand' were replaced with 'hand on screen'. These self-report measures were taken to explore the relationship between physical similarities between observed and own hand, embodiment and empathy with significant vicarious touch amplitude modulations of SCx activity.

2.2.2. Experiment 2: hard and soft touch during other- and self-directed touch

In the first half of the experiment the image sequence showed the same hand as in experiment 1 with the same stick moving to touch the hand and back (i.e. other-directed touch condition). On half of the trials the same rubber tip was shown as in experiment 1, on the other half of trials the stick was shown with a foam tip forming the hard and soft touch conditions, respectively. In this first part the hand shown was superimposed with a green circle indicating the touch location (Fig. 1c). In the second half, only the green circle indicating the movement endpoint - and no hand - was shown (Fig. 1d). Participants were instructed that the stick was moving to touch their hand and to feel the touch by the tip (i.e. self-directed touch condition). Like in experiment 1, tactile probes were randomly presented on half of all trials and conditions, and each touch sequence was followed by the same go/no-go task. At the end of this experiment participants were asked to rate on a scale from 1 (soft) to 8 (hard) the softness/hardness of the touch experience during the other-directed touch condition, and separately, the self-directed touch condition. Due to a technical issue the responses to all four ratings were only recorded for a subset of participants ($n = 11$).

2.3. Procedure

Participants completed first 10 practise trials to familiarize them with the experimental task and tactile probes. Then they proceeded with
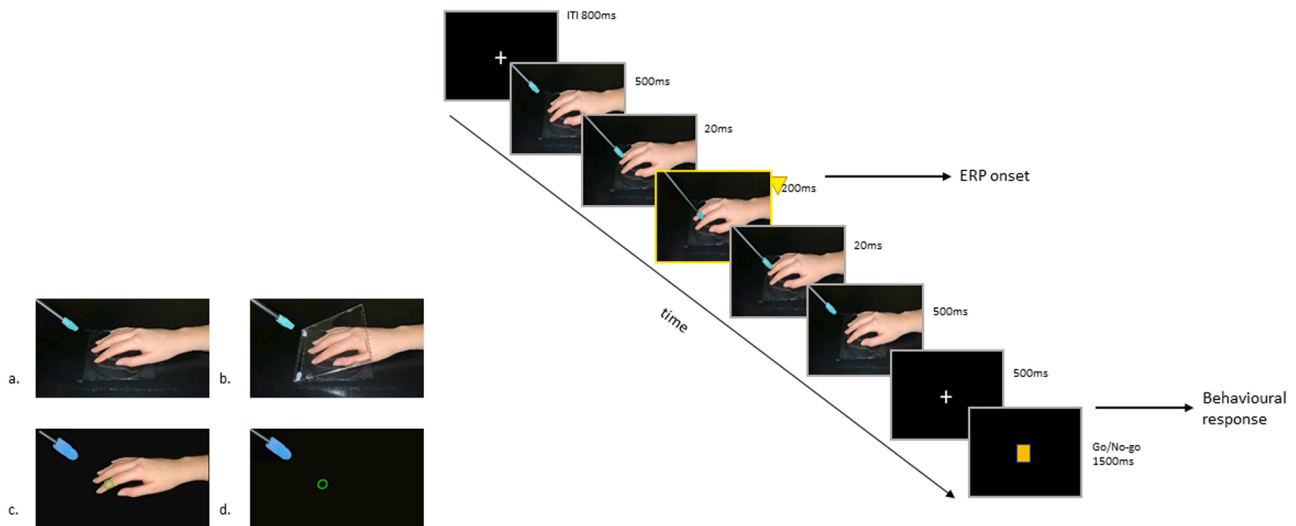
Fig. 1. Touch sequences shown to participants. On the left the start image for four different experimental conditions are shown. Image a and b are the start images of the touch and the no-touch conditions of experiment 1. Image c is the start image of the soft, other-directed touch condition and image d shows the start image of the soft, self-directed touch condition shown in experiment 2. The timeline shows the sequence and duration of images presented. The yellow triangle and highlight around the image indicate the delivery of the tactile probe at the onset of the vicarious touch image which is also time zero for the ERP analyses. Following each touch sequence, a rectangle was shown and participants had to either response by pressing the space bar on a keyboard or withhold the response which allowed calculation response times from the onset of the rectangle and response accuracy.

experiment 1 which was followed by the similarity rating task followed by the ES and IRI questionnaires. They then completed experiment 2. Each of the trials of the experiments started with the presentation of a fixation cross for 800 ms. This was followed by an image of a hand in the centre of the screen and a stick in the left top corner (or only a stick and a circle for the self-directed touch condition) for 510 ms followed for 30 ms by an image with the stick halfway towards the index finger and then 200 ms of an image with the stick touching the index finger or the circle or the no-touch. On half of the trials the start of the touch image was accompanied by a task-irrelevant tactile probe randomly delivered by small solenoids to top of the right and left index finger for 5 ms. The touch image was followed by the image with the stick in the intermediate position for 20 ms and the image with the stick in the starting position for 500 ms. This image sequence (see Fig. 1) was followed a fixation cross for 500 ms and then either an orange or purple rectangle for up to 1500 ms if no response occurred. Participants responded with their thumbs by pressing the space bar on go trials (80 %) while keeping the hands static on top of the keyboard. In total, there were 960 trials: 384 go trials and 96 no-go trials in each of the experiments. Throughout the experiments white noise (~65 dB) was presented from a speaker in front of participants to mask any noise from the tactile stimulators, and participants were monitored via a camera positioned above the monitor.

### 2.4. Electrophysiological recordings

Participants were seated in an electromagnetically shielded, sound attenuated, dimly lit room, viewing a 60 Hz computer monitor at a distance of about 80 cm. EEG was recorded (BrainProducts Recorder software) from 64 Ag/AgCL active electrodes of which 60 were mounted equidistantly on an elastic cap (M10 montage; EasyCap GmBH, Herrsching, Germany) and standard EEG recording preparation procedures were used to ensure good signal quality (i.e. degreasing of skin and use of electrolyte). Electrodes were referenced to the right earlobe and re-referenced off-line to the average of the scalp mounted electrodes. The horizontal electrooculogram (HEOG) was recorded by placing two electrodes about 1 cm lateral to the external canthi of each eye, and the vertical EOG was recorded by placing one electrode about 2 cm under the left eye. Continuous EEG was recorded using a BrainAmp amplifier (BrainProducts; amplifier bandpass 0.01–100 Hz) and a 500

Hz sampling rate. Off-line, EEG analysis was performed using Brain Vision Analyzer 2.2 software (Brain Products GmbH, Gilching, Germany). The data was digitally low-pass-filtered at 30 Hz (Butterworth zero phase filters). The EEG signal recorded during the touch observation experiments were epoched into segments lasting from 100 ms before to 500 ms after the onset of the image showing a stick touching the skin, the barrier or green circle which was also the onset of a tactile probe delivered to the index fingers on half of the trials. Segments were then baseline corrected to the first 100 ms. Eye movements were corrected (Gratton et al., 1983) and trials with other artifacts (voltage exceeding $\pm$ 100 mV relative to baseline at any electrode except those on the outer rim of the cap) were excluded from the analysis.

