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Behavioural and Electrophysiological evidence for the effect of target-distractor separation in a tactile search task

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RUNNING HEAD: Target-distractor separation modulates target selection

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Abstract

Evidence suggests that the N140cc component of event-related potentials (ERP) observed in tactile search tasks reflects the attentional selection of the target. Here, we investigated whether the target selection processes are affected by the separation between the target and an ipsilateral singleton distractor (singletons delivered to contiguous or non-contiguous fingers of the same hand). In addition, the external distance between search items was varied through posture (splayed or touching fingers). Accuracy improved when target and distractor were delivered to contiguous fingers that were also touching. Regardless of target-distractor separation, the N140cc was larger when the external distance between search-array stimuli decreased (touching fingers). Importantly, a smaller N140cc was observed at reduced target-distractor separations, suggesting a narrower attentional focus for contiguous singletons. These findings reveal that the mechanisms responsible for tactile target selection in the presence of an ipsilateral singleton distractor are fundamentally different from those emerged in vision.

Keywords: touch, selective attention, event-related potentials, N140cc, target-distractor separation, touching and splayed fingers

1. Introduction

Due to the limited capacity of our sensory systems, stimuli that reaches our senses simultaneously compete for representation (Desimone & Duncan, 1995). Competition between potentially relevant stimuli can be biased through selective mechanisms that direct enhanced processing resources to stimuli that are task-relevant and/or particularly salient at the expenses of others. However, competition can also be biased through mutually suppressive interactions. For example, brain activity in extra-striate visual areas is decreased when distractors are presented simultaneously with the target as compared to target only conditions suggesting the presence of mutually suppressive mechanisms (e.g. Kastner, De Weerd, Desimone & Ungerleider, 1998; Hillmire & Corballis, 2014).

Suppressive interactions become particularly evident when the spatial separation between potentially relevant stimuli is decreased, because progressively overlapping neural resources represent those objects (e.g. Desimone & Gross, 1979; Kastner & Ungerleider, 2001; Smith, Singh, Williams, & Greenlee, 2001). Psychophysiological evidence has shown stronger interference between salient visual stimuli when their spatial separation was reduced (e.g. Hillmire, Mounts, Parks & Corballis, 2009; 2010; Gaspar & McDonald, 2014). In one of these studies (Hillmire et al., 2009), participants performed a visual search task reporting the orientation of a singleton target (green or orange T) while ignoring a singleton distractor (L of the other color) as well as all homogeneous distractors (grey Ts) presented in a circular array. Importantly, the distance between target and singleton distractor within the same hemifield was manipulated, resulting in varying degrees of competition for representation between these singleton items. Behavioural results demonstrated reduced accuracy and longer RTs with decreasing target-distractor separation. Furthermore, the amplitude of the N2pc component of event-related potentials (ERPs) elicited by the presentation of the search array was reduced at small target-distractor separations as compared to larger distances. Because the N2pc is widely considered the electrophysiological marker of target selection (c.f. Luck, 1994; Eimer, 1996; see Woodman, 2013; Eimer, 2014; Gaspelin & Luck, 2018 for recent reviews), these findings were interpreted as evidence that competition for representation is spatially mediated and degrades the processes of target selection (Hillmire et al., 2009; 2010).

The aim of the present study was to investigate whether spatially mediated target-distractor interactions can be observed during the selection of task-relevant information in a tactile search task. While the mechanisms of visual selective attention have been widely investigated, only a few studies to date have addressed the question of attentional selectivity in touch. Similarly to the visual modality, the presence of a singleton distractor in a tactile search array results in attentional costs, as demonstrated by slower and less accurate responses on distractor present as compared to distractor absent trials (Mena et al., 2020). These attentional costs were larger when the singleton distractor was delivered next to the target (ipsilateral distractor trials) than to the opposite hand (contralateral to the target; Mena et al., 2020), suggesting the presence of a between-hands distance-mediated interference effect. However, the four items search array used in that study (with stimuli presented to two fingers on each hand) did not allow to explore the question of spatially mediated interactions between ipsilateral singletons because ipsilateral singletons were always contiguous.

To determine whether tactile target selection is modulated by the *separation*¹ within the search array between the target and an ipsilateral singleton distractor, in the present study we recorded ERPs over and close to somatosensory brain areas during a tactile search task in which six stimuli were simultaneously delivered to three fingers of the left and right hand. On each trial, one target, one singleton distractor and four homogeneous distractors were presented. These stimuli were characterised by different vibro-tactile frequencies (adapted from Mena et al., 2020, Exp. 2). Target and singleton distractors were always presented to different fingers of the same hand and participants were instructed to localise the exact target position within the hand. Importantly, on different trials the target and singleton distractor were presented either at contiguous or non-contiguous positions within the search array (i.e. contiguous fingers: index and middle or ring and middle fingers; or to non-contiguous fingers: index and ring; see Figure 1). That is, the *within-hand* separation between the target and singleton distractor was manipulated. Recent studies have shown the

¹ It is worth noting that on all trials six tactile stimuli were delivered to three fingers of the left and of the right hand (index, middle and ring fingers). The separation between target and singleton distractor was varied randomly on each trial, so that these singletons were delivered either to contiguous or to non-contiguous fingers of the same hand. It is likely that this manipulation of target-distractor separation within the search array involved changes to the distance between these singletons according to both somatotopic as well as external space.

existence of a lateralized ERP component, labelled N140cc, that may reflect the selection of task-relevant items presented in the search array (e.g. Forster, Tziraki & Jones, 2016; Katus, Grubert & Eimer, 2015; Katus & Eimer, 2019; Ambron, Mas Casadesus & Gherri, 2018; Mena, Lang & Gherri, 2020), similarly to the N2pc observed in visual search tasks. Typically, ERPs elicited over the hemisphere contralateral to the target are more negative than those observed over the ipsilateral hemisphere (e.g. Forster et al., 2016; Katus et al., 2015; Katus & Eimer, 2019; Ambron et al., 2018; Mena et al., 2020). This lateralized component is maximal over central electrodes and its onset overlaps with the sensory-specific N140 component (e.g. Forster et al., 2016). If target selection mechanisms in touch and vision operate in a similar fashion, smaller N140cc components and worst performance are expected when the target and the singleton distractor are presented to contiguous as compared to non-contiguous fingers, that is when these stimuli are more likely to be represented by overlapping neural resources. However, initial evidence from our lab has suggested that the attentional selection of the target indexed by the N140cc is not degraded by the presence of an ipsilateral distractor (Mena et al., 2020). It is therefore possible that the mechanisms responsible for target selection in touch operate according to different spatial principles.

A distinctive feature of touch is that the distance between tactile stimuli can vary not only in terms of stimulus separation on the skin surface (somatotopic distance) but also with respect to external space. While tactile stimuli are initially encoded relative to the position of the stimulated mechanoreceptors on the skin within skin-based somatotopic representations (cf. Merzenich, Kaas, Sur & Lin, 1978; Kaas, 1983), during later processing stages this information is remapped onto external posture-dependent representations based on multisensory visual and proprioceptive input (Longo, Azanon & Haggard, 2010; Medina & Coslett, 2010).

The impact of external space on the attentional selection of tactile targets has been reported in studies in which one target and one distractor were presented to different hands and their distance was varied in different blocks of trials (e.g. Driver & Grossenbacher, 1996; Ambron et al., 2018). Results revealed impaired target selection and reduced N140cc components when the hands were placed close together as compared to far apart, demonstrating that the attentional selection of task-relevant tactile information is based at least in part on an external reference frame. However, it remains unknown whether the

attentional selection of the target is modulated by its external distance from the distractors when these stimuli are delivered to different fingers of the same hand.

Behavioural studies investigating the effect of external space on *tactile perception* through a postural manipulation (fingers open vs. closed) have shown an improvement of performance when the fingers were splayed rather than close together (e.g. Overvliet, Anema, Brenner, Dijkerman & Smeets, 2011; Tame', Dransfield, Quettier & Longo, 2017). It was suggested that proprioceptive information about finger posture reduces the overlap between neuronal resources involved in the coding of tactile stimuli, disambiguating the position of stimuli presented to nearby fingers (Overvliet et al., 2011).

To investigate whether target selection is affected by the target-distractor separation in external space, we varied the external distance between the stimuli of the search array by asking participants to perform the same tactile search task while holding their fingers spread apart (splayed fingers) or close together (touching fingers) in different blocks of trials (see Figure 1, the distance between the two hands was held constant). This manipulation of the external distance between the fingers (and consequently of the external distance between the tactile stimuli of the search array) involved postural and proprioceptive changes caused by modifications of the hand configuration which have been shown to modulate tactile processing (Craig, 2003; Riemer, Trojan, Kleinbohl & Holzl, 2010; Overvliet et al. 2011; Wada et al., 2012). We asked whether the attentional mechanisms responsible for target selection varied as a function of the distance in external space between the stimuli of the search array (touching vs. splayed fingers) and whether this postural manipulation contributed to modulate the interactions between the target and the singleton distractor.

2. Material and Method

2.1. Participants

Twenty-eight university students were recruited in this experiment (age range 20-31 years, $M = 25$, $SD = 3.03$; 12 females, 14 males; 2 left handed by self-report). All of them reported no history of neurological disorders and gave written informed consent to participate in the study after the nature of the study had been explained to them. The study

was conducted in accordance with the Declaration of Helsinki and was approved by the PPLS Research Ethics Committee of the University of Edinburgh. Four participants were excluded from data analyses because they performed below chance level (accuracy < 33.3%) and two additional participants were excluded due to a low number of trials in the ERP analysis after artefacts rejection. Thus, the remaining sample consisted of twenty-two participants aged between 20 and 31 years (age $M = 25.18$, $SD = 3.23$; 10 females, 12 males; 2 left-handed by self-report).

2.2. Apparatus, Stimuli and procedure

Participants were seated in an electrically-shielded, sound-attenuating and dimly lit cabin. They were instructed to place their hands palms down on a table at a distance of 22 cm (11 cm to the left and right of participants' body midline). The hands were rotated medially (at an angle of approximately 45°) until ring, index and middle finger of each hand were aligned and parallel to the mid-sagittal plane of the body (see Figure 1). While the distance between hands was held constant throughout the experiment, the distance between participants' fingers of each hand was manipulated in different blocks of trials. Participants either splayed their fingers or closed their fingers, so that the fingers of each hand were in contact with each other. Once in the correct position, the hands were covered with a black cardboard, on top of which there was a white pin aligned with the body midline which served as fixation-point. Responses were provided using three pedals: two were vertically arranged and positioned under the same foot (top and bottom pedals, operated by the toes and the heel, respectively), while the third pedal (middle pedal) was positioned under the opposite foot. Tactile stimuli were presented using 12V solenoids (Heijo Research Electronics, UK) driving a metal rod with a blunt conical tip. The tip of the tactile stimulators touched the skin whenever a current passed through the solenoid. Six solenoids were attached with adhesive medical tape to the top phalanxes of the left and right index, middle and ring fingers. To mask the sounds made by tactile stimulators, one speaker was centrally positioned on the table, between the two hands, and presented white noise (65 dB SPL) throughout the experimental blocks.

Each trial started with a 300-ms empty interval, which was followed by the presentation of the six stimuli search array (405-ms duration) to three fingers of the left and right hand (index, middle and ring fingers). On each trial, one target and one singleton distractor were

presented to contiguous or non-contiguous fingers of the same hand while four homogenous distractors were delivered to the remaining four fingers. Target, singleton distractor and homogeneous distractor differed with respect to their vibration frequencies (100 Hz, 40 Hz or 12.5 Hz, respectively). Each frequency consisted of a rapid sequence of pulses during which the rod was in contact with the skin for 5 ms, followed by a variable inter-pulse interval set at 5ms, 20ms and 75ms for target, singleton distractor and homogeneous distractor, respectively. The tactile search array started and ended with all the stimulators touching the skin simultaneously to prevent participants from using the offset of the stimuli to complete the task. Stimulus presentation was followed by a 1,800-ms interval, which was used to collect responses.

Each participant completed eight blocks of 96 trials. The target was presented randomly and with equal probability to the index, middle or ring finger of the left or right hand. The distractor was presented with equal probability to one of the two remaining fingers of the hand where the target was presented. Analyses focused exclusively on trials in which the target was presented to either the ring or index fingers (top and bottom locations), because on these trials the distractor could be presented with equal probability to the contiguous and to the non-contiguous finger. By contrast, when the target was presented to the middle finger the singleton distractor could only be presented to a contiguous finger (either ring or index finger). These trials were not included in the behavioural and ERP analyses.

Participants completed four consecutive blocks of trials in which they kept their fingers splayed and four blocks of trials with their fingers touching. The order of these conditions was counterbalanced across participants so that half of the participants started the experiment with their fingers touching and the remaining half with their fingers splayed.

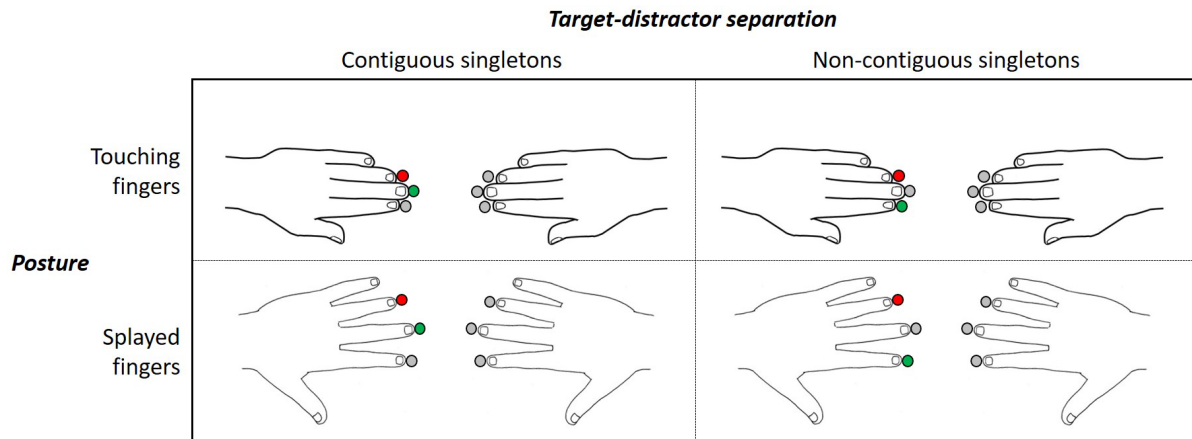


Figure 1. Schematic representation of the six-item search array in the different experimental conditions. The separation between target (red circle) and singleton distractor (green circle) varied randomly within each block of trials. These singletons were always presented to the same hand either to contiguous or to non-contiguous fingers, while the homogenous distractors were delivered to the remaining four fingers (grey circles). The external distance between fingers (i.e. the stimuli of the search array) was varied through a postural manipulation whereby participants performed the same tactile search task with their fingers splayed or touching in different blocks of trials.

Participants' task was to identify the location of the target within each hand (i.e. regardless of whether the target was delivered to the left or right hand). They had to press the top, middle or bottom pedal when the target was presented to the ring, middle or index finger, respectively. Participants were instructed to keep their eyes on the central fixation at all times and to respond as fast and as accurately as possible. They were not explicitly informed that target and singleton distractor were always presented to the same hand. While the stimulus-to-response key arrangement (e.g. ring finger – top pedal) was held constant throughout the experiment, to avoid ERP contamination from motor responses, the responding foot-to-response pedal arrangement was changed every two blocks. For each participant, the left toes and heel operated the top and bottom pedals while the right foot operated the middle pedal on half of the blocks, while the opposite arrangement was followed in the remaining blocks. The initial foot-pedal arrangement was counterbalanced across participants. Participants completed an extensive training phase before the beginning of the experiment. First, they were presented the three different vibration frequencies one

at the time (target, singleton distractor and homogeneous distractor, respectively) within one block of 96 trials in which each vibration was sequentially presented to the three possible stimulus locations (ring, middle and index finger) on each hand. Then, they were asked to complete two practice blocks of 48 trials each in which the six stimuli search array was presented on each trial. In the first training block, the sequence of target locations was predictable (sequential order) to allow participant to familiarise with the sensation of the simultaneous vibrations presented in the search array. In the second training block the sequence of trials was randomised (similarly to the experiment). Whenever necessary, the second practice block was repeated until the average accuracy rate for the block reached 50% (chance level 33.3%). During this training phase, participants had the opportunity to be presented the different tactile frequencies again if they felt it would be beneficial to improve performance.

2.3. Behavioural data analysis

Data (RTs and accuracy) were analysed using multilevel modelling in R (3.30). A basic model with subjects as random intercepts was compared with models containing our variable(s) of interest as fixed factors with ANOVA function. These were target-distractor separation (contiguous vs. non-contiguous), posture (touching vs. splayed fingers) coded as categorical factors. In the Results, we reported the final models containing the fixed-factor(s) that best predicted our data compared to random-factor only model.

2.4. EEG data acquisition and pre-processing

EEG was recorded using a BIOSEMI ActiveTwo amplifier 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 were placed on the earlobes. Horizontal eye movements (HEOG) were recorded from two electrodes

placed at the outer canthi of each eye. Vertical eye movements (VEOG) were recorded from two electrodes positioned above and below the right eye. The EEG was sampled at 512Hz.

EEG data was analysed using Brain Vision Analyser (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). The EEG was epoched into 500ms intervals starting 100ms before and ending 400ms after the search array onset. Trials with eye blinks (voltage exceeding $\pm 60\mu\text{V}$ on the VEOG channel), horizontal eye movements (voltage exceeding $\pm 40\mu\text{V}$ on the HEOG channel) and other artefacts (voltage exceeding $\pm 80\mu\text{V}$ at all other electrode sites) were excluded from further analysis, as were trials with response errors.

ERPs were averaged relative to a 100ms pre-stimulus baseline separately for all combinations of target-distractor separation (contiguous vs. non-contiguous), posture (touching vs. splayed) and target side (left vs. right hand). ERP mean amplitude values were computed for each participant at electrodes C3/4 and C5/6 (in line with previous studies, Ambron et al., 2018; Mena et al., 2020; Forster et al., 2016; Katus & Eimer, 2019), within two consecutive measurement windows centred on the N140 somatosensory ERP component (120 – 260 ms and 260-400ms). These time windows were based upon our previous work on tactile search (Exp. 2 in Mena et al., 2020) in which we observed that with this specific selection of vibro-tactile frequencies for target, singleton distractor and homogenous distractor, the N140cc component emerged around 120 ms and was reliably present until 400 ms post-array onset.

To investigate whether the electrophysiological signature of attentional target selection (N140cc) is modulated by target-singleton distractor separation within the search array and/or by the postural manipulation of their separation in external space, repeated-measures analyses of variance (ANOVA) were conducted for the factors target-distractor separation (contiguous vs. non-contiguous singletons), posture (touching vs. splayed fingers) and laterality (ERPs elicited over the hemisphere contralateral vs. ipsilateral to the target side). In these analyses, the presence of reliable lateralized components was reflected by the main effect of the factor laterality, indicating significant differences between the hemisphere contralateral and ipsilateral to the target side. Therefore, interactions involving the factor laterality were of interest in these ERP analyses.

3. Results

3.1. Behavioural Results

For the accuracy, the final model comprised the main effect of the target-distractor separation (contiguous vs. non-contiguous singletons) and the main effect of posture (touching vs. splayed fingers) (comparison with a model with target-distractor separation only as fixed factor: $\text{logLik} = -7662$, $\chi^2(1) = 13.7$, $p < 0.001$). Participants were more accurate when target and distractor were contiguous ($M = 48\%$, $SE = 0.03$) than non-contiguous ($M = 45\%$, $SE = 0.01$). They were also more accurate when the fingers were touching ($M = 49\%$, $SE = 0.03$) as compared to splayed ($M = 45\%$, $SE = 0.01$). The model with the interaction between these two factors was a better predictor of the accuracy than the model with only the main effects ($\text{logLik} = -7659$, $\chi^2(1) = 5.7$, $p = 0.02$). Exploring the interaction further, when target and distractor were *contiguous* ($z = 4.3$, $p < 0.001$), participants were more accurate with touching ($M = 52\%$, $SE = 0.02$) than splayed fingers ($M = 46\%$, $SE = 0.03$), whereas no effect of posture ($z = -0.9$, $p = 0.35$) was present when target and distractor were *non-contiguous* (touching fingers, $M = 46\%$, $SE = 0.02$; splayed fingers, $M = 44\%$, $SE = 0.02$). In addition, while no significant effect of target-distractor separation was observed when the fingers were *splayed* ($z = -1.0$, $p = 0.29$), when the fingers were *touching*, participants were more accurate when target and distractor were contiguous than non-contiguous ($z = 4.4$, $p < 0.001$).

For the RT, none of the factors or interaction contributed significantly to the model fit ($\text{logLik} = -40811$, $\chi^2(3) = 1.5$, $p = 0.66$). Participants were equally slow to respond to the target location when the distractor was presented to the contiguous ($M = 1049$ ms, $SE = 20$ ms) as compared to the non-contiguous finger ($M = 1049$ ms, $SE = 19$ ms), as suggested by the absence of a reliable main effect of target-distractor separation. Similarly, no effect of posture was observed, with comparable RTs for touching (close $M = 1051$ ms, $SE = 20$ ms) and for splayed fingers ($M = 1047$, $SE = 20$).

3.2. ERP results: Lateralized ERP components elicited by the search array

As shown in Figure 2 and 3, ERPs elicited over the hemisphere contralateral to the hand where both target and singleton distractor were presented were more negative than those measured over the ipsilateral hemisphere. Statistical analyses confirmed a significant main effect of laterality, demonstrating the presence of reliable N140cc lateralised components between 120 and 400 ms post-array onset (120-260 ms time window, $F(1, 21) = 67.3$, $p < 0.001$, $np^2 = 0.72$; 260-400 ms time window, $F(1, 21) = 14.9$, $p < 0.001$, $np^2 = 0.4$).

Figure 2 shows the effect of target-distractor separation on the amplitude of the N140cc component. As shown in this figure the N140cc amplitude was larger when target and distractor were delivered to non- contiguous fingers ($M = -1.15 \mu V$, $SE = 0.15 \mu V$) rather than to contiguous ones ($M = -0.9 \mu V$, $SE = 0.15 \mu V$). Statistical analyses revealed a significant *laterality x target-distractor separation* interaction ($F(1, 21) = 4.3$, $p = 0.048$, $np^2 = 0.14$) in the early N140cc time window (120-260 ms). The presence of reliable N140cc components when the singletons were delivered to contiguous ($F(1, 21) = 39$, $p < 0.001$, $np^2 = 0.6$) as well as to non-contiguous fingers ($F(1, 21) = 65.7$, $p < 0.001$, $np^2 = 0.7$) – as revealed by follow-up comparisons conducted separately for each target-distractor separation - confirmed that the interaction between *laterality and target-distractor separation* was driven by a N140cc amplitude difference between these conditions. In the late N140cc time window (260-400 ms), the laterality x target-distractor separation interaction was not significant ($F(1, 21) = 1.1$, $p = .3$, $np^2 = 0.05$).

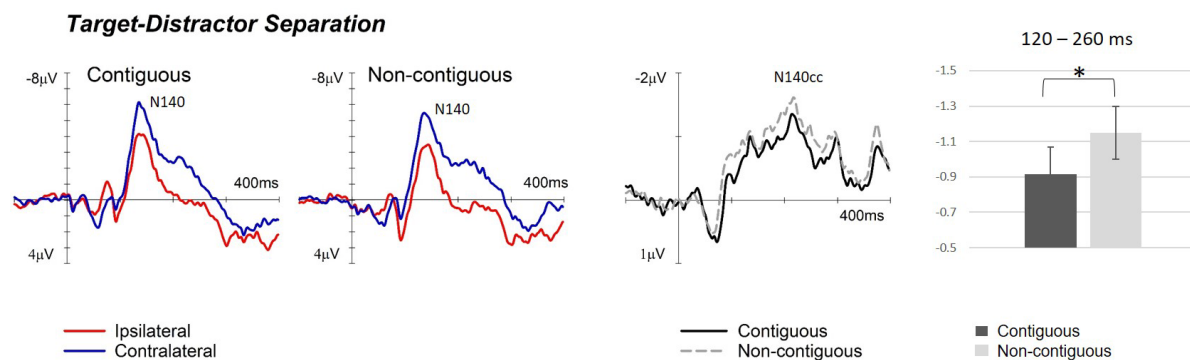


Figure 2. The effect of target-distractor separation on the N140cc component. Left and middle panels show ERPs elicited over pooled electrodes C3/4 and C5/6 contralateral (blue lines) and ipsilateral (red lines) to the hand where target and distractor were presented, either to contiguous or non-contiguous fingers, respectively. The corresponding difference waveforms showing the N140cc amplitude are depicted in the right panel, separately for contiguous (dark grey) and non-contiguous (dashed light grey) singletons. For both target/distractor separations, statistically reliable N140cc were observed.

The bar graphs represents the mean amplitude values of the N140cc for contiguous (dark grey) and non-contiguous (light grey) target and distractors, measured over pooled electrodes C3/4 and C5/6 in the 120-260 ms time window. The asterisk indicates a significant difference ($p < 0.05$) between contiguous and non-contiguous N140cc amplitudes. Error bars represent the standard errors of the means.

Figure 3 shows the effect of *posture* on the amplitude of the N140cc component. Between 120 and 260 ms post-array onset, no statistically significant amplitude difference was observed between the N140cc with splayed and touching fingers (laterality x posture interaction, $F(1, 21) = 1.6$, $p = .2$, $np^2 = 0.06$). In the following 260 - 400 ms post-array onset time window, the N140cc was larger when the fingers were touching ($M = -0.8 \mu V$, $SE = 0.19 \mu V$) than when they were splayed ($M = -0.4 \mu V$, $SE = 0.16 \mu V$). This difference was reflected in a significant interaction between *laterality and posture* ($F(1, 21) = 6.3$, $p = 0.02$, $np^2 = 0.23$) emerged. Follow-up comparisons carried out for each posture revealed the presence of reliable N140cc components when the fingers were splayed ($F(1, 21) = 6.9$, $p = 0.016$, $np^2 = 0.25$) as well as when they were touching ($F(1, 21) = 18.2$, $p < 0.001$, $np^2 = 0.47$), confirming that the laterality x posture interaction observed in this time-window reflected an amplitude difference between splayed and touching fingers.

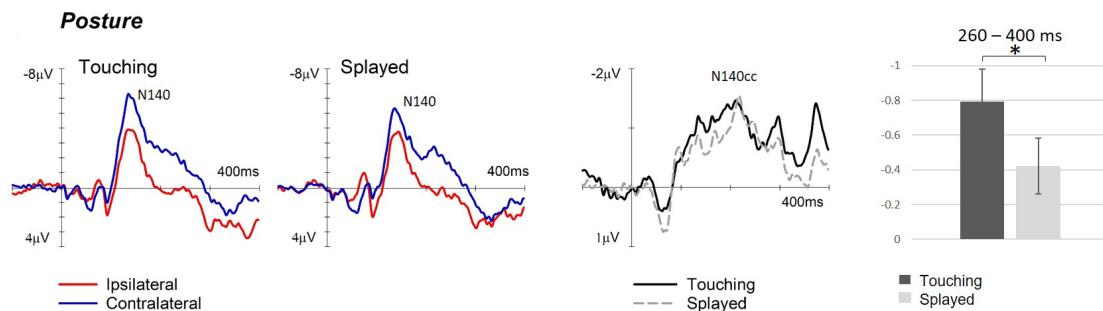


Figure 3. The effect of posture on the N140cc component. Left and middle panels show ERPs elicited over pooled electrodes C3/4 and C5/6 contralateral (blue lines) and ipsilateral (red lines) to the hand where target and distractor were presented, when the search array was delivered to touching or splayed fingers, respectively. The corresponding difference waveforms showing the lateralised N140cc components are depicted in the right panel, separately for touching (dark grey) and splayed fingers (light grey). For both finger postures, statistically reliable N140cc were observed. The bar graphs represents the mean amplitude values of the N140cc for touching (dark grey) and splayed fingers (light grey), measured over pooled electrodes C3/4 and C5/6 in the 260-400 ms time windows. The asterisk indicates a significant difference ($p < 0.05$) between touching and splayed fingers N140cc amplitudes. The error bars represent the standard errors of the means.

There were no significant interactions between *laterality*, *target-distractor separation* and *posture* in the 120-260 ms ($F(1, 21) = 0.18, p = 0.67, \eta^2 = 0.007$) or in the 260-400 ms time windows ($F(1, 21) = 0.2, p = 0.6, \eta^2 = 0.012$).

4. Discussion

The present study investigated whether the attentional selection of the target was modulated by its separation from an *ipsilateral* singleton distractor in a tactile search task in which the stimuli were delivered to three fingers of the left and right hand. The separation between these singletons within the search array was varied randomly on each trial so that they were either presented to contiguous or to non-contiguous fingers of the same hand. Furthermore, the separation between the stimuli of the search array in external space was also manipulated by asking participants to perform the same tactile search task with splayed or touching fingers. Behavioural results revealed that the localization of the tactile target in the search array was modulated by the target-distractor separation within the array *and* by their distance in external space. Specifically, the most accurate performance was observed when target and singleton distractor were presented to contiguous fingers when the fingers were touching. Thus, the attentional selection of the tactile target improved at reduced target-distractor separations both within the search array *and* according to external space (touching fingers).

In visual search tasks, the ability to select a target while ignoring a singleton distractor is mediated by their separation within the search array. Because the neural representation of visual stimuli in and beyond secondary visual areas is relatively distributed (e.g. Luck, Girelli, McDermott & Ford, 1997), distractors presented in close proximity to the target (and within the same hemifield) have been shown to degrade the attentional selection of the target (e.g. Gaspar & McDonald, 2014; Hillmire et al., 2009; 2010). Although, the way in which vibro-tactile signals are processed and integrated across different mechanoreceptors channels and different body locations remains poorly understood, evidence suggests that the somatosensory system operates in a distributed manner, similar to what observed in the visual system. For example, neurophysiological evidence has shown the presence of a distributed

body representation in the somatosensory system with most receptive fields in SII showing overlapping finger representations (e.g. Fitzgerald, Lane, Thakur & Hsiao, 2006), and some degree of overlap also in SI (e.g. McKenna, Whitsel, & Dreyer, 1982). Furthermore, while different mechanoreceptor channels are typically considered to process different tactile frequencies independently (e.g. Johansson, Landstrom & Lundstrom, 1982), recent evidence has demonstrated that already in SI some individual neurons receive peripheral input from several channels (e.g. Pei, Denchev, Hsiao, Craig & Bensmaia, 2009). Despite the fact that both somatosensory and visual system operate in a relatively distributed manner, our results suggests that the resolution of local (within-hand) ambiguity in touch operates according to fundamentally different mechanisms than those observed in visual search tasks.

The discrimination and identification of tactile frequencies is a complex process that appears to require the direct comparison between stimuli of different frequencies (Harris, Harris & Diamond, 2001; Harris, Arabzadeh, Fairhall, Benito & Diamond, 2006; Kuroki, Watanabe & Nishida, 2017). Thus, vibro-tactile frequencies cannot be fully processed pre-attentively. Indeed, in a tactile search task in which a singleton distractor was simultaneously presented with the target, the correct identification/localization of the target required the attentional processing of the potentially relevant singleton distractor (Mena et al., 2020). It is therefore likely that the correct localization of the target in the present study required in depth processing and direct comparison of the singletons frequencies. We speculate that the comparison between the potentially task-relevant frequencies of target and singleton distractor was facilitated when these singletons were contiguous because participants were able to focus on fewer items and to compare directly the singletons' frequencies. By contrast, when target and distractor were non-contiguous, the additional vibro-tactile frequency (the homogeneous distractor frequency) presented to the interleaving finger forced participants to attend non-consecutive items, hindering the comparison between the singletons' frequencies and the identification of the target location.

Notably, the distribution of attention to tactile space was not only determined by the position of the singletons within the array (and consequently by the stimulated mechanoreceptors on the skin) but also by their separation in external space. Results revealed that target localization improved for contiguous as compared to non-contiguous singletons when the fingers were touching rather than splayed, that is when their separation decreased

also according to external space. In the present study, external distance was varied through a postural manipulation of the fingers (touching and splayed). It has been suggested that postural changes of the hand can produce real time changes in the somatotopic maps of the somatosensory cortex (Longo 2015; 2017). Specifically, neuroimaging evidence has shown that the distance between the brain representation of the contiguous fingers was increased when the fingers were splayed as compared to close together (Hamada & Suzuki, 2003; 2005), revealing a certain degree of rapid plasticity within the somatosensory cortex induced by postural changes. In line with this evidence, we observed that the ability to localize the target was determined not only by its relative distance from the singleton distractor within the array but also by its distance from it in external space. The observation that performance improved at reduced target-distractor separations suggests improved frequency comparison processes when the different frequencies are delivered to neighbouring portion of skins that are also in close postural proximity.

Direct insights into the effects of target-distractor separation on the attentional mechanisms mediating tactile target selection were offered by the analysis of the electrocortical responses to the search array recorded over the somatosensory cortex ipsilateral and contralateral to the hand where the singletons were presented. In line with existing evidence (Forster et al., 2016; Ambron et al., 2018; Katus et al., 2015; Katus & Eimer, 2019; Mena et al., 2020), ERPs elicited over the hemisphere contralateral to the target (and distractor) were more negative than those elicited over the ipsilateral hemisphere from around 120 ms to 400 ms post-array onset.

Crucially, the target-singleton distractor separation within the search array modulated the amplitude of the N140cc. Reduced N140cc amplitudes were observed for contiguous than non-contiguous singletons in the earlier phase of the N140cc, measured between 120 and 260 ms post array onset (see Figure 2). Given that responses were more accurate when target and distractor were contiguous than non-contiguous, this difference cannot be interpreted as evidence for degraded target selection due to increased competitive interactions at reduced target-distractor separations (c.f. Hillmire et al., 2009). Instead, the reduced N140cc amplitude observed for contiguous than non-contiguous singletons may reflect differences in the size of the attentional focus and/or the number of items attended by participants. When the homogenous distractor was delivered in between the target and the singleton distractor

(non-contiguous trials), participants may have broadened their attentional focus attending all the ipsilateral stimuli in order to identify the target frequency and select its location. Evidence from visual search studies has indicated that the amplitude of the N2pc can reflect the size of the attentional focus, with larger N2pc amplitudes when participants were explicitly instructed to broaden their attentional focus to cover a larger portion of visual space (Zhang, Liang, Zhang, Fu & Wu, 2018). Furthermore, increasing the number of task-relevant targets within a visual search array resulted in increased N2pc amplitudes (Pagano & Mazza, 2012). Thus, in the present study, the increased N140cc amplitude observed for non-contiguous singletons may reflect a broader attentional focus or an increased number of attended items. It is also possible that the larger N140cc observed for non-contiguous singletons may reflect an increased number and/or length of attentional shifts within the hand/hemifield necessary to select the target, as suggested by visual attention studies in which a smaller N2pc amplitude was associated with fewer attention shifts (Hillmire et al., 2010).

Results also revealed an effect of posture on the N140cc amplitude during the later phase of this lateralised component (260-400 ms post-stimulus), with larger amplitudes for touching as compared to splayed fingers. Because this effect of posture on target selection was not mediated further by the target-distractor separation, it is likely to reflect a differential distribution of attention over the whole hand (search array) when the fingers were touching as compared to splayed, irrespective of the relative distance between target and singleton distractor. One possible explanation for the reduced N140cc amplitudes observed for splayed as compared to touching fingers is that attentional resources were diluted when the fingers were splayed. If the distance between contiguous fingers represented in the brain increases when the hand is open as compared to close (Hamada & Suzuki, 2003; 2005), it is conceivable to assume a reduction of attentional resources available at each finger location when the fingers were splayed because the same resources were spread across a larger portion of the somatosensory homunculus. Alternatively, it is possible that the spread of attention across the whole hand was facilitated when the fingers were touching because their reduced external distance allowed the perceptual grouping of tactile information from the array (see Gallace & Spence, 2011 for a recent review). Indeed, proprioceptive information can facilitate the integration of the tactile stimuli presented to the different fingers into an object when the fingers are close together, increasing the efficiency of the tactile search (Overvliet, Mayer,

Smeets & Brenner, 2008). Thus, the larger N140cc observed in the present study for touching than splayed fingers could reflect an increased saliency of the perceptually grouped stimuli. This may have facilitated the orienting and spread of attention across the perceptual group as suggested by evidence in the visual domain (e.g. Marini & Marzi, 2016; Conci, Gramann, Mueller & Elliott, 2006). Both these hypotheses are highly speculative and future studies should determine whether this effect of posture on tactile target selection, as indexed by the N140cc component, is primarily mediated by the position of the fingers and the underlying changes to their representation within the somatosensory cortices or by the position of the tactile stimuli and their perceptual grouping.

Results of the present study are interesting because they reveal potentially relevant differences between the mechanisms responsible for visual and tactile target selection. In contrast to the visual modality in which performance worