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On the spread of spatial attention in touch: Evidence from event-related brain potentials

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ABSTRACT

To investigate the distribution of tactile spatial attention near the current attentional focus, participants were cued to attend to one of four body locations (hand *or* shoulder on the left or right side) to respond to infrequent tactile targets. In this Narrow attention task, effects of spatial attention on the ERPs elicited by tactile stimuli delivered to the hands were compared as a function of the distance from the attentional focus (Focus on the hand vs. Focus on the shoulder). When participants focused on the hand, attentional modulations of the sensory-specific P100 and N140 components were followed by the longer latency Nd component. Notably, when participants focused on the shoulder, they were unable to restrict their attentional resources to the cued location, as revealed by the presence of reliable attentional modulations at the hands. This effect of attention outside the attentional focus was delayed and reduced compared to that observed within the attentional focus, revealing the presence of an attentional gradient. In addition, to investigate whether the size of the attentional focus modulated the effects of tactile spatial attention on somatosensory processing, participants also completed the Broad attention task, in which they were cued to attend to two locations (both the hand *and* the shoulder) on the left or right side. Attentional modulations at the hands emerged later and were reduced in the Broad compared to the Narrow attention task, suggesting reduced attentional resources for a wider attentional focus.

1. Introduction

A significant body of evidence from behavioural studies shows that covertly directing endogenous spatial attention to a body location has a strong impact on the processing of tactile stimuli. Typically, responses to tactile stimuli are faster (e.g. Spence et al., 2000) and more accurate (e.g. Sathian & Burton, 1991) when the tactile stimulus is presented to the attended location compared to other unattended locations. Furthermore, the detection of tactile stimuli is more efficient at attended than unattended body locations (e.g. Butter et al., 1989; Bradshaw et al., 1992, Whang et al. 1991; for reviews see Johansen-Berg and Lloyd, 2000; Gallace & Spence, 2014).

Electrophysiological studies have started to investigate the time-course of the neural mechanisms responsible for the effect of spatial attention in touch (for reviews see Gomez-Ramirez, Hysaj & Niebur, 2016; Sambo & Forster, 2011). In a series of event-related potential (ERP) studies (e.g. Eimer & Forster, 2003a; Forster & Eimer, 2004; García-Larrea, Lukaszewicz & Mauguire, 1995; Michie, Bearpark, Crawford & Glue, 1987; Van der Lubbe, Buitenweg, Boschker, Gerdes & Jongsma, 2012; Van der Lubbe, Blom, De Kleine, Bohlmeijer, 2017), a symbolic cue instructed participants to covertly attend to their left or right hand. After a short interval, a tactile stimulus, either a target or a non-target, was presented to the cued or uncued hand. Participants had to covertly orient their attention to the cued location in order to respond to infrequent targets at cued locations, while ignoring uncued targets as well as all non-target stimuli, regardless of their location. The comparison of ERPs elicited by non-targets presented to the cued and uncued hand showed enhanced amplitudes of early- and mid-latency

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sensory-specific components (i.e. N80, P100 and N140) (e.g. Eimer & Forster, 2003a; Forster & Eimer, 2004; García-Larrea et al., 1995; Michie et al., 1987; Van der Lubbe et al., 2012)*. These ERP components are thought to relate to sensory-specific processing in the primary and secondary somatosensory cortices (Frot & Mauguiere, 1999; Hämäläinen et al., 1990; Mima et al., 1998). Thus, their attentional modulations suggest enhanced activity of neurons within somatosensory cortical areas with receptive fields anchored to the cued body location. The attentional enhancement of the mid-latency ERP components is typically followed by a sustained negativity for cued as compared to uncued stimuli (starting approximately from 200 post-stimulus) which has been suggested to reflect in-depth processing of potentially task-relevant stimuli (e.g. Michie, 1984; Michie et al., 1987). Thus, the study of the time-course of tactile spatial attention has demonstrated the presence of attentional effects both at perceptual and post-perceptual processing stages. Interestingly, although the effects of attention can occur during the early stages of stimulus processing, single-cell studies have shown that the strength and magnitude of these attentional modulations increase as the sensory signal reaches higher order somatosensory areas (e.g. Hsiao et al., 1993; Gomez-Ramirez et al., 2014; see Gomez-Ramirez et al., 2016, for a detailed review).

A number of task-specific factors can modulate the time-course and the amplitude of the effects of spatial attention on touch. For example, attentional modulations of somatosensory processing occur earlier when participants attend to the same body location throughout a block of trials as compared to when the task-relevant body location is cued on a trial-by-trial basis (sustained vs. transient attention, c.f. Eimer & Forster, 2003a; Zopf, et al., 2004; but see also Van der Lubbe et al., 2017; Blom & Van der Lubbe, 2011; 2017; for different results with electrical nociceptive stimuli). The timing of the attentional modulations of early somatosensory processing is also affected by the sensory modality of the cue, with earlier attentional effect when a visual instead of tactile cues are used (Forster, Sambo & Pavone, 2009) suggesting that the engagement of the visual system alters mechanisms of tactile spatial selection. Furthermore, the difficulty of the target/non-target discrimination can selectively change the onset time of the attentional modulation during a tactile spatial attention task (Gherri & Berreby, 2017).

Crucially, however, the majority of these studies have contrasted ERPs elicited by stimuli presented to the cued vs. uncued hand. That is, on each trial, the tactile stimulus was presented to one of two possible body locations. For this reason, questions about the size and boundary of the focus of attention in touch remain almost completely unexplored. One initial attempt to address this question was carried out by Eimer and Forster (2003b). In this ERP study the spatial distribution of tactile spatial attention within the right hand was investigated by presenting a tactile stimulus to one of four possible locations. In the 'one location task' stimuli could be presented to one of two phalanxes of the middle and index fingers and participants were instructed to attend to one of the different phalanxes on different blocks of trials (one out of four possible locations). When participants attended to one of those locations, the effect of attention was stronger when the unattended stimulus was delivered to the phalanxes on the uncued finger as compared to the uncued phalanx of the attended finger. This reveals that participants are less capable of filtering out unattended stimuli when these are close to the attentional focus. Nevertheless, the presence of an attention effect within the same finger reveals that it is possible to attend to an area as small as the phalanx. This shows that attention can be intentionally narrowed, and that an attentional gradient exists within the hands.

More recently, Kida and colleagues (Kida, Tanaka & Kakigi, 2018) investigated the within-hand distribution of the effects of spatial attention to individual or multiple finger(s) of the same hand on cortical MEG responses to tactile stimuli. The MEG SIc response at 60 ms was greater for the attended finger than for the unattended finger, suggesting within-hand, across-finger attentional selectivity in the early somatosensory cortex. Furthermore, the strength of the MEG SIIc response at 85 ms (likely corresponding to the P100 ERP component) for the stimulation of the unattended finger decreased as a function of its distance from the attended finger. Thus, the effects of tactile attention in the SIIc are not completely selective, and instead they show a gradient (Kida et al., 2018). While the size of the attentional focus in Kida et al.'s study (2018) was larger than the one manipulated in Eimer and Forster study (2003b), i. e. one finger vs. one phalanx, the presence of an attentional gradient in both studies may simply be due to the fact that attentional selectivity could not operate efficiently on such a small scale. In other words, the area of the attentional focus was too small to be efficiently selected by spatial attention in these studies. On the other hand, the presence of an attentional gradient may also be a constant feature of tactile spatial attention, independent of the size of the attentional focus.

Thus, one question that remains unanswered is whether tactile spatial attention can efficiently select (i.e. can be restricted to) the cued location, without spreading to contiguous but uncued body locations, when the size of the attentional focus is increased. In the present study, participants completed two transient attention tasks. In the *Narrow attention task*, a visual cue presented at the beginning of each trial instructed participants to attend to one of four possible locations. Here, the cue indicated both the side (left or right) *and* the body part (hand or shoulder) that participants had to attend (e.g. LH = left hand, LS = left shoulder, RH = right hand, or RS = right shoulder) (Fig. 1, left and middle panels). Thus, the size of the body area that had to be attended/selected was increased in the present study compared to Eimer and Forster's study (2003b) and to Kida et al.'s study (2018), because participants had to attend either to the hand or to the shoulder on the cued side of the body. After a 1 s interval, a tactile stimulus was presented at one of these four locations and could consist of either a target or a non-target tactile stimulus (a fast or a slow vibration, respectively). Participants had to vocally respond, by saying 'PA', to the target only when it was presented to the location indicated by the cue. They were instructed to ignore the target when it was presented at uncued locations, as well as all non-target stimuli at any locations. The speed and accuracy of participants' responses to the target were recorded together with ERPs elicited by non-target stimuli (which were equally likely to appear at any of the four locations).

One aim of this study was to investigate whether spatial attention can be restricted to one body location (either the hand or the shoulder) or whether it spills over to the ipsilateral but unattended location (the shoulder or the hand, respectively). Due to the relevant differences between ERPs elicited by the tactile stimuli to the hand and to the shoulders (in terms of time course, shape and scalp distribution), analyses were restricted to trials in which a tactile stimulus was delivered to the hand. Hence, effects of spatial attention for ERPs elicited by tactile non-target stimuli to the hand were calculated separately when participants attended to one hand (Focus on the hand, Narrow attention, Fig. 1, left panels (1)) and when they attended to one shoulder (Focus on the shoulder, Narrow attention, Fig. 1, middle panels (2)). When participants focused on one hand (Fig. 1, left panels (1)), we expected to observe attentional modulations (differences between ERPs elicited by stimuli to the hand on the attended vs. unattended side) similar to those already reported in the literature (e.g. Eimer & Forster, 2003a; Forster & Eimer, 2004; García-Larrea et al., 1995; Michie et al., 1987; Van der Lubbe et al., 2012; 2017). The critical question was whether effects of

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[1] It is worth noting that similar findings were also obtained in ERP studies using the classic Posner cuing paradigm to investigate tactile spatial attention (e.g. Jones & Forster, 2014). Here, a symbolic cue indicates the side of a forthcoming target with 80% probability. After an interval a target is presented and participants are asked to detect its presence, and to refrain from responding on catch trials when the target is absent. This task has the advantage of producing reliable behavioural effects of spatial attention (difference between cued and uncued responses). Disadvantages of this task for ERP measures are related to the different number of cued and uncued trials in each block, and to the possible artifacts elicited by the motor response on each trial.

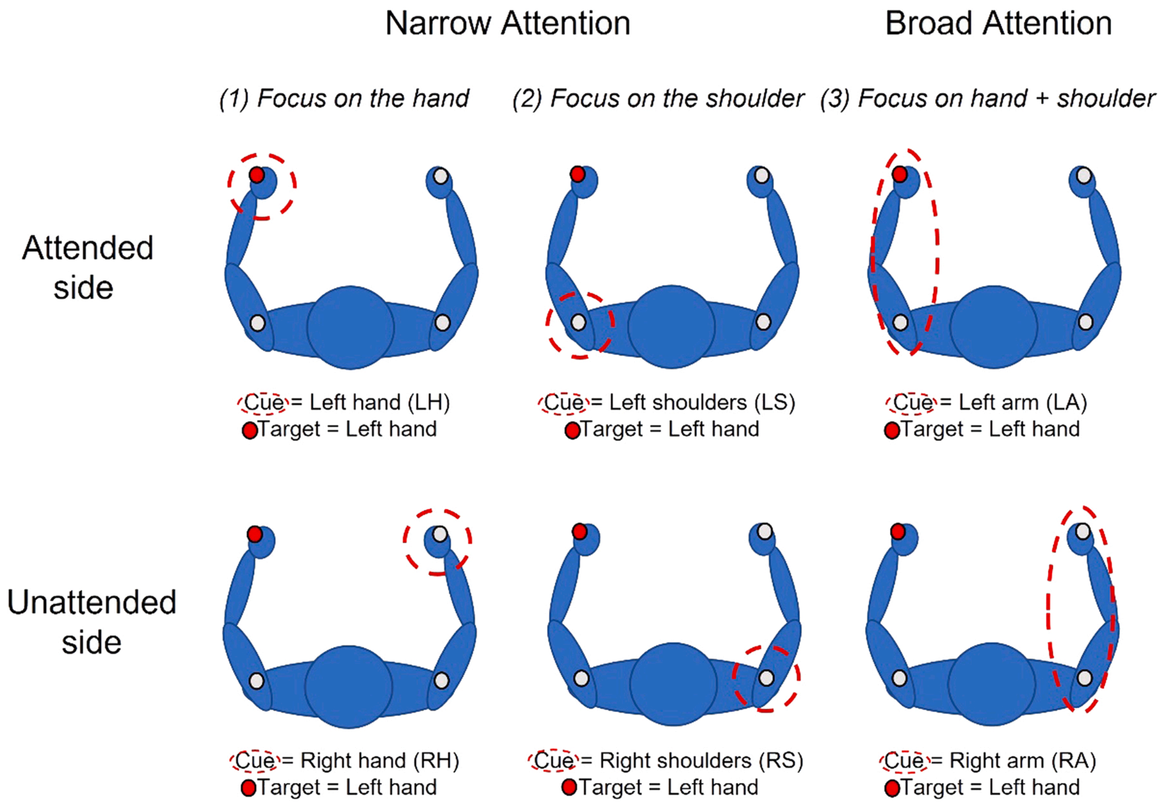

Fig. 1. Schematic representation showing the attentional manipulations in the Narrow (left and central panels) and Broad (right panels) attention tasks. The location of the four tactile stimulators positioned on participants hands and shoulders is represented by light grey circles. In the *Narrow attention task*, participants were instructed by a visual cue to attend to either the hand *or* the shoulder of the left or right side (one out of four possible locations). In the *Broad attention task*, participants were instructed to attend to both the hand *and* the shoulder of the left or right side (two out of four possible locations). Dashed red ovals indicate the cued target location(s) (the visual cue consisted of the letters ‘LH’, ‘RH’, ‘LS’ or ‘RS’ on different trials of the Narrow attention task and of the letters ‘LA’ or ‘RA’ on different trials of the Broad attention task). 1000 ms after cue onset a tactile stimulus (either a target or a non-target) was delivered to one of the four possible locations. In this figure, red filled circles represent the location of the tactile stimulus (see the Method section for further details). Participants were instructed to covertly direct attention to the location(s) indicated by the cue. They had to respond vocally (by saying ‘PA’) to tactile targets presented at the cued location while ignoring targets at uncued locations as well as all non-targets. Note that in this figure tactile stimuli are always presented to the left hand, however in the experiment tactile stimuli were presented randomly to all four locations on different trials.

attention would also be observed at the hands (differences between ERPs elicited by stimuli to the hand on the attended and unattended side) when attention was focused on one shoulder (see Fig. 1, middle panels (2)). If the focus of attention can be narrowly restricted to one shoulder, no effects of attention will be observed at the hand. By contrast, if attention cannot be focused solely on to the shoulder and ‘spills over’ onto the ipsilateral hand, effects of spatial attention will also be observed at the hand.

In addition to the Narrow attention task, participants also completed the *Broad attention task* (Fig. 1, right panels, (3)) in which they were explicitly instructed to widen their attentional focus to attend to both the hand and the shoulder of the attended side of the body (i. e. two out of four body locations) in order to respond to targets presented at either location. In this task, the cue indicated the whole arm that participants had to attend (left or right arm; LA, or RA), encompassing both hand and shoulder. This experimental manipulation allowed us to contrast directly the effects of spatial attention (differences between ERPs elicited by stimuli to the hand on the attended and unattended side) when participants were instructed to distribute their attentional resources across both hand and shoulder on the attended side (Broad attention task, Fig. 1, right panels (3)) and when they were instructed to focus exclusively on the hand (Narrow attention task, Focus on the hand, Fig. 1, left panels (1)). If attention can be narrowly focused on one hand, we expect to observe earlier and/or stronger effects of attention as compared to the Broad attention task, in which attentional resources are distributed across both hand and shoulder. By contrast, if attention cannot be fully restricted to one hand, differences between attentional modulations observed in the Narrow attention, Focus on the hand task (Fig. 1, (1)) and Broad attention task (Figs. 1, (3)) will be less evident.

2. Method

2.1. Participants

An a priori power analysis was conducted using G*Power version 3.1.9.7 (Faul et al., 2007) for sample size estimation, based on data previously published from our lab (Gherri & Berreby, 2017; N = 12). The effect size for the effect of attention in the experimental condition comparable to the one used in the present study was $\eta p^2 = .4$. With a significance criterion of $\alpha = .05$ and power =[0.80 the minimum sample size needed with this effect size was N = 15. To control for possible drop-out or exclusion of participants we tested nineteen paid volunteers in this experiment. Three participants were excluded due to excessive residual HEOG in the EEG trace (see below). Thus, the sample contained 16 participants (12 women, 4 right-handed, aged 18–25). All had normal or corrected-to-normal vision and were naïve as to the purpose of the study.

The study was approved by the PPLS Research Ethics Committee of the University of Edinburgh and was carried out in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments. Participants gave written consent to participate in this study prior to the beginning of the study after the nature of the study had been explained to them. They completed the study in exchange for a small monetary reward.

2.2. Apparatus and stimuli

Participants were tested in a sound-attenuated, dimly lit cabin, facing a computer screen at a distance of approximately 50 cm. They were seated with arms resting on chair supports and their hands resting on the table (palms face down) with index fingers located approximately shoulder width apart. To mask any sounds made by tactile stimulators, participants wore earplugs, and a speaker positioned centrally below the computer screen presented white noise at 65 dB SPL throughout the experimental blocks. Participants' arms were covered by a black cloth during the experiment to make sure that visual information about the body would not affect tactile processing. A microphone placed on the table recorded vocal responses.

Tactile stimuli were presented using 4.5 V solenoids that were driving a metal rod with a blunt conical tip to the fingers which made contact with the skin whenever a current was passed through the solenoid. Four tactile stimulators were attached with adhesive medical tape to two different locations (index finger and shoulder) of the left and right arm. A black cloth was placed over participants' hands and arms to prevent their visibility.

Visual cues consisted of two letters presented for 100 ms from the centre of the screen (2 ×2 of visual angle). One letter indicated the cued side ('L′ for left and 'R′ for right) while the other the cued body part ('H′ for hand, 'S′ for shoulders for the cue in the Narrow attention task and 'A′ for arm for the cues in the Broad attention task). A central fixation cross presented on the screen (1 ×1) replaced the visual cue after their offset and remained visible throughout the trial.

Tactile stimuli (205 ms long) were either slow vibrations (the rod touched the skin for 5 ms followed by a 35 ms empty interval, repeated 5 times), or a fast vibration (the rod touched the skin for 5 ms followed by a 5 ms empty interval repeated 20 times).

2.3. Procedure

The experiment consisted of 18 blocks with 108 trials per block. Each trial started with the presentation of the visual cue on the screen for 100 ms which indicated the task-relevant location(s). This was replaced by a visual fixation cross which remained visible until the end of the trial. After 900 ms from cue offset, a tactile stimulus was delivered to one of the four possible body locations (205 ms duration). The following trial started after an inter-trial interval which varied randomly between 1200 and 1300 ms.

Participants performed two tasks: The Narrow attention task, consisting of 12 blocks, and the Broad attention task, consisting of 6 blocks. Different number of blocks for the two tasks were necessary in order to have the same number of non-target trials – upon which the ERP analysis was based – for all cued and uncued locations in both the Narrow and Broad attention tasks.

In the *Narrow attention task*, the cue indicated both the task-relevant side (left vs. right) and the task-relevant body part (hand vs. shoulder). Thus, participants were instructed to focus their attention on one of the four locations (LH left hand, RH right hand, LS left shoulder or RS right shoulder) while ignoring the remaining three locations. In the Narrow attention task, 80 non-targets were presented in each block. 20 non-targets were delivered to the location indicated by the cue, while the remaining 60 were equally likely to be presented in one of the three remaining uncued locations. In each block, a tactile target was presented on 28 trials - 16 times to the cued location, thus requiring a response, and 12 times to the remaining three uncued locations (4 trials each).

In the *Broad attention task*, the cue indicated the task-relevant side (left vs. right arm, 'LA' left arm, 'RA' right arm). Participants were instructed to attend to both body parts (hand and shoulder) on the cued side while ignoring the remaining two body parts on the opposite uncued side. On each block of the Broad attention task, a non-target stimulus was presented on 80 trials, 40 times to the cued arm and 40 times to the uncued arm. On the remaining 28 trials, a target was presented instead, 16 times to the cued arm, thus requiring a response, and 12 times to the uncued arm.

In both tasks, tactile stimuli were presented in a random order. On half of all trials, stimuli were presented to the left or right hand, and on the remaining half, to the left or right shoulder. Participants were instructed to covertly attend to the location indicated by the cue. They had to respond vocally (by saying 'PA') to tactile targets presented at the cued location while ignoring targets at uncued locations as well as all non-targets. They were also instructed to keep their eyes on the central fixation on the screen at all times and to responds as quickly and as accurately as possible upon the presentation of the tactile stimulus.

After the end of each block, participants were allowed to take a break and were given visual feed-back about their overall performance (RTs and accuracy) The order in which the tasks were completed (Narrow attention task followed by Broad attention task or viceversa) was counterbalanced across participants. Participants completed one block of training (108 trials) before each task.

2.4. EEG recording and data analysis

EEG was recorded using a BIOSEMI system from 64 active electrodes (Fpz, Fp1, Fp2, AFz, AF7, AF3, AF4 AF8, Fz, F7, F5, F3, F1, F2, F4, F6, F8, FCz, FT7, FC5, FC3, FC1, FC2, FC4 FC6, FT8, Cz, T7, C5, C3, C1, C2, C4, C6, T8, CPz, TP7, CP5, CP3, CP1, CP2, CP4, CP6, TP8, Pz, P9, P7, P5, P3, P1, P2, P4, P6, P8, P10, POz, PO7, PO3, PO4, PO8, Oz, O1, O2, Iz) positioned according to the 10–20 system. Two additional electrodes placed on the earlobes served as offline references and their impedances were kept as equal as possible. Horizontal EOG was recorded from two electrodes placed at the outer canthi of each eye and vertical EOG was recorded from two electrodes positioned above and below the right eye.

EEG and EOG were sampled with a digitization rate of 512 Hz and stored on disk for offline analysis. Data were analysed using the Brain Vision Analyser software (version 2.0.4.368). EEG was digitally re-referenced to the average of the left and right earlobe and was digitally filtered offline (high-pass filter 0.53 Hz, low-pass filter 40 Hz and notch filter 50 Hz). EEG was epoched into 450 ms intervals starting 100 ms before and ending 350 ms after non-target onset. Trials with eye blinks (voltage exceeding ± 60 μV on the VEOG channel), horizontal eye movements (voltage exceeding ± 40 μV on the HEOG channel) and other artefacts (voltage exceeding ± 80 μV at all other electrode sites) were excluded from further analysis, as were trials with response errors. Gaze direction can alter the processing of tactile information (Gherri & Forster, 2015) and modulate tactile attention (Gherri & Forster, 2014) even when the tactually stimulated body part (e.g. the hand) is hidden from view. Accordingly, and in line with the analysis procedure used in previous studies from our lab (Gherri & Eimer, 2008; Gherri & Forster, 2012a; 2012b; 2014; 2015; 2017), we checked the hEOG data for residual eye movement activity towards the cued side. Averaged HEOG waveforms obtained in the cue-target interval in response to cues were scored for systematic deviations of eye positions. Residual HEOG deflections exceeding ± 4 μV led to the exclusion of three participants.

To avoid contamination by vocal responses to the cued targets, only ERPs elicited by non-targets stimuli were included in the ERP analysis, in line with existing literature. Because the timing and shape of early somatosensory components elicited by stimuli presented to the hands and shoulder is different, only ERPs elicited by non-target stimuli presented to the hands were included in the analyses. ERPs recorded on these trials were averaged relative to a 100 ms pre-stimulus baseline for all combinations of attention (attended vs. unattended side), and task (Narrow attention, Focus on the hand (1) vs. Narrow attention, Focus on the shoulder (2) vs. Broad attention (3)) and stimulated hand (left vs. right hand). ERP mean amplitudes were computed at lateral electrodes FC3/4, C3/4, CP3/4, FC5/6, C5/6, CP5/6 for each participant within successive measurement windows centred on the P100 (90–120 ms) and the N140 (130–170 ms) components, as well as for longer latencies (Nd1, 180–290 ms and Nd2, 290–350 ms post-stimulus onset). Appropriate time windows were selected based on our earlier studies on tactile spatial attention in combination with an inspection of the grand-average waveforms. For the early sensory specific P100 and N140 components we used time windows previously considered in our earlier work (Gherri & Forster, 2012; Gherri & Berreby, 2017). For the later Nd component, we chose two consecutive time windows (c.f. Gherri & Berreby, 2017). These later time windows were centered on the N2 and on the later P3 components, as determined by visual inspection of the grand-average waveforms.

Mean amplitude values were analyzed using repeated measures ANOVAs, including the factors attention (attended vs. unattended side), task (Narrow attention, Focus on the hand vs. Narrow attention, Focus on the shoulder vs. Broad attention), laterality (hemisphere contralateral vs. ipsilateral to the stimulated hand) and electrode site (FC3/4, C3/4, CP3/4, FC5/6, C5/6, CP5/6). In these ANOVAs, we were specifically interested in attention x task interactions reflecting systematic differences between the spatial attention effects measured under different attentional gradient conditions (Narrow attention, Focus on the hand (1) vs. Narrow attention, Focus on the shoulder (2) vs. Broad attention (3)). To this end, following significant attention x task interactions, we first assessed the presence of reliable attention effect separately for each of the three gradients (shown in Fig. 2). The absence of effects of attention observed at the hand when participants focused on the shoulder in the Narrow task (2), would show that under narrowly focused attention conditions, effects of spatial attention were restricted to the attended shoulder. By contrast, their presence would suggest that attention spilled over from the shoulder to the hand on the attended side. Next, we calculated the effects of spatial attention by subtracting ERPs elicited by stimuli to the unattended side from those elicited on the attended side, separately for the three tasks. These difference waveforms (shown in Fig. 3) were then compared between tasks (appropriate corrections for multiple comparisons were applied). First, we compared attention effects in the Narrow task (Focus on the hand (1) vs. Focus on the shoulder (2)) to determine the presence of an attentional gradient whereby effects of attention decrease as the stimuli are presented further away from the attentional focus. Then, we compared the effects of spatial attention observed under narrowly focused conditions (Narrow attention, Focus on the hand (1)) and those observed under broadly focused conditions (Broad attention task (3)) to determine whether the size of the attentional focus modulated the effects of tactile spatial attention on somatosensory processing.

Greenhouse–Geisser adjustments to the degrees of freedom were performed when appropriate, and adjusted F and p values were reported.

Because the ERP analysis only included trials in which tactile stimuli were delivered to one of the hands, the behavioural analysis was also restricted to the same trials. In both the Narrow and Broad attention tasks, only targets presented at the cued location(s) required a vocal response. Thus, when participants focused on the left or right shoulder (Narrow attention, Focus on the shoulder (2)) and the tactile stimuli were delivered to the hands (i.e. to the uncued body location), no vocal

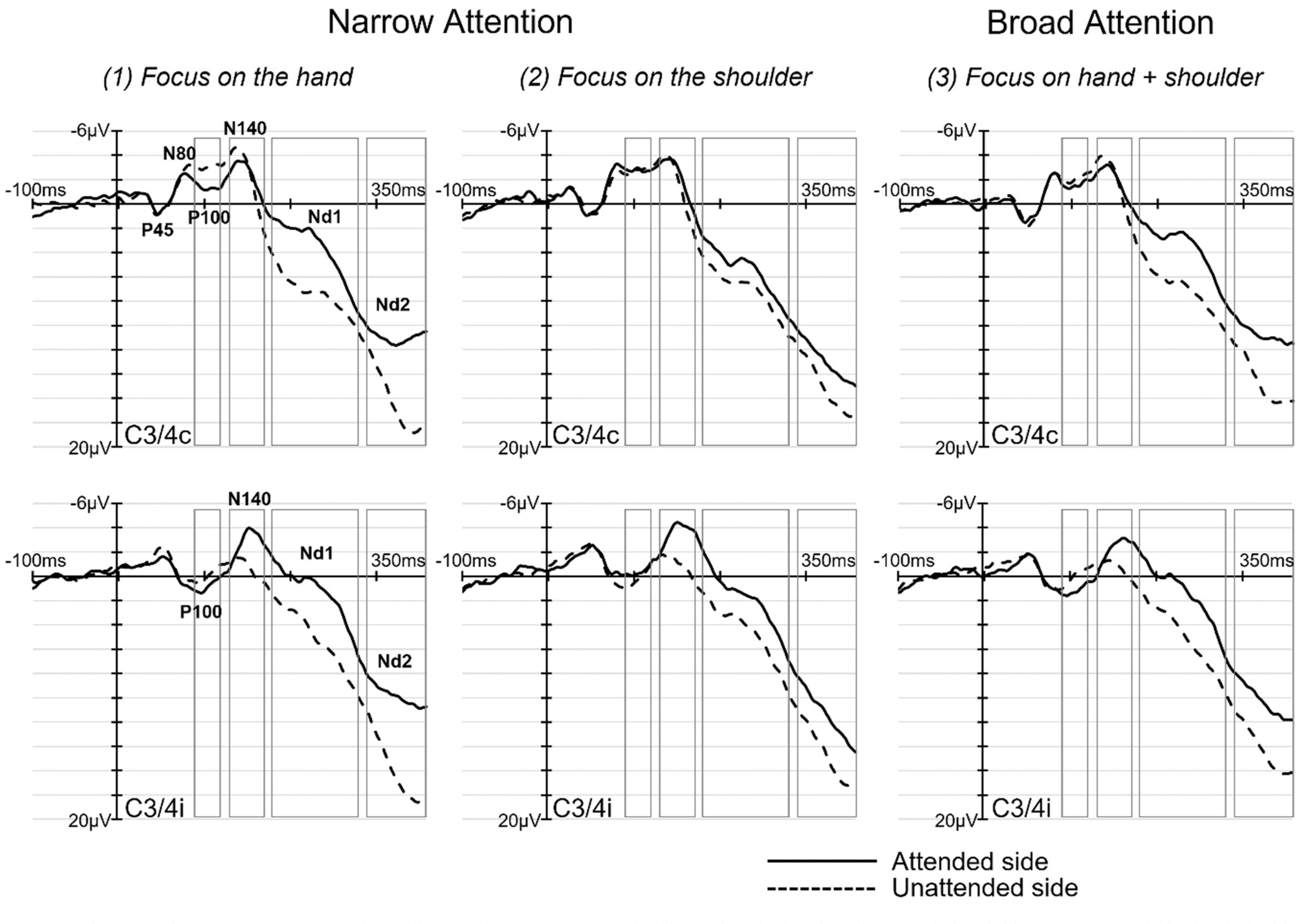

Fig. 2. Grand-averaged somatosensory ERPs elicited by tactile non-target stimuli delivered to the hand on the attended (solid line) or unattended side (dashed line) in the 350 ms following stimulus onset (relative to a 100 ms pre-stimulus baseline) at central electrode sites C3/4 contralateral (c) and ipsilateral (i) to the stimulated hand. These ERP waveforms are represented separately for tactile non-target stimuli in the *Narrow attention task,* when participants focused on the hand (1) or when they focused on the shoulder (2) on the attended side, and in the *Broad attention task* when participants focused on both hand and shoulder (3) on the attended side.

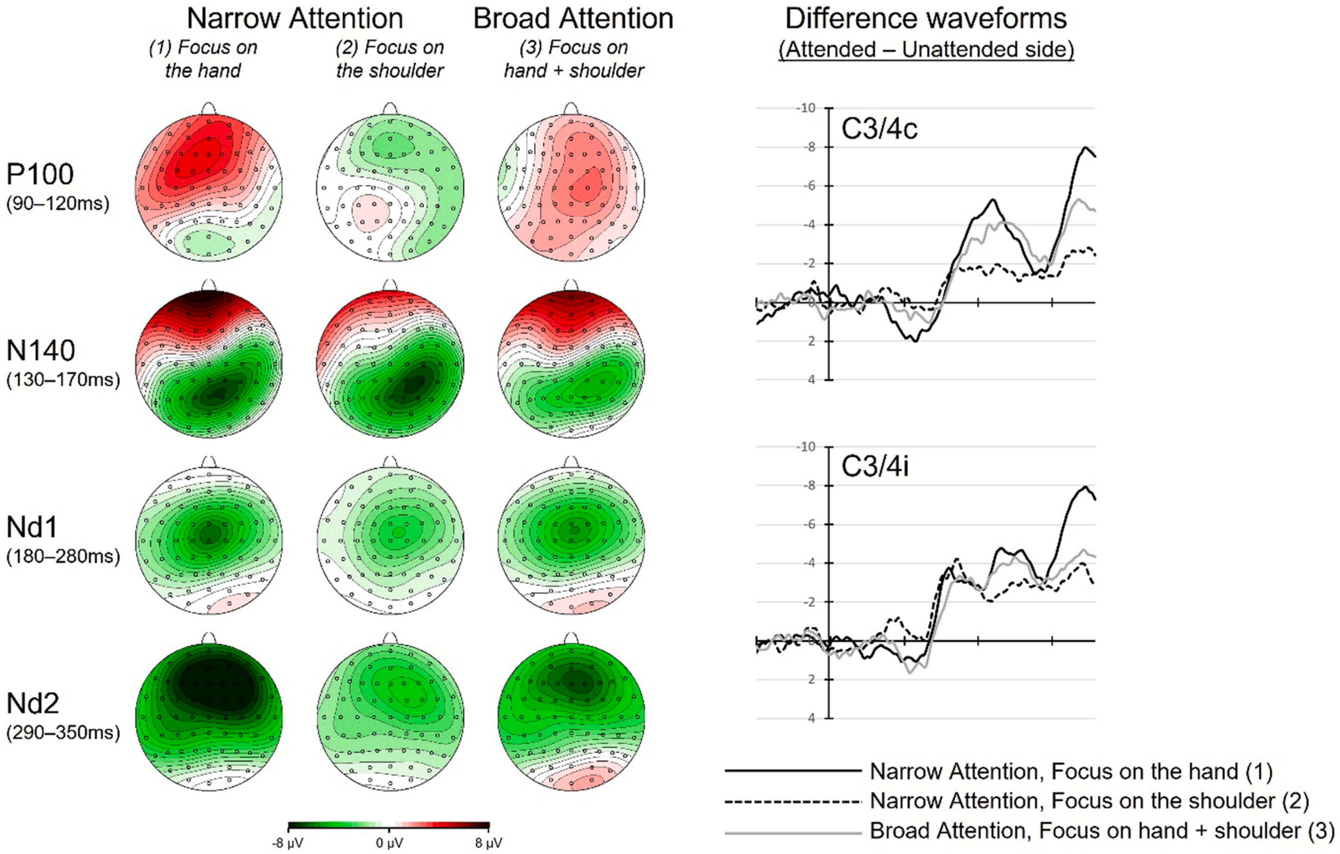

Fig. 3. Difference waveforms at central electrode sites C3/4 contralateral (c) and ipsilateral (i) to the stimulated hand, obtained by subtracting ERPs elicited by tactile non-target stimuli to the hand on the attended side from those on the unattended side. These difference waveforms were calculated separately for the *Narrow attention task,* when attention was focused on the hand (black solid line, (1)), for the *Narrow attention task,* when attention was focused on the shoulder (black dashed line, (2)), and for the *Broad attention task* when attention was focused on both hand and shoulder (solid grey line, (3)). The corresponding topographical maps for these conditions are shown separately for the four time-windows considered, corresponding to the ERP components of interest: P100 (90–120 ms), N140 (130–170 ms), Nd1 (180–280 ms) and Nd2 (290–350 ms). In these maps, electrodes on the left hemisphere are contralateral to the tactually stimulated hand, while those on the right hemisphere are ipsilateral to the tactually stimulated hand.

response was required. Hence, vocal responses were only present for cued targets in the Narrow attention task, Focus on the hand (1) and in the Broad attention tasks (3). The first analysis compared the speed and error rates (failure to respond) observed in the Narrow attention task, Focus on the hand (1), and in the Broad attention task (3), on cued target trials in which the target was delivered to the hand. Next, the accuracy rates observed on non-target trials were submitted to an ANOVA with attention (stimulus on the attended vs. unattended side) and task (Narrow attention, Focus on the hand (1) vs. Narrow attention, Focus on the shoulder (2) vs. Broad attention (3)) as within subject factors.

3. Results

3.1. Behavioural performance

The first comparisons involved performance on cued target trials in which the target was delivered to the hand. No reliable differences emerged between the speed of vocal responses to tactile *targets* presented to the cued hand in the Narrow task, Focus on the hand (1) (557 ms) and in the Broad attention task (3) (554 ms), F(1, 15)= 0.068, p =[0.79 ηp^2= .005. Also the number of errors on cued target trials (failure to respond) did not differ statistically between tasks (F(1, 15)= 0.66, p = .42, ηp^2= .043). Participants failed to respond on 3.4% of cued targets in the Narrow task, Focus on the hand (1), and on 4.4% of these trials in the Broad attention task (3).

Non-target stimuli had to be ignored regardless of their locations (thus no vocal response was expected on these trials). Accuracy rates on non-target trials were analyzed with a repeated measures ANOVA with attention (attended vs. unattended side) and task (Narrow task, Focus on the hand (1) vs. Narrow task, Focus on the shoulder (2) vs. Broad attention task (3)) as within-subjects factors. The main effect of attention (F(1, 15)= 7.1, p = .018, ηp^2= .32) revealed that participants were more accurate on trials in which the non-target was presented to the unattended rather than to the attended side (99.9% vs. 99.7%, respectively). Participants were more likely to make errors (false alarms) on the attended side because only on that side did they have to discriminate between targets and non-targets. The interaction between attention and task failed to reach significance (F(1.6, 24.1)= 3.27, p = .065, ηp^2= .18).

3.2. Somatosensory ERPs elicited by tactile non-target stimuli presented to the hands

Fig. 2 shows ERPs elicited by non-target stimuli presented to the hand located on the attended and unattended side (solid and dashed lines, respectively) for electrode sites C3/4 located over the hemisphere contralateral (c) and ipsilateral (i) to the tactually stimulated hand. The effect of spatial attention is represented separately for the three experimental conditions. Left and central panels show ERPs in the Narrow attention task. Here, the effect of spatial attention (ERPs elicited on the attended vs. unattended side) is represented separately when participants focused on the hand (Fig. 2, left panels, (1)), when they focused on the shoulder (Fig. 2, middle panels, (2)), and when they focused on both the hand and the shoulder (Fig. 2, right panels, (3)) on the attended side. The corresponding difference waveforms (attended side-minus-unattended ERPs) are shown in Fig. 3, separately for electrodes C3/4 ipsilateral and contralateral to the stimulated hand. Black lines represent the Narrow attention task with solid and dashed lines indicating the effect of spatial attention when participants focused on the hand (1) and when they focused on the shoulder (2), respectively. Grey lines represent the Broad attention task in which they focused on both hand and shoulder (3). The scalp distribution of these difference waveforms is also shown in Fig. 3 for four time-intervals between 90 and 350 ms post-stimulus, corresponding to the ERP components of interest (P100, N140, Nd1 and Nd2), and separately for the different experimental conditions.

As can be seen from these figures, differences between ERPs elicited by stimuli to the hand on the attended and unattended side emerged earlier and were stronger when attention was focused exclusively on the hand (Narrow attention task, Focus on the hand (1); see Fig. 2, left panels and Fig. 3, solid black line) rather than spread between the hand and the shoulder (Broad attention task (3); see Fig. 2, right panels and Fig. 3, grey line). However, an effect of spatial attention also emerged at the hands when participants focused on the shoulder in the Narrow attention task (2) (see Fig. 2, middle panels and Fig. 3, dashed black line), suggesting that even when attention was focused on one single location it spilled over to adjacent body locations.

In the P100 latency range (90–120 ms post-stimulus), results revealed a significant main effect of attention (F(1, 15)= 5.6, p = .031, ηp^2= .27) demonstrating the overall presence of attentional modulations in this time window. Importantly, however, systematic differences emerged between the main effect of attention in the three tasks, as indicated by the attention x task (F(1.893, 28.395)= 4.1, p = .027, ηp^2= .22) and the attention x task x laterality (F(1.861, 27.9)= 5.4, p = .012, ηp^2= .26) interactions. Separate analyses were carried out for each of the three tasks to investigate the presence of reliable main effects of attention in the P100 time range. In the *Narrow task, Focus on the hand (1)*, a significant main effect of attention (F(1, 15)= 7.8, p = .013, ηp^2= .34) was further modulated by laterality (F(1, 15)= 5.7, p = .031, ηp^2= .27). Reliable P100 attentional modulations were observed over electrodes contralateral to the stimulated hand (F(1, 15)= 10.4, p = .006, ηp^2= .4) but not over ipsilateral ones (F(1, 15)= 2.7, p = .12, ηp^2= .15). No P100 modulations were present *in the Narrow task, Focus on the shoulder* (2) (main effect of attention, F(1, 15)= 1.9, p = .18, ηp^2= .117; attention x laterality, F(1, 15)= 3.2, p = .093, ηp^2= .17). In the *Broad attention task (3)*, neither the main effect of attention (F(1, 15)= 2.6, p = .12, ηp^2= .15) nor the attention x laterality interaction (F (1, 15)= 3.9, p = .064, ηp^2= .2) were statistically significant. This pattern of results revealed that the effects of attention on the P100 component were exclusively present when tactile spatial attention was narrowly focused on the hand on the attended side over contralateral electrodes (see Fig. 2). This conclusion was further substantiated by the comparison of the attention effects (calculated as the difference between attended and unattended waveforms) between tasks, see Fig. 3. The effect of attention observed at the hand when participants focused on the hand (Narrow attention (1)) was stronger than the ones observed when they focused on the shoulder (Narrow attention (2)), t(15) = 2.25, p = .04, d= 0.56, and when they focused on both hand and shoulder (Broad attention task, (3)), t(15) = 2.3, p = .035, d= 0.58.

In the following time window (130–170 ms post-stimulus), significant main effects of attention (F(1, 15)= 14.2, p = .002, ηp^2= .48) were reflected by enhanced N140 components for stimuli on the attended as compared to the unattended side. Importantly, no significant differences emerged between the amplitude of the N140 attentional modulations measured in the three different tasks depicted in Fig. 1, as suggested by the absence of attention x task (F(1.757, 26.35)= .9, p =[0.38 ηp^2= .06) and by attention x task x laterality (F(1.4, 21.09)= .69, p = [0.46 ηp^2= .04) interactions. Spatial attention effects were reliably present in all experimental conditions as confirmed by follow-up analyses (main effect of attention, all F(1, 15)> 5.3, all p < .036, all ηp^2> .26. As can be seen in Figs. 2 and 3, the presence of similar N140 attentional modulations when participants focused on the hand and when they focused on the shoulder in the Narrow attention task, (1) vs. (2), suggests that spatial attention was broadly distributed across both locations on the attended side in this time window. Indeed, effects of attention in the Narrow task were also similar to those observed when participants were explicitly instructed to broaden their attentional focus to the whole arm (Broad attention task, (3)).

Between 180 and 280 ms post-stimulus onset, ERPs elicited by stimuli presented on the attended side were more negative than those presented on the unattended side as revealed by the main effect of attention (F(1, 15)= 37.9, p < .001, ηp^2= .7). This sustained attentional negativity (negative difference, Nd) for stimuli on the attended as compared to the unattended side was present in a similar fashion in the three experimental tasks as suggested by the absence of attention x task (F(1.51, 22.646)= 1.8, p = .19, ηp^2= .1) and of attention x task x laterality (F(1.56, 23.44)= 1.9, p = .15, ηp^2= .11) interactions. Separate analyses conducted for each task, confirmed the presence of main effects of attention in all tasks (all tasks F(1, 15)> 14.2, all p > .002, all ηp^2> .48). Analogously to the results observed in the N140 time window, this pattern of results suggests a wide focus of attention spreading over the entire attended side in the Narrow attention task (both in (1) and (2)), similar to the result observed in the Broad attention task (3).

In the final time window (290–350 ms post-stimulus), the presence of the late phase of the attentional Nd was indicated by the main effect of attention (F(1, 15)= 54.9, p < .001, ηp^2= .78). As can be seen in Figs. 2 and 3, attentional ERP modulations were most pronounced in the Narrow task, when participants focused on the hand (1). This difference across the three tasks was substantiated by an attention x task interaction (F(1.62, 24.311)= 8.3, p = .003, ηp^2= .35). Reliable effects of attention were present in all tasks (all t(15) > 4.7, p < .001, d> 1). The attended-minus-unattended waveforms, shown in Fig. 3, were calculated separately for the three experimental tasks and compared across. The attentional modulations observed at the hand were stronger when participants focused on the hand in the Narrow condition (1) compared to when they focused on the shoulder (2) (t(15) = −3.59, p = .003, d= .9). As can be seen in Figs. 2 and 3, this difference suggests a narrower focus of attention during later processing stages, but also the presence of an attentional gradient. The attentional modulations observed when participants focused on the hand in the Narrow condition (1) were also stronger than those observed when they focused on both hand and shoulder (Broad attention task (3)) (t(15) = 3.5, p = [0.003 d= .88). This suggests that the size of the attentional focus modulates the effects of tactile spatial attention on somatosensory processing, with smaller attention effects for broader foci (See Figs. 2 and 3).

4. General discussion

Most studies of tactile spatial attention have focused on the comparison between ERPs elicited by tactile stimulus presented either to the attended hand or to the opposite unattended hand. Although these studies have provided valuable information about the time course of the attentional modulations of somatosensory processing, the comparison between stimuli delivered to homologous body parts on opposite sides of the body (e.g., attended vs. unattended hand) does not allow for a detailed analysis of the spatial distribution of tactile attention near the focus of attention. This is typically achieved by presenting tactile stimuli at different distances from the attended location (Eimer & Forster, 2003b; Kida et al., 2018).

The present ERP study sought to investigate the spatial characteristics of attentional selectivity in touch. On each trial a tactile stimulus was delivered to one of four possible body locations (hand or shoulder of the left or right side of the body). Crucially, in different experimental tasks (Fig. 1), a visual cue presented at the beginning of each trial instructed participants to focus their attention on one task-relevant location out of four possible ones (Narrow attention task (1) and (2)) or to broaden their attentional focus to include two possible target locations on the same side of the body (Broad attention task (3)). The aim of this study was twofold. First, we investigated whether it is possible to direct all attentional resources exclusively to the body location indicated by the cue (e.g., the hand or the shoulder) when participants were explicitly instructed to focus their attention on one single location (Narrow attention task) or whether part of these resources spills over to uncued locations. Second, we investigated whether the size of the attentional focus affects the attentional modulations of somatosensory processing by comparing the effects of spatial attention observed when participants were explicitly instructed to focus on one single location (Narrow attention task) and when they broadened their attentional focus to include two ipsilateral body locations (Broad attention task).

In line with previous ERP studies of tactile attention (e.g. Desmedt & Robertson, 1977) we observed reliable attentional modulations of somatosensory processing (i.e. differences between ERPs elicited by stimuli to the hand on the attended or unattended side of the body) during sensory-specific (P100 and N140) as well as during post-perceptual processing stages (Nd component) (e.g., Michie, 1984; Michie et al., 1987). Crucially, however, in the Narrow attention task, systematic differences were present between the attentional modulations observed when participants focused on one hand (Figs. 1, (1)) and when they focused on one shoulder (Figs. 1, (2)). Specifically, enhanced P100 components were observed over contralateral electrodes for stimuli to the hand on the attended vs. unattended side when tactile spatial attention was narrowly focused on one hand (Narrow attention, Focus on the hand, (1)). No such attentional modulations were observed when the tactile stimuli were presented to the hand on the attended vs. unattended side and participants focused on one shoulder (Narrow attention, Focus on the shoulder, (2)). This observation suggests that tactile spatial attention can be successfully restricted or focused on one task-relevant body location during the initial stage of tactile selectivity. Because the neural generator of the P100 somatosensory component has been identified in contralateral SII (e.g. Fujiwara et al., 2002; Hamada et al., 2003; Hoechstetter et al., 2000; Kida et al., 2007; Mima et al., 1998; Thees et al., 2003), our results suggest that the attentional focus in touch had a narrow spatial tuning during early sensory-specific processing stages.

By contrast, attentional modulations of the following N140 component elicited by non-target stimuli to the hands were similarly present when participants focused on one hand and when they focused on one shoulder in the Narrow attention task. In both these conditions of the Narrow attention task, (1) and (2), the N140 components elicited by stimuli presented on the attended side were more negative than those on the unattended side and no reliable difference emerged between the attention effects observed in these two conditions. Thus, in the N140 time window, the attentional focus was no longer restricted to the attended location but broadened (or spilled over) to include adjacent locations on the attended side of the body. In other words, when participants focused on one shoulder, stimuli delivered to the ipsilateral hand were not excluded from the attentional processing.

Strong effects of spatial attention were also present during post-perceptual stages of tactile processing. Differences between ERPs elicited by stimuli on the attended and unattended side are characterized by a sustained negativity (negative difference, Nd), classically assumed to reflect in-depth processing of the task-relevant stimulus feature (e. g. Michie, 1984; Michie et al., 1987). Recently, however, the nature of this late attentional modulation has been called into question. Studies with neutral cues have shown that the Nd component is driven primarily by a difference between unattended and neutral trials (attentional cost) rather than a difference between attended and neutral trials (Forster & Eimer, 2005; Forster & Gillmeister, 2011). Some researchers have suggested that this late component should instead be interpreted as an increased positivity for unattended over attended or neutral stimuli, possibly reflecting an active suppression of rejected trials (Kida et al., 2018). Other researchers have interpreted this enhancement of unattended stimuli as evidence for an exogenous re-orienting of attention from the location indicated by the cue to the location of the unattended tactile stimulus (Van der Lubbe et al., 2012; Van der Lubbe et al., 2017). In the present study, Nd attention effects for stimuli to the hands were observed both when participants focused on the hand and when they focused on the shoulder starting from about 180–200 ms post-stimulus onset. However, while the early phase of the Nd (measured between 180 and 280 ms post-stimulus) appeared to have similar amplitudes in both conditions of the Narrow attention task (Focus on the hand (1) and Focus on the shoulder (2)), beyond 300 ms larger Nd amplitudes were present when participants focused on the hand, suggesting that the focus of attention was narrowed again onto the attended location in this condition. Thus, the spatial tuning of tactile attention became narrower in the late phase of the Nd component, following an earlier phase characterized by a broad spread of attention. Importantly, the presence of a reliable Nd component when the attention was focused on the shoulder (but stimuli were presented to the hands) revealed that stimuli to the hand were not completely excluded from the focus of attention in this later phase. This decrease in attention effects as the distance between the focus of attention and the stimulated body location increases is in line with the idea of an attentional gradient in touch (Eimer & Forster, 2003b; Kida et al., 2018). It is worth noting that the finding of reduced Nd components when tactile stimuli were presented further away from the attentional focus is compatible with both a decreased rejection of unattended stimuli (c.f. Kida et al., 2018) and a reduced exogenous re-orienting to unattended stimuli (c.f. Van der Lubbe et al., 2012; 2017; 2018). However, in the absence of a neutral condition it is not possible to determine the relative impact of enhancement and suppression of attended and unattended stimuli, respectively, and to investigate fully the nature of the late Nd component.

Overall, the evidence observed in the present study seems to suggest that attentional selectivity in touch begins as a highly precise filtering mechanisms which then becomes broadly distributed across different locations on the cued side of the body, only to narrow again closer to the response selection stage. These findings complement and expand the existing evidence on the spatial distribution of attentional selectivity in touch within the hand (Eimer & Forster, 2003; Kida et al., 2018). In the ERP study by Eimer and Forster (2003b), the somatotopic (and external) distance between the four possible target locations was extremely small (i.e. two contiguous phalanxes on two adjacent fingers of the right hand). By contrast, in the present study, the four possible locations were distributed over two limbs (left and right arm), with a larger distance between the ipsilateral stimulus locations (hands and shoulders). Our findings suggest that tactile spatial attention was fully and effectively focused on the task-relevant body location in the P100 time window (stimuli on the hand when participants focused on the shoulder were not modulated by spatial attention). In Eimer and Forster's study in which the distance between possible target locations was minimal (single phalanx of one finger), stimuli on the irrelevant phalanx of the attended finger were not completely excluded from attentional processing. This might indicate that during the early stages of sensory processing there is a minimum size of the basic unit upon which attention can efficiently operate.

Results of a recent MEG study (Kida et al., 2018) support this observation. Participants were asked to attend to one finger of their right hand and the tactile stimulus was presented to one of the fingers of the same hand. Initial effects of attention were exclusively observed at the attended location (SIc, 50–70 ms, Kida et al., 2018). However, later effects of attention observed in SIIc (80–100 ms, Kida et al., 2018) were not fully restricted to the attended location (i.e. were not completely selective), but showed a gradient with stronger attentional modulations for locations closer to the attentional focus. The authors argued that these different effects of attention (selective vs. gradient) found respectively in SIc and SIIc may reflect the different levels of spatial definition of the body maps present in these cortical areas (Fitzgerald et al., 2004, 2006a; 2006b; Gomez-Ramirez et al., 2016). Because maps in SIIc are less detailed than those in SIc, the attentional selection of a small body location within these maps (e.g. phalanx or finger) will additionally result in effects of attention over contiguous body locations, giving rise to an attentional gradient. Our results expand these observations by showing that even attentional effects observed in the time range of the P100 component (generated in SII and characterized by less detailed body maps) can demonstrate selectivity so long as the distance between relevant body locations is increased. Thus, when the size of the attentional focus is sufficiently large, attention can be restricted to the cued location at least initially.

During later processing stages, the efficiency of the attentional filter did not appear to depend on the size of the cued body area. In Eimer and Forster's study (2003b) effects of attention in the Nd time range, were observed not only for stimuli at the task-relevant location (phalanx) but also for stimuli presented to the contiguous but task-irrelevant phalanx on the attended finger. Crucially, these attention effects decreased as the distance between the attentional focus and the tactile stimulus increased, suggesting the existence of an attentional gradient in touch (Eimer & Forster, 2003b). The fact that a similar pattern of results was observed in the Narrow condition of the present study suggests that during later processing stages an attentional gradient is present regardless of the size of the attentional unit considered.

Our results demonstrate that even when the distance between the relevant and the irrelevant locations is sufficient for an efficient attentional selection (as observed in the P100 time window), attention appears to spill-over to the uncued body part in the Nd time window. This conclusion is in line with the only other study to date that has specifically assessed the effects of attention on non-contiguous body locations when their distance in external space was manipulated through changes in body posture (Heed and Röder, 2010). In this ERP study participants were instructed to attend to the left or right hand or foot, while a tactile stimulus was presented to one of these four locations. Importantly, the hands and/or the feet were positioned near each other under crossed and uncrossed limb conditions (Heed and Röder, 2010). Results revealed that the effects of attention spread over different limbs when these are located close together in external space. For example, when the feet were crossed, attending to the left foot resulted in selective enhancement of ERPs elicited by stimuli to the right hand, because these were presented within the focus of attention (Heed and Röder, 2010). Because body posture was not manipulated in our study (the distance between hands and shoulders was exactly the same according to both somatotopic and external space), our findings are not informative about the specific frame of references that was used to encode tactile stimuli and to guide tactile spatial attention during the task. Nevertheless, it is worth noting that our findings provide additional evidence for the hypothesis that the effects of attention are not fully restricted to the attended location.

Although the ERP methodology allows one to track the operations of spatial attention with an extremely high temporal resolution, the present study only represents a coarse measure of the spatial distribution of the tactile attentional gradient. The number of possible stimulus locations in the present and previous ERP studies was constrained by the large number of trials needed to reach a sufficient signal-to-noise ratio. However, the investigation of the exact shape and spatial distribution of the attentional gradient requires the systematic manipulation of the distance between the stimulus location and the focus of attention, hence the inclusion of several possible stimulus locations. The idea of an attentional gradient that decreases as the distance between the focus of attention and the stimulus increases was initially suggested in visuospatial attention studies (e.g. Downing & Pinker, 1985; La Berge, 1983; Mangun & Hillyard, 1988; Shulman et al., 1985). For example, ERPs elicited by visual stimuli presented at varying distances from an attended locus were characterized by progressively smaller amplitudes (e.g. Mangun & Hillyard, 1988; Eimer, 2000). In addition to the spread of spatial attention beyond the attentional focus, some studies have also reported the presence of localized areas of suppression surrounding the focus of visuo-spatial attention where enhanced processing was observed (e.g. Steinman et al., 1995; Cutzu & Tsotsos, 2003; Mounts, 2000; Müller et al., 2005). Whether similar effects of spread of attention and surround inhibition also exist in touch remains an open question. Importantly, existing evidence in touch has shown that tactile attention is mediated both by the facilitation of sensory processing at attended body locations, and by the suppression of somatosensory stimuli at unattended locations (Forster & Eimer, 2005; Forster & Gillmeister, 2011). Thus, the direct investigation of the spatial distribution of these facilitatory and inhibitory effects on tactile processing appears particularly relevant and timely.

In summary, results of the present study demonstrated that the attentional focus in touch is a flexible mechanism which can change size and adjust its spatial tuning over time. When participants had to select one out of four possible locations (Narrow attention task), the earliest effects of tactile attention on somatosensory processing (P100 time-range) were exclusively present at the cued body location (the hand). This initial narrow spatial tuning of attention was followed by a broader focus (in the N140 and early Nd time-windows) with attentional resources similarly distributed between the hand and the shoulder on the attended side. Finally, in the late phase of somatosensory processing (late Nd time-window), stronger effects of spatial attention at the hand were present when participants focused on the hand, although smaller effects were also observed when participants focused on the shoulder. Thus, attentional selectivity in touch began as a highly precise filtering mechanism which then became broadly distributed, only to narrow again closer to the final processing stages.

The second aim of the present study was to investigate whether the attentional resources available to process tactile stimuli depended on the size of the attentional focus. Evidence from visual attention suggests that the focus of spatial attention can be voluntarily expanded and contracted to cover small or large areas of the visual field, to include a single or multiple potential task-relevant locations (e.g. Eriksen and St James, 1986; Castiello & Umiltà, 1990). Recent evidence has further suggested a causal role of the right frontal eye field (FEF) in the control of attentional zooming processes (Ronconi et al., 2014). Importantly, the efficiency of visual processing increases as the focus of attention narrows (e.g. Eriksen and James, 1986; Castiello & Umiltà, 1990). To investigate whether a similar pattern is present for spatial attention to touch, we compared the ERPs elicited by tactile stimuli presented to the hand on the attended and unattended side following cues indicating one or two task-relevant body parts (Narrow attention condition, Focus on the hand (1) vs. Broad attention condition (3), respectively). Results revealed that effects of attention were delayed in the Broad as compared to the Narrow attention task, as suggested by the fact that reliable attentional modulations were already present in the P100 time range over contralateral electrodes in the Narrow attention task but only emerged in the later N140 time window in the Broad attention task. In addition, effects of attention were stronger in the Narrow than in the Broad task during the late Nd time window. The reduced attentional modulation of tactile processing observed in the Broad compared to the Narrow attention task may suggest that fewer attentional resources were available at each cued location when attention had to be directed simultaneously to two as opposed to one task-relevant location. In other words, when the size of the attentional focus was larger (monitoring two possible target locations – Broad attention condition (3) compared to one, Narrow attention (1)) effects of attention were less pronounced.

However, it is worth noting that while monitoring two possible target locations on the same limb (Broad attention task) resulted in reduced effects of spatial attention at post-perceptual processing stages (late Nd time window), behavioural results did not show relevant differences between the speed or accuracy of vocal responses to targets presented to the *attended* hand in the Narrow and Broad attention tasks.

We were unable to compare vocal responses for unattended targets (and the overall behavioural effects of attention) between tasks because no overt response was required for these targets in the present task (c.f. Hillyard et al., 1973). Given that effects of spatial attention on performance are driven both by benefits (advantage of attended compared to neutral trials) and costs (disadvantage of unattended compared to neutral trials) (c.f. Forster & Eimer, 2005; Forster & Gillmeister, 2011) and that the costs can be stronger than the benefits (Forster & Eimer, 2005), it is possible that we simply did not capture the difference between Narrow and Broad attention tasks because there were no responses for unattended targets. In line with this possibility, Kida et al. (2018) also found no behavioural differences between tasks when they asked participants to attend to one single location (equivalent to our Narrow attention task) or to two locations (comparable to our Broad attention task) and to count targets presented at attended locations throughout a block of trials. Thus, future behavioural studies using a different paradigm better suited to measure overt motor responses should directly address the question of whether behavioural performance improves as the size of the attentional focus in touch decreases.

In conclusion, the comparison between attention tasks in which attention could be fully focused on one single location (Narrow attention task) or was distributed between two contiguous locations (Broad attention task) revealed that the focus of attention could be expanded and contracted in a flexible manner to cover larger or smaller areas of the body. Specifically, the attentional modulations in the Broad attention task were delayed and reduced compared to the Narrow attention task, suggesting that reduced attentional resources were available when attention was directed simultaneously to two body locations compared to just one.

Data availability

Data will be made available on request.

References

Blom, J. H., & Van der Lubbe, R. H. (2017). Endogenous spatial attention directed to intracutaneous electrical stimuli on the forearms involves an external reference frame. *International Journal of Psychophysiology, 121*, 1–11.

Blom, J. H. G., & Van der Lubbe, R. H. J. (2011). The influence of transient shifts of spatial attention on electrocutaneous stimulus evoked potentials. *European Journal of pain supplements, 5*(S1), 22-22.

Bradshaw, J. L., Howard, M. J., Pierson, J. M., Phillips, J., & Bradshaw, J. A. (1992). Effects of expectancy and attention in vibrotactile choice reaction time tasks. *The Quarterly Journal of Experimental Psychology, 44*(3), 509–528.

Butter, C. M., Buchtel, H. A., & Santucci, R. (1989). Spatial attentional shifts: Further evidence for the role of polysensory mechanisms using visual and tactile stimuli. *Neuropsychologia, 27*(10), 1231–1240.

Castiello, U., & Umiltà, C. (1990). Size of the attentional focus and efficiency of processing. *Acta Psychologica, 73*(3), 195–209.

Cutzu, F., & Tsotsos, J. K. (2003). The selective tuning model of attention: psychophysical evidence for a suppressive annulus around an attended item. *Vision Research, 43*(2), 205–219.

Desmedt, J. E., & Robertson, D. (1977). Differential enhancement of early and late components of the cerebral somatosensory evoked potentials during forced-paced cognitive tasks in man. *The Journal of Physiology, 271*, 761–782.

Downing C.J., & Pinker, S. (1985). The spatial structure of visual attention. In: M. I. Posner & O. S. Marin (Eds.). Attention and Performance XI. Erlbaum. (pp. 171–87).

Eimer, M. (2000). An ERP study of sustained spatial attention to stimulus eccentricity. *Biological Psychology, 52*, 205–220.

Eimer, M., & Forster, B. (2003a). Modulations of early somatosensory ERP components by transient and sustained spatial attention. *Experimental Brain Research, 151*(1), 24–31.

Eimer, M., & Forster, B. (2003b). The spatial distribution of attentional selectivity in touch: evidence from somatosensory ERP components. *Clinical Neurophysiology, 114* (7), 1298–1306.

Eriksen, C. W., & St James, J. D. (1986). Visual attention within and around the field of focal attention: A zoom lens model. *Perception & Psychophysics, 40*(4), 225–240.

Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G* Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39*(2), 175–191.

Fitzgerald, P. J., Lane, J. W., Thakur, P. H., & Hsiao, S. S. (2004). Receptive field properties of the macaque second somatosensory cortex: Evidence for multiple functional representations. *Journal of Neuroscience, 24*, 11193–11204.

Fitzgerald, P. J., Lane, J. W., Thakur, P. H., & Hsiao, S. S. (2006a). Receptive field (RF) properties of the macaque second somatosensory cortex: RF size, shape, and somatotopic organization. *Journal of Neuroscience, 26*, 6485–6495.

Fitzgerald, P. J., Lane, J. W., Thakur, P. H., & Hsiao, S. S. (2006b). Receptive field properties of the macaque second somatosensory cortex: Representation of orientation on different finger pads. *Journal of Neuroscience, 26*, 6473–6484.

Forster, B., & Eimer, M. (2004). The attentional selection of spatial and non-spatial attributes in touch: ERP evidence for parallel and independent processes. *Biological Psychology, 66*(1), 1–20.

Forster, B., & Eimer, M. (2005). Vision and gaze direction modulate tactile processing in somatosensory cortex: evidence from event-related brain potentials. *Experimental Brain Research, 165*(1), 8–18.

Forster, B., & Gillmeister, H. (2011). ERP investigation of transient attentional selection of single and multiple locations within touch. *Psychophysiology, 48*(6), 788–796.

Forster, B., Sambo, C. F., & Pavone, E. F. (2009). ERP correlates of tactile spatial attention differ under intra-and intermodal conditions. *Biological Psychology, 82*(3), 227–233.

Frot, M., & Mauguiere, F. (1999). Timing and spatial distribution of somatosensory responses recorded in the upper bank of the sylvian fissure (SII area) in humans. *Cerebral Cortex, 9*, 854–863.

Fujiwara, N., Imai, M., Nagamine, T., Mima, T., Oga, T., Takeshita, K., Toma, K., & Shibasaki, H. (2002). Second somatosensory area (SII) plays a significant role in selective somatosensory attention. *Brain Research Cognitive Brain Research, 14*, 389–397.

Gallace, A., & Spence, C. (2014). *In touch with the future: The sense of touch from cognitive neuroscience to virtual reality*. Oxford: OUP,.

García-Larrea, L., Lukaszewicz, A. C., & Mauguière, F. (1995). Somatosensory responses during selective spatial attention: The N120-to-N140 transition. *Psychophysiology, 32* (6), 526–537.

Gherri, E., & Eimer, M. (2008). Links between eye movement preparation and the attentional processing of tactile events: An event-related brain potential study. *Clinical Neurophysiology, 119*(11), 2587–2597.

Gherri, E., & Forster, B. (2012a). Crossing the hands disrupts tactile spatial attention but not motor attention: Evidence from event-related potentials. *Neuropsychologia, 50*(9), 2303–2316.

Gherri, E., & Forster, B. (2012b). The orienting of attention during eye and hand movements: ERP evidence for similar frame of reference but different spatially specific modulations of tactile processing. *Biological Psychology, 91*(2), 172–184.

Gherri, E., & Forster, B. (2014). Attention to the body depends on eye-in-orbit position. *Frontiers in Psychology, 5*, 683.

Gherri, E., & Forster, B. (2015). Independent effects of eye gaze and spatial attention on the processing of tactile events: Evidence from event-related potentials. *Biological Psychology, 109*, 239–247.

Gherri, E., & Berreby, F. (2017). The effect of perceptual load on tactile spatial attention: Evidence from event-related potentials. *Brain Research, 1673*, 42–51.

Gomez-Ramirez, M., Hysaj, K., & Niebur, E. (2016). Neural mechanisms of selective attention in the somatosensory system. *Journal of Neurophysiology, 116*(3), 1218–1231.

Gomez-Ramirez, M., Trzcinski, N. K., Mihalas, S., Niebur, E., & Hsiao, S. S. (2014). Temporal correlation mechanisms and their role in feature selection: a single-unit study in primate somatosensory cortex. *PLoS Biology, 12*(11), Article e1002004.

Hamada, Y., Okita, H., & Suzuki, R. (2003). Effect of interstimulus interval on attentional modulation of cortical activities in human somatosensory areas. *Clinical Neurophysiology, 114*, 548–555.

Hämäläinen, H., Kekoni, J., Sams, M., Reinikainen, K., & Näätänen, R. (1990). Human somatosensory evoked potentials to mechanical pulses and vibration: Contributions of SI and SII somatosensory cortices to P50 and P100 components. *Electroencephalography and Clinical Neurophysiology, 75*(1–2), 13–21.

Heed, T., & Röder, B. (2010). Common anatomical and external coding for hands and feet in tactile attention: evidence from event-related potentials. *Journal of Cognitive Neuroscience, 22*(1), 184–202.

Hillyard, S. A., Hink, R. F., Schwent, V. L., & Picton, T. W. (1973). Electrical signs of selective attention in the human brain. *Science, 182*(4108), 177–180.

Hoechstetter, K., Rupp, A., Meinck, H. M., Weckesser, D., Bornfleth, H., Stippich, C., Berg, P., & Scherg, M. (2000). Magnetic source imaging of tactile input shows task-independent attention effects in SII. *Neuroreport, 11*, 2461–2465.

Hsiao, S. S., O'shaughnessy, D. M., & Johnson, K. O. (1993). Effects of selective attention on spatial form processing in monkey primary and secondary somatosensory cortex. *Journal of Neurophysiology, 70*(1), 444–447.

Johansen-Berg, H., & Lloyd, D. M. (2000). The physiology and psychology of selective attention to touch. *Frontiers in Bioscience-Landmark, 5*(3), 894–904.

Jones, A., & Forster, B. (2014). Neural correlates of endogenous attention, exogenous attention and inhibition of return in touch. *European Journal of Neuroscience, 40*, 2389–2398.

Kida, T., Tanaka, E., & Kakigi, S. (2018). Adaptive flexibility of the within-hand attentional gradient in touch: An MEG study. *Neuroimage, 179*, 373–384.

Kida, T., Inui, K., Wasaka, T., Akatsuka, K., Tanaka, E., & Kakigi, R. (2007). Time-varying cortical activations related to visual-tactile cross-modal links in spatial selective attention. *J. Neurophysiol., 97*, 3585–3596.

Mangun, G. R., & Hillyard, S. A. (1988). Spatial gradients of visual attention: Behavioral and electrophysiological evidence. *Electroencephalography and Clinical Neurophysiology, 70*(5), 417–428.

Michie, P. T. (1984). Selective attention effects on somatosensory event-related potentials. *Annals of the New York Academy of Sciences, 425*, 250–255.

Michie, P. T., Bearparic, H. M., Crawford, J. M., & Glue, L. C. (1987). The effects of spatial selective attention on the somatosensory event-related potential. *Psychophysiology, 24*(4), 449–463.

Mima, T., Nagamine, T., Nakamura, K., & Shibasaki, H. (1998). Attention modulates both primary and second somatosensory cortical activities in humans: a magnetoencephalographic study. *Journal of Neurophysiology, 80*(4), 2215–2221.

Mounts, J. R. (2000). Attentional capture by abrupt onsets and feature singletons produces inhibitory surrounds. *Perception & Psychophysics, 62*(7), 1485–1493.

Müller, T. J., Federspiel, A., Horn, H., Lövblad, K., Lehmann, C., Dierks, T., & Strik, W. K. (2005). The neurophysiological time pattern of illusionary visual perceptual transitions: a simultaneous EEG and fMRI study. *International Journal of Psychophysiology, 55*(3), 299–312.

Ronconi, L., Basso, D., Gori, S., & Facoetti, A. (2014). TMS on right frontal eye fields induces an inflexible focus of attention. *Cerebral Cortex, 24*, 396–402.

Sambo, C. F., & Forster, B. (2011). Sustained spatial attention in touch: modality-specific and multimodal mechanisms. *Scientific World Journal, 18*(11), 199–213.

Sathian, K., & Burton, H. (1991). The role of spatially selective attention in the tactile perception of texture. *Perception & Psychophysics, 50*(3), 237–248.

Shulman, G. L., Wilson, J., & Sheehy, J. B. (1985). Spatial determinants of the distribution of attention. *Perception & Psychophysics, 37*(1), 59–65.

Spence, C., Lloyd, D., McGlone, F., Nicholls, M. E., & Driver, J. (2000). Inhibition of return is supramodal: a demonstration between all possible pairings of vision, touch, and audition. *Experimental Brain Research, 134*(1), 42–48.

Steinman, B. A., Steinman, S. B., & Lehmkuhle, S. (1995). Visual attention mechanisms show a center—surround organization. *Vision Research, 35*(13), 1859–1869.

Thees, S., Blankenburg, F., Taskin, B., Curio, G., & Villringer, A. (2003). Dipole source localizationand fMRI of simultaneously recorded data applied to somatosensory categorization. *Neuroimage, 18*, 707–719.

Van der Lubbe, R. H., Blom, J. H., De Kleine, E., & Bohlmeijer, E. T. (2017). Comparing the effects of sustained and transient spatial attention on the orienting towards and the processing of electrical nociceptive stimuli. *International Journal of Psychophysiology, 112*, 9–21.

Van der Lubbe, R. H., De Kleine, E., Schreurs, K. M., & Bohlmeijer, E. T. (2018). Does mindfulness training modulate the influence of spatial attention on the processing of intracutaneous electrical stimuli? *PloS One, 13*(8), Article e0201689.

Van der Lubbe, R. H., Buitenweg, J. R., Boschker, M., Gerdes, B., & Jongsma, M. L. (2012). The influence of transient spatial attention on the processing of intracutaneous electrical stimuli examined with ERPs. *Clinical Neurophysiology, 123* (5), 947–959.

Whang, K. C., Burton, H., & Shulman, G. L. (1991). Selective attention in vibrotactile tasks: detecting the presence and absence of amplitude change. *Perception & Psychophysics, 50*(2), 157–165.

Zopf, R., Giabbiconi, C. M., Gruber, T., & Müller, M. M. (2004). Attentional modulation of the human somatosensory evoked potential in a trial-by-trial spatial cueing and sustained spatial attention task measured with high density 128 channels EEG. *Cognitive Brain Research, 20*(3), 491–509.