2.5. Statistical analyses: ERPs

In line with previous ERP studies (Adler and Gillmeister, 2019; Adler et al., 2016; Rigato et al., 2019), we investigated vicarious touch effects on ERP amplitudes over SCx following touch (or no touch) observations on visuotactile trials when SCx activity was probed by tactile stimuli. In addition, we also investigated any purer SCx modulations by isolating SCx activity from potential visual carry-over activity by subtracting brain activity on trials that contained activity only due to visual evoked responses (i.e., VEPs on visual-only trials) from trials that contained a combination of visual and somatosensory evoked responses due to the combined visual and tactile stimulus presentation (i.e., VEPs and SEPs on visual-tactile trials) (Fig. 2). This method (see Galvez-Pol et al., 2020, 2021; and Fig. 2A) allowed examining somatosensory processing (SEPs) free of visually evoked activity (VEP-free). To avoid any biases, we ensured a similar level of signal-to-noise ratio between visual-tactile and visual-only trial types. We ran repeated measures ANOVAs on mean amplitudes of grand averages with the factors hemisphere (left versus right) and touch (touch versus no-touch) for experiment 1, and with the factors hemisphere (left versus right), touch direction (self- versus other-directed) and touch texture (soft versus hard) for experiment 2, separately for ERPs elicited on visuotactile trial (analyses a) and for SEPs free of VEPs (analyses b). It has been recommended to pool ERP amplitudes over electrode sites of interest to minimize Type I errors (Luck and Gaspelin, 2017). We therefore pooled ERPs on visuotactile trials, and separately VEP-free SEPs over 6 electrode sites over the left and

A. Schematic illustration of trial types and elicited activations
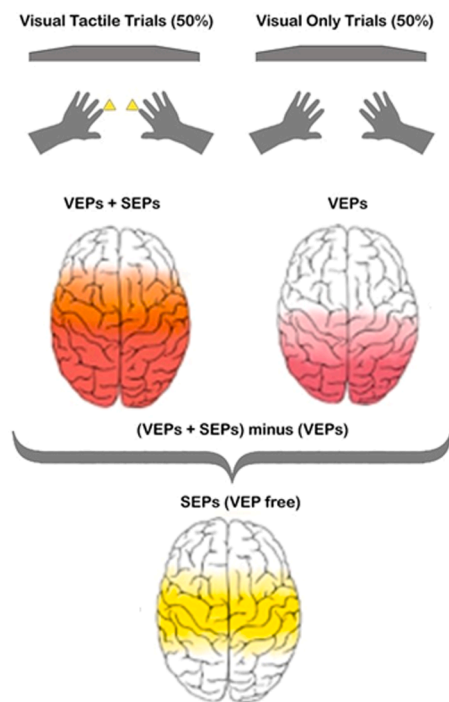
B. ERPs elicited on visual only and visuotactile trials and their difference VEP-free SEPs
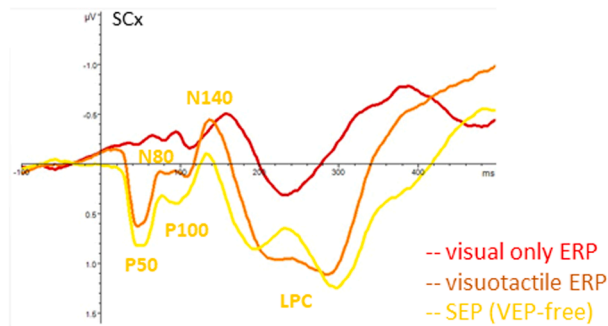
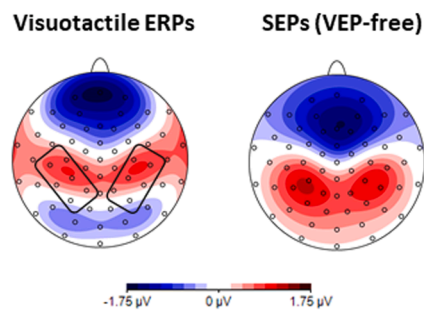## C. Topographic maps of the P50

Fig. 2. ERP analysis approach. Panel A illustrates the subtraction method used whereby ERPs elicited on visual only trials are subtracted from trials on which somatosensory activity is probed (visuotactile) to generate VEP-free SEPs. Panel B shows ERPs elicited on visual only (red) and visuotactile (brown) trials, and their difference resulting in VEP-free SEP (yellow). Timepoint zero is the onset of the tactile probe and equivalent in time on visual only trials. The waveforms are grand averaged ERPs pooled over electrodes over right and left somatosensory cortex and across all visual only and visuotactile trials across both experiments and all touch observation conditions. Panel C shows topographic maps for the P50 of visuotactile ERPs and VEP-free SEPs including two boxes encompassing the electrodes included in the analyses.

right hemisphere overlapping with SCx and where early SEP components were clearly visible as confirmed by topographic mapping of early SEP components in grand averages generated across all touch observation conditions of visuotactile ERPs and separately VEP-free SEPs (Fig. 1c). These electrode locations matched previous studies (Adler and Gillmeister, 2019; Adler et al., 2016); that is, for left hemisphere electrodes 17, 16, 15, 31, 30, 29 of our M10 equidistance system (https://www.easycap.de/wp-content/uploads/2018/02/Easycap-Equidistant-Layouts.pdf) corresponding to C3, CP3, P1, C5, between CP5-P5 and between P5-PO3 and for the right hemisphere 11, 12, 13, 24, 25, 26 corresponding to C4, CP4, P2, C6, between CP6-P6 and between P6-PO4 of the 10/10 system. As tactile stimuli were crucial to probe SCx activity we inspected the morphology of each participants' grand averaged SEP waveform across all conditions for the presence of early SEP components (i.e. P50, N80, P100, N140) which led to exclusion of the data of 4 participants from analysis as SCx activity was not sufficiently probed possibly due to one or both tactile stimulators becoming dislodged during testing. We calculated mean amplitudes for analyses time windows centred on the early somatosensory components which were based on grand average waveform across all conditions and participants (i.e. P45 (40 – 60 ms), N80 (66 – 92 ms), P100 (94 – 124 ms), and N140 (120–150 ms), and late positive complex (LPC (180 - 320 ms) for explorative analysis) matching previous ERP analyses approaches which have shown modulation of ERPs over SCx when comparing touch with no-touch observations. As we averaged amplitudes over 6 electrode sites and thus may have eliminated any more localized vicarious touch effects, we also ran explorative Bayesian t tests on mean amplitudes for each component at each electrode site for the different vicarious touch conditions of experiment 1 for the factor touch (touch versus no-touch), and for touch texture (soft versus hard) and separately for touch

direction (self- versus other- directed) in experiment 2. Bayesian analysis allows to confirm the strength of the evidence for either the null ($BF_{10} < 1$) or alternative hypothesis ($BF_{10} > 1$). This analysis is reported in the supplementary material.

2.6. Statistical analysis: behavioural measures

Go/no-go task. Five hundred milliseconds after the end of the vicarious touch sequence, participants responded on 80 % of trials to the onset of a coloured rectangle and withheld the response to a different coloured rectangle on the reminder of randomly intermixed trials. This was to engage participants in a task and allowed to investigate any post-perceptual, higher cognitive effects on motor processes (e.g. Galang et al., 2017) in addition to the early perceptual effects investigated ERP amplitude changes. We analysed both mean accuracy and response times (RTs) after visual only sequences for each of the experiments and vicarious touch conditions using *t*-tests (Exp.1: factor touch (touch versus no-touch) and repeated measures ANOVAs (Exp. 2: factors texture (soft versus hard) and touch direction (other- versus self-directed)).

Self-report questionnaires. We measured participants perceived perceptual similarity between their own and the hand image presented, their embodiment of the hand image and empathy. These measures were taken to explore whether these relate to early perceptual effects on SCx activity (i.e. amplitude differences on touch minus no-touch, soft minus hard, and self- minus other-directed touch trials). Lastly, we also asked participants to rate the softness/hardness of the touch in the other- and self-directed conditions to ensure that these were perceived as different.

All statistical analyses were performed with JASP (version 0.17.1.0) and are available at OSF (DOI:10.17605/OSF.IO/XWSP3).

3. Results

3.1. Experiment 1: vicarious touch and no-touch

3.1.1. P50 analysis

(a) The analysis of visuotactile trials showed no main effect of hemisphere (F(1,42) = 1.46, p = .23, n^2 = 0.01), touch (F(1,42) = 0.65, p = .43, n^2 = 0.007) or interaction between the two factors (F(1,42) = 1.13, p = .29, n^2 = 0.005). (b) Furthermore, the analysis of VEP-free SEPs showed also no main effect of hemisphere (F(1,42) = 0.31, p = .58, n^2 = 0.002), touch (F(1,42) = 0.54, p = .47, n^2 = 0.006) or interaction between the two factors (F(1,42) = 0.16, p = .69, n^2 < 0.001). Taken together, these analyses confirm an absence of any vicarious touch effects (i.e. amplitude differences between touch and no-touch conditions) on primary SCx activity (see Fig. 3A).

3.1.2. N80 analysis

a) Analysis of amplitudes on visuotactile trials showed no significant main effects (touch: (F(1,42)=0.04, p=.85, n^2<0.001) or hemisphere: (F(1,42)=3.95, p=.053, n^2=0.044), but a significant hemisphere by touch interaction (F(1,42)=5.021, p=.03, n^2=0.015). Follow up t tests contrasting amplitudes on touch and no-touch trials separate for each hemisphere did not show any significant differences (t(42) = 1.15 and −1.19, p= .26 and 0.24, d = 0.18 and −0.18). (b) Analysis of the VEP-free SEPs showed also no significant main effects (hemisphere: (F(1,42) = 00.75, p=.39, n2 = 0.006) and touch: (F(1,42) = 0.005, p=.94, n^2 < 0.001)) or interaction between the two (F(1,42) = 0.12, p = .73, n^2 < 0.001). Taken together, neither analysis of visuotactile trials or isolated SEPs (VEP-free) showed any amplitude differences between touch and no-touch.
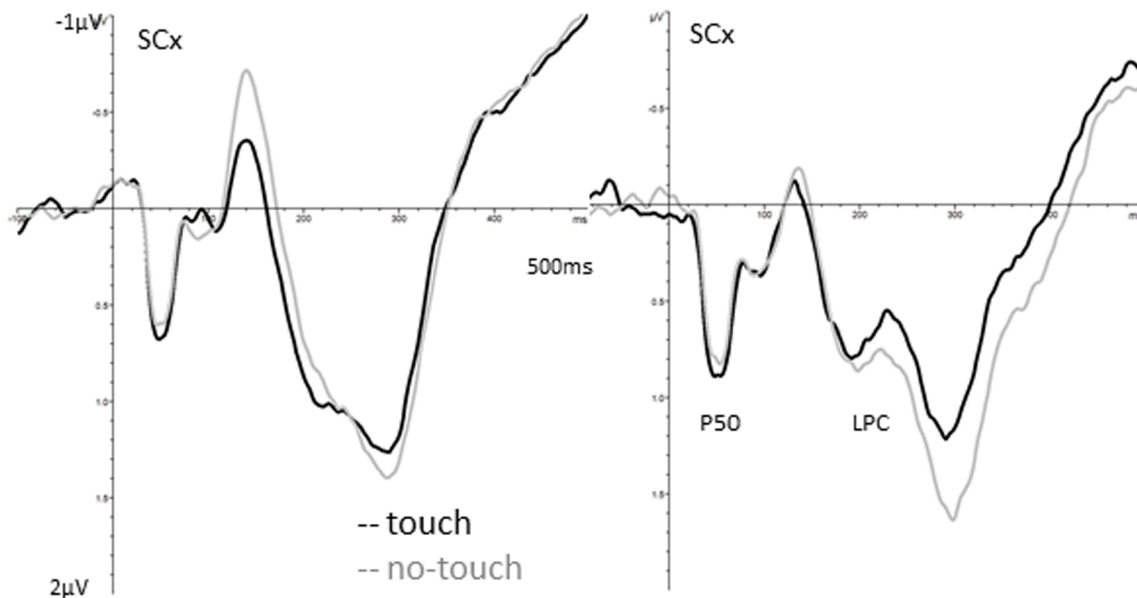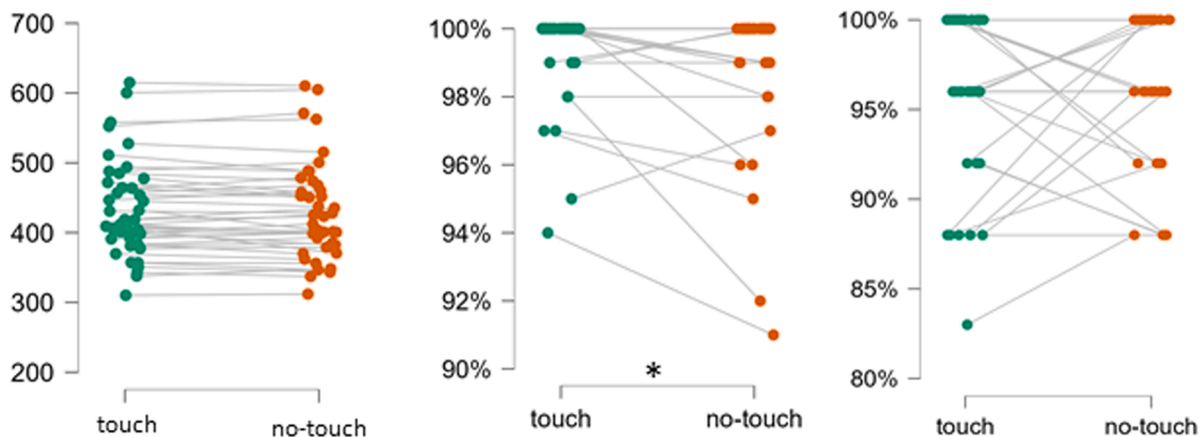
Fig. 3. Effects of seeing touch and no-touch on ERPs and behavioural responses. Panel A: averaged ERPs are shown that are averaged over all left and right SCx electrodes included in the analysis and averaged separately for visuotactile ERPs (left) and VEP-free SEPs (right) and for the touch (black) and no-touch (grey) conditions of experiment 1. Panel B: Distribution of individual mean response times (left) and accuracies (right) on go and no-go trials are shown for touch (green) and no-touch (orange) conditions. Asterix indicates significant difference between touch and no-touch conditions.

3.1.3. P100 analysis

(a) The analysis of visuotactile trials showed no main effects (hemisphere: $F(1,42) = 0.08$, $p = .78$, $n^2 = 0.001$) and touch: ($F(1,42) = 0.72$, $p = .40$, $n^2 = 0.004$)) but an interaction between the two factors ($F(1,42) = 6.12$, $p = .018$, $n^2 = 0.014$). Follow up t-test contrasting touch and no-touch amplitudes over the right and left hemisphere separately showed no significant amplitude difference (Bonferroni adjusted p level < 0.025; left hemisphere: $t(42) = -2.03$, $p = .049$, $d = -0.31$; right hemisphere: $t(42) = -0.618$, $p = .54$, $d = 0.09$). (b) The analysis of VEP-free SEPs showed no main effect of hemisphere ($F(1,42) = 0.005$, $p = 0.94$, $n^2 < 0.001$), touch ($F(1,42) = 0.04$, $p = .84$, $n^2 < 0.001$) or interaction between the two factors ($F(1,42) = 0.94$, $p = .34$, $n^2 = 0.002$). Taken together, neither analysis of visuotactile trials or isolated SEPs (VEP-free) showed any amplitude differences between touch and no-touch.

3.1.4. N140 analysis

(a) The analysis of visuotactile trials showed main effects of hemisphere ($F(1,42) = 4.74$, $p = .035$, $n^2 = 0.068$) and touch ($F(1,42) = 8.82$, $p = .005$, $n^2 = 0.04$) but no interaction between the two factors ($F(1,42) = 2.46$, $p = .13$, $n^2 = 0.005$). (b) In contrast, the analysis of VEP-free SEPs showed no main effect of hemisphere ($F(1,42) = 1.20$, $p = 0.28$, $n^2 = 0.01$), touch ($F(1,42) = 0.14$, $p = .71$, $n^2 = 0.001$) or interaction between the two factors ($F(1,42) = 0.05$, $p = .82$, $n^2 < 0.001$). Taken together, these analyses show that vicarious touch effects present on visuotactile trials are accounted for by visual carry-over effects and thus an absence of vicarious touch modulations on secondary SCx activity.

3.1.5. LPC analysis

(a) Analysis of amplitudes on visuotactile trials for the later LPC pooled over SCx electrodes showed no significant main effect of touch ($F(1,42) = 0.04$, $p = .85$, $n^2 < 0.001$) but a significant main effect of hemisphere ($F(1,42) = 14.54$, $p < .001$, $n^2 = 0.171$), and hemisphere by touch interaction ($F(1,42) = 4.12$, $p < .05$, $n^2 = 0.008$). Follow up t tests contrasting amplitudes on touch and no-touch conditions separate for each hemisphere did not show any significant differences ($t(42) = 1.43$ and -0.74, $p = .16$ and 0.46, $d = 0.22$ and -0.11). (b) Analysis of the VEP-free SEPs showed no significant main effect of hemisphere ($F(1,42) = 0.12$, $p = .73$, $n^2 < 0.001$), touch ($F(1,42) = 3.49$, $p = .07$, $n^2 = 0.04$) or interaction between the two ($F(1,42) = 0.02$, $p = .89$, $n^2 < 0.001$). Taken together, neither analysis of visuotactile trials or isolated SEPs (VEP-free) showed any amplitude differences between touch and no-touch conditions.

3.1.6. Go/no-go task analysis

Paired samples t tests were conducted to analyse any effects of the touch conditions on response times and accuracies to coloured rectangles presented after observing the touch sequence. Participants response times on go trials were similar when previously seeing touch ($M = 432.4$, $SD = 66.8$) compared to no-touch ($M = 429.9$, $SD = 69.9$; ($t(42) = 1.31$, $p = .19$, $d = 0.20$). Interestingly, participants missed responding significantly more often after no-touch ($M = 99.0$ %, $SD = 1.4$) than after seeing touch ($M = 99.4$ %, $SD = 1.4$; $t(42) = 2.2$, $p = .03$, $d = 0.34$). There was no effect of touch (touch: $M = 96.6$ % $SD = 0.05$; No-touch: $M = 96.8$ % $SD = 0.04$) on accurately withholding a response on no-go trials ($t(42) = -0.33$, $p = .74$, $d = -0.05$). These behavioural results (see Fig. 3B) suggest an effect of vicarious touch on sensorimotor processes in that seeing touch modulates response initiation in line with post-perceptual effects of vicarious touch.

3.2. Experiment 2: vicarious hard and soft touch during other- and self-directed touch

3.2.1. P50 analysis

(a) The analysis of visuotactile trials showed significant main effects of a touch direction ($F(1,42) = 23.93$, $p < .001$, $n^2 = 0.112$) and

hemisphere ($F(1,42) = 5.50$, $p = .025$, $n^2 = 0.035$), and interactions between hemisphere and touch direction ($F(1,42) = 8.96$, $p = .005$, $n^2 = 0.008$), and touch direction and texture ($F(1,42) = 5.35$, $p = .026$, $n^2 = 0.012$). There was no other main effect (texture: $F(1,42) = 0.21$, $p = .65$, $n^2 < 0.001$) or significant interactions (all $F(1,42) < 3.78$, $p > .058$, $n^2 < 0.015$). We followed up the hemisphere by touch direction interaction with t tests separate for each hemisphere showing a significant difference (Bonferroni adjusted p level < 0.025) between self- and other-directed touch only for amplitudes over the left hemisphere ($t(42) = 4.24$, $p < .001$, $d = 0.65$). We followed up the touch direction by texture interaction in two ways (Bonferroni adjusted p level > 0.015); and only found a significant difference for amplitudes on self-directed compared to other-directed touch on soft texture trials ($t(42) = 3.85$, $p < 0.001$, $d = 0.59$) when following up the interaction separately for texture. (b) Analysis of VEP-free SEPs showed also a significant main effect of touch direction ($F(1,42) = 8.23$, $p = .005$, $n^2 = 0.041$) but no other main effects or interactions (all $F(1,42) < 1.83$, $p < .19$) suggesting that any hemisphere differences reported on visuotactile trials may be mainly driven by carry-over effects from visual evoked responses. Taken together, these results show no effect of observed touch texture on P50 amplitudes (see Fig. 4) but show a difference on primary SCx activity during self-compared to other-directed touch (see Fig. 5).

3.2.2. N80 analysis

(a) Analysis of amplitudes over SCx on visuotactile trials showed a significant main effect of hemisphere ($F(1,42) = 5.40$; $p = .025$, $n^2 = 0.035$) and touch direction ($F(1,42) = 23.19$; $p < .001$, $n^2 = 0.112$), and interaction between the two ($F(1,42) = 8.96$; $p = .005$, $n^2 = 0.015$). There was no other significant main effect (texture: $F(1,42) = 0.21$, $p = .65$, $n^2 < 0.001$) or interactions (all $F(1,42) < 3.79$; $p > .06$, $n^2 < 0.001$). We followed up the significant interaction with separate t tests for each hemisphere showing a significant difference between self- and other-directed touch trials for amplitudes over the left (($t(42) = -5.29$, $p < .001$, $d = 0.81$) and right ($t(42) = 2.86$, $p = .007$, $d = 0.13$) hemispheres (Bonferroni adjusted p level < 0.025). (b) Analysis of VEP-free SEPs also showed a significant main effect of touch direction ($F(1,42) = 8.83$; $p = .005$, $n^2 = 0.04$) but no other significant main effects or interactions (all $F(1,42) < 1.82$; $p > .18$, $n^2 < 0.007$). Taken together, these results further support the significant touch direction difference already present at the P50 component (Fig. 5).

3.2.3. P100 analysis

(a) Analysis of visuotactile trials showed a significant main effect of self-/other-directed touch ($F(1,42) = 18.8$; $p < .001$, $n^2 = 0.08$) and significant hemisphere by touch direction ($F(1,42) = 5.4$; $p = .025$, $n^2 = 0.002$) and hemisphere by texture interactions ($F(1,42) = 10.85$; $p < .01$, $n^2 = 0.009$). Follow up t tests for each interaction (Bonferroni adjusted p level < 0.025) separate for each hemisphere showed significant amplitude differences between other- and self-directed touch over the left hemisphere ($t(42) = 4.8$, $p < .001$, $d = 0.73$). As for the right hemisphere amplitudes the test of normality was not met (Shapiro-Wilk test $p = .042$), Wilcoxon signed-rank test was run which also showed a significant difference ($z = 2.61$, $p = .008$, $d = 0.46$). Further, there was no significant difference in amplitudes between textures over the left ($t(42) = 1.2$, $p = .22$, $d = 0.11$) and right (Shapiro-Wilk test $p = .022$; $z = -0.71$, $p = .48$, $d = -0.13$) hemisphere. (b) Analysis of VEP-free SEP amplitudes showed also a main effect of touch direction ($F(1,42) = 10.77$; $p = .006$, $n^2 = 0.03$) with no other main effects or interactions (all $F(1,42) < 1.43$, $p > .24$). Taken together, these results support an overall significant touch direction effect also on P100 amplitudes when seeing touch (Fig. 5) but no touch texture effects (Fig. 4).

3.2.4. N140 analysis

(a) Analysis of visuotactile trials showed a significant main effect of hemisphere ($F(1,42) = 5.26$; $p = .027$, $n^2 = 0.035$) and touch direction ($F(1,42) = 13.85$, $p < .001$, $n^2 = 0.056$), and significant interaction
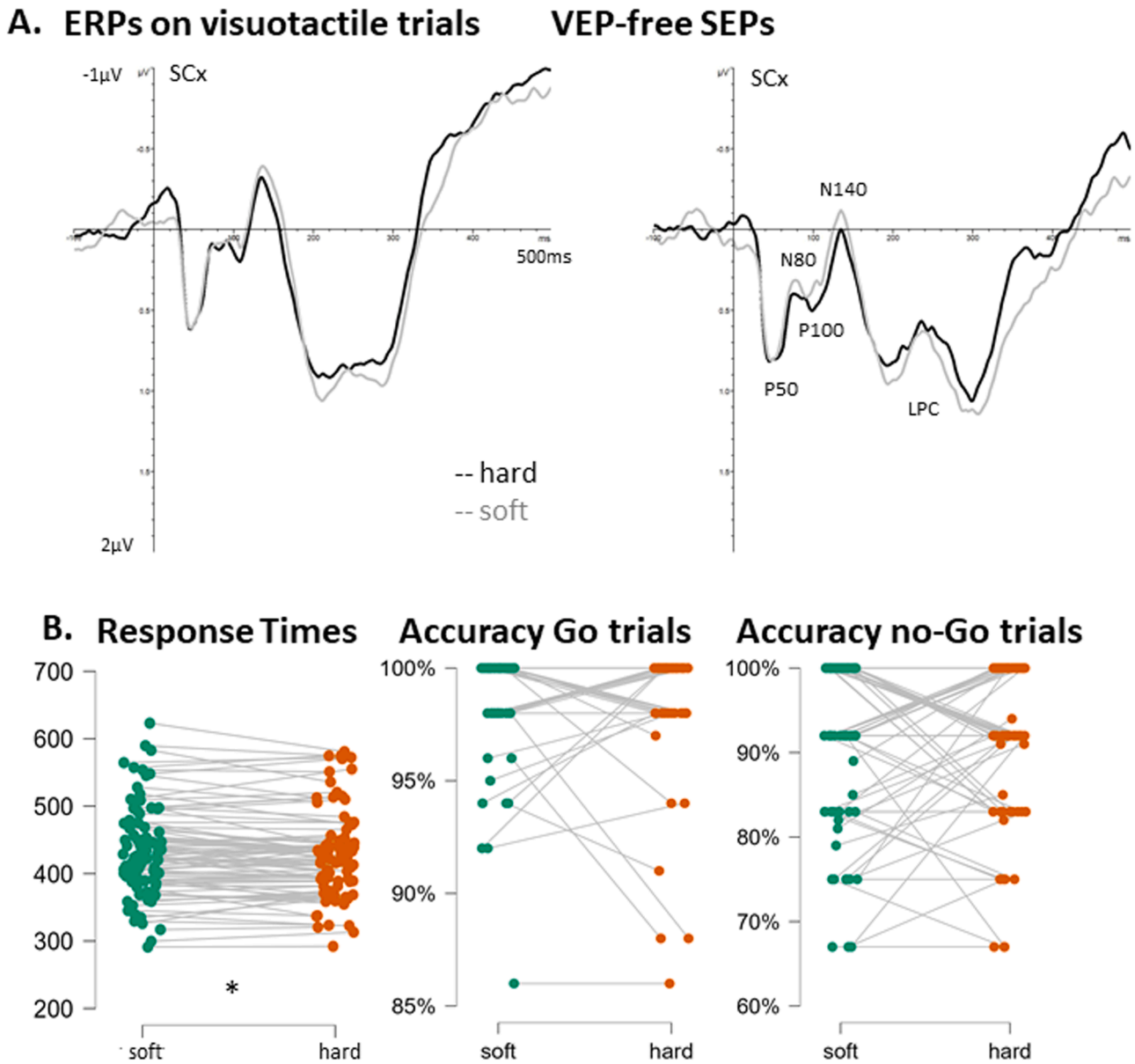
Fig. 4. Effects of vicarious touch texture on ERPs and behavioural responses. Panel A: grand averaged ERPs over SCx electrodes are shown that are averaged over left and right hemispheres and averaged separately for visuotactile ERPs (left) and VEP-free SEPs (right) and for the hard (black) and soft (grey) touch texture conditions of experiment 2. Panel B: Distribution of individual mean response times (left) and accuracies (right) on go and no-go trials are shown for hard (orange) and soft (green) touch texture conditions. Asterix indicates significant difference between touch texture conditions.

between hemisphere and touch direction (F(1,42) = 5.23, p = .027, n²=0.009) but no other main effects or interactions (all F(1,42) < 1.21, p > .28, n² <0.005) . To follow up the interaction we ran t tests separate for each hemisphere (Bonferroni adjusted p level > 0.025) showing a significant difference between self- and other-directed touch only over the left (t (42) = 4.14, p < .001, d = 0.115) but not the right (t (42) = 1.95, p = .058, d = 0.099) hemisphere. (b) Analysis of VEP-free SEP amplitudes showed a main effect of touch direction (F(1,42) = 6.45, p = 0.015, n²=0.029) but no other main effects or interactions (all F(1,42) < 2.97, p > .09). Taken together, these results show no significant texture effect (Fig. 4), but presence of a significant touch direction effect on N140 amplitudes (Fig. 5). While there was a lateralized touch direction effect on visuotactile trials, this effect was not present once visual carry-over effects are excluded.

3.2.5. LPC analysis

(a) Analysis of amplitudes elicited on visuotactile trials showed

significant main effects of hemisphere (F(1,42) = 10.46, p = .002, n²=0.069) and significant hemisphere by touch direction (F(1,42) = 7.21, p = .01, n² = 0.012), and hemisphere by texture (F(1,42) = 4.39; p = .042, n² =0.004) interactions, and no other significant main effects or interactions (all F(1,42) ⟨ 3.83, P ⟩ .057). To follow up the hemisphere interactions we ran t tests separately for each hemisphere but did not find significant amplitude differences with regards to touch direction or texture (all t(42) <0.62, p > 0.54). (b) Analysis of VEP-free SEP amplitudes showed no significant main effects or interactions (all F(1,42) ⟨ 0.52, p ⟩ .47). Together, these results show no significant touch direction or texture effects on this late processing stage (Figs. 4 and 5).

3.2.6. Go/no-go task analysis

Repeated measurement ANOVAs with the factors touch direction (other- versus self-directed) and texture (soft versus hard) were conducted on response times and accuracies in the go/no-go task following the vicarious touch sequence. For response times there was a main effect
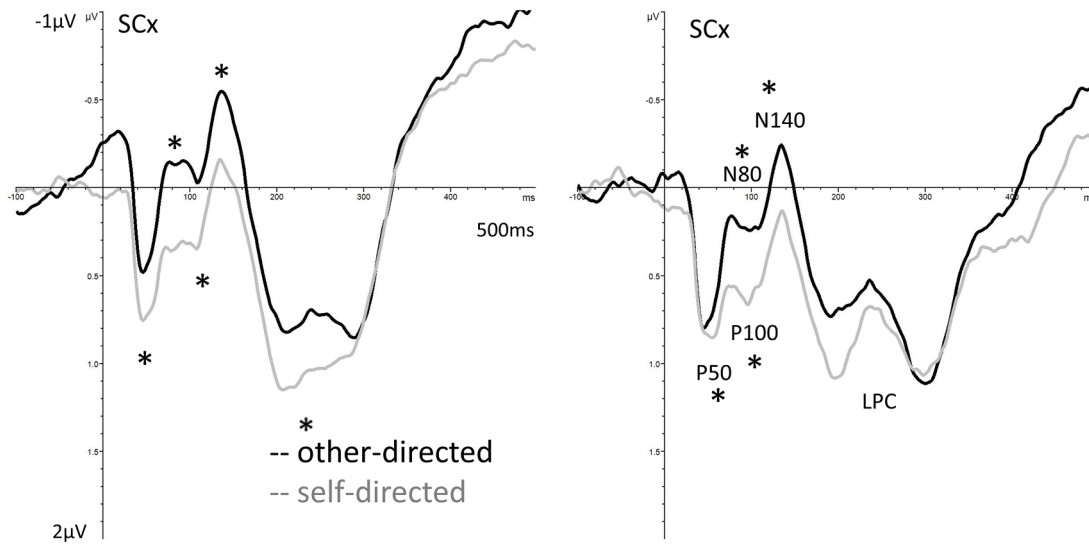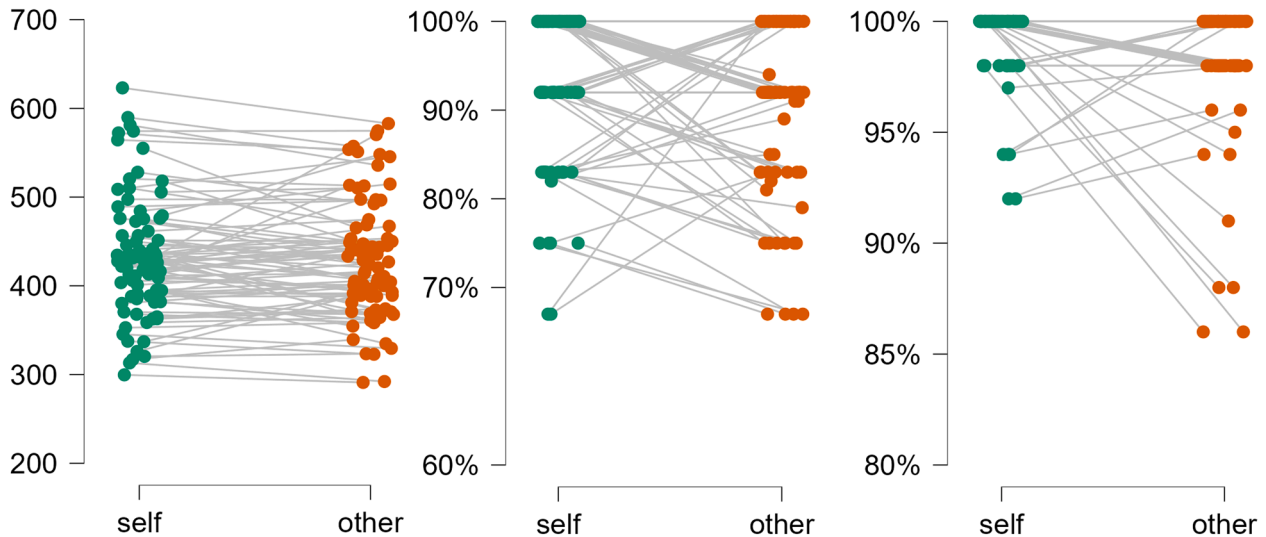
Fig. 5. Effects of vicarious touch on ERPs and behavioural responses. Panel A: grand averaged ERPs are shown that are averaged over left and right hemispheres separately for visuotactile ERPs (left) and VEP free SEPs (right) and for the other- (black) and self-directed (grey) touch conditions of experiment 2. Asterixis indicate significant differences between self- and other-directed touch conditions. Panel B: Distribution of individual mean response times (left) and accuracies (right) on go and no-go trials are shown for other- (orange) and self-directed (green) touch conditions.

of texture (F(1, 42) = 4.60, p = .04, n^2 = 0.015) with RTs following the observation of a soft foam surface touching a hand (M = 427 ms, SD = 62) on average 5 ms faster than observation of a hard, rubber touch (M = 432 ms, SD = 65). There was no main effect of touch direction (F(42, 1) = 0.28, p = .60, n^2 = 0.005) or interaction between touch direction and texture (F(42, 1) = 2.88, p = .1, n^2 = 0.009). There were no significant main effects or interaction on response accuracy on go and no-go trials (all F(42,1) ⟨ 2.94, p ⟩ .09). Together, these findings show an effect on motor activations following touch observations of different textures (Figs. 4B and 5B). This finding of a texture difference on behavioural level is further corroborated by a sample (n = 11) of participants' ratings of touch texture for self- and other-directed touch. Participants rated on average the foam touch experience as clearly softer for both other- (3.5) and self-directed (3.8) compared to the rubber surface for self- (6.7) and other-directed (6.4) touch.

3.3. Self-report measurement analyses

We were interested to further explore whether the amplitudes of reliable vicarious touch effects on SCx activity were related to ratings of the similarity between the viewed hand and the participants' own (M = 2.5; SD = 1), their embodiment of the observed hand (M=−1.3; SD = 1.3) or empathy (M = 2.3; 0.3). As there were no significant effects on VEP-free SEP amplitudes between touch and no-touch conditions in experiment 1, and soft and hard texture conditions in experiment 2, we did not run correlations between the self-report measures and VEP-free SEP amplitude differences between these conditions. As there were significant differences between self- and other-directed touch in experiment 2, we first averaged amplitudes over right and left SCx for each early and mid-latency component and then calculated the touch direction effect as the amplitude difference between self- and other-directed touch conditions. We did not find any significant relationships between

the amplitudes of touch direction effects at early and mid-latency components and any of the self-report measures (all r ⟨ 0.25, p ⟩ .1).

4. Discussion

It has repeatedly been stated that vicarious touch leads to an automatic activation of early sensory brain areas normally involved in processing of touch on the skin surface of the observer as reflected in the modulation of primary and secondary SCx activity (Gallese and Ebisch, 2013; Keysers et al., 2010). However, it has been suggested that supporting neuroimaging studies have mis-localised SCx vicarious touch activations (Chan and Baker, 2015) and previous ERP studies (Adler and Gillmeister, 2019; Adler et al., 2016; Bufalari et al., 2007; Rigato et al., 2019) have not controlled for possibly confounding variables. We used ERP methodology and an innovative experimental and analysis approach to address to what extent observers feel touch that they see. Somatosensory ERPs allowed us to tease apart vicarious touch effects on early perceptual (i.e. P50, N80, P100, N140 components) from post-perceptual processes (i.e. LPC and behavioural responses). Moreover, we investigated whether the engagement of early sensory SCx activations during vicarious touch reflects different touch qualities as expected with a full simulation of others' touch experiences. In two separate experiments participants observed touch sequences with the first contrasting touch with no-touch and the second contrasting two touch textures (i.e. soft foam and hard rubber) while touch was either other- or self-directed. Despite a large participant sample ($n = 43$), neither the touch/no-touch or soft/hard touch contrast showed significant modulations of early and mid-latency components (see also explorative Bayesian analyses in the supplementary material providing further evidence of absence of any early perceptual vicarious touch effects). However, we found effects on behavioural responses in the subsequent go/no-go task, in line with the notion of post-perceptual effects of vicarious touch on higher order somatosensory and motor cortex. In contrast, comparing amplitudes elicited on self- compared to other-directed touch trials showed strong modulation of early and mid-latency components, in line with the activations of primary and secondary SCx. Importantly, like in the other-directed touch condition also in the self-directed touch condition no difference between touch textures on early and mid-latency SCx components was present. Taken together, our findings show that when vicarious touch observation is purely observational (i.e. other-directed touch) no early sensory SCx modulations are found, showing that SCx activation is not automatic in vicarious touch. Only when participants were instructed that the observed touch is self-directed and to feel the touch early SCx modulations were observed. However, also in this condition no modulations of early SCx activity by touch texture was present, indicating that the early sensory aspect of the observed touch experience is not be fully simulated.

Previous ERP studies of vicarious touch (Adler and Gillmeister, 2019; Adler et al., 2016; Bufalari et al., 2007; Rigato et al., 2019) have delivered tactile stimuli concurrent to visually observed touch or no-touch. Such a paradigm is akin to crossmodal congruency paradigms which have shown that tactile discrimination and somatosensory ERPs are affected by task irrelevant visuospatial distractors that mismatch the tactile location (e.g. Igarashi et al., 2004; Pavani et al., 2000; Sambo and Forster, 2009). Moreover, none of the prior vicarious touch ERP studies have accounted for any visual evoked activity by the observed movement which may have distorted the somatosensory probed activity. Our experimental paradigm diminished spatial congruency effects and allowed us to isolate SCx activity from visual carry-over effects (see Galvez-Pol et al., 2020, 2021). In contrast to previous studies (Adler and Gillmeister 2019; Adler et al., 2016; Bufalari et al., 2007; Rigato et al., 2019), we did not find any significant vicarious touch effects (touch versus no-touch) in experiment 1, neither on visuotactile trials or once any visual carry-over effects were subtracted out. We also did not find any touch texture effects in experiment 2. However, we did find

amplitude differences between self- and other-directed touch on early and mid- latency components in experiment 2. These effects were stronger over the left hemisphere on visuotactile trials for the P50 and N140 components. However, this lateralization may reflect mainly visual carry over effects as it was diminished in the analysis of VEP-free SEPs. We only found evidence for behavioural modulations of responses to a go/no-go stimulus presented after each vicarious touch sequences suggesting differential representations of touch and no-touch, and touch textures in higher cognitive and motor processes.

Our finding of an absence of any touch observation modulations on early SCx components is in line with recent fMRI studies suggesting posterior parietal rather than SCx is involved in touch observation (Chan and Baker, 2015; Sharma et al., 2018). In these studies participants were instructed to perform a task at fixation while task-irrelevant touch observation videos were presented. One explanation for the absence of SCx touch observation effects in these studies may be that participants' attention was diverted away from observing the touch. In our study, participants were instructed to merely observe touch (Experiment 1 and first half of Experiment 2) without engaging simultaneously in another task. Yet, we also did not find early SCx modulations. Importantly, only when participants were instructed that the touch is self-directed and to feel the touch, rather than merely observe, strong modulations of early and mid-latency SCx components (i.e. P50, N80, P100, N140) were present. Likewise, previous fMRI studies that have reported SCx involvement have instructed participants to attend to the vicarious touch to either judge its frequency (Ebisch et al., 2008; Schaefer et al., 2009, Schaefer et al., 2012, 2013) or quality (Blakemore et al., 2005; E. Kuehn et al., 2014 Kuehn et al., 2013, 2018). Together these findings suggest that SCx engagement in vicarious touch is driven by attention to the observed tactile sensations as required by task instructions. Similarly, theories of grounded and embodied cognition (Barsalou, 1999; Damasio, 1989) have suggested that SCx engagement reflects modality specific simulations as part of ongoing cognitive processes related to the instructed task. In contrast, theories of embodied simulation (Gallese and Ebisch, 2013) have argued for an automatic engagement of SCx when observing touch. Our findings together with previous research show that SCx is purposely engaged, only when attention is directed to the somatosensory modality suggesting that top-down, cognitive control rather than automatic, stimulus-driven processes drive modulations of SCx activity in vicarious touch.

Previous studies of vicarious touch have usually compared a movement sequence where a hand or body part was touched by an object to a sequence where no touch occurred. Differences in SCx activations in these observation conditions have been interpreted as sensory simulation including the 'extraction and mapping of the sensory qualities' (Keysers et al., 2010; Bufalari et al., 2007). However, to understand whether such engagement of SCx in touch observation fully simulates the observed touch experience it is necessary to show that touch qualities, like texture, are reproduced as part of such a simulation. Touch is optimally designed to distinguish between textures with several different types of receptors in the skin contributing to texture perception and this information is processed in primary and secondary SCx (Ballesteros et al., 2009; Chung et al., 2013; Genna et al., 2018; Lieber and Bensmaia, 2019; Lederman und Klatzky, 2009). We found no reliable effects of tactile texture on early SCx components, even under conditions when participants were instructed to feel the touch texture. This latter point is supported by the fact that there was no interaction between the factors touch direction and touch texture in experiment 2. While we did not find evidence for texture effects during vicarious touch, studies investigating tactile imagery have shown differential activation patterns in primary and secondary SCx for different tactile texture (Nierhaus et al., 2023; see also Yakovlev et al., 2023). However, in tactile imagery studies participants are repeatedly presented with the tactile stimuli they subsequently imagine. In our study participants experienced all the experimental objects once before the start of the experiments and were encouraged to touch these. Data of a subset of participants showed that

they rated foam tip touch as softer than rubber tip touch. Likewise, participants showed texture dependent modulations of behavioural responses to the go/no-go stimulus following the vicarious touch sequences. Such post-perceptual texture effects suggest that seeing tactile texture activates concepts stored in higher order cortex about these textures (see also Smith et al., 2023). Importantly, our data does not support a full perceptual simulation of the texture experience itself in sensory cortex as proposed by embodied simulation theories. Our findings are in line with theories of embodied and grounded cognition that have suggested that while modality specific information is situated in modality specific representations (Barsalou, 2010), such activations of neural representations may not be complete (Barsalou et al., 2003, 2005), and thus, not fully match the neural representation of the sensory experience.

Taken together, our findings suggest that higher cognitive processes related to the current cognitive task engage primary and secondary SCx in vicarious touch. Such purposeful engagement of SCx may aid our understanding of other's experiences. Yet, it comprises a partial simulation of other's perceptual, tactile experiences in SCx, as it lacks the perceptual quality of the observed touch which is nevertheless manifested in post-perceptual processing. Thus, SCx activations during vicarious touch reflect purposely situated activity rather than automatic sensory simulations.

CRediT authorship contribution statement

Bettina Forster: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Sonia Abad-Hernando:** Writing – review & editing, Software, Methodology, Investigation, Formal analysis, Data curation.

Declaration of competing interest

None.

Data availability

Data underlying the analyses presented here and related material are available through the Open Science Framework (DOI 10.17605/OSF.IO/XWSP3).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.neuroimage.2024.120561.

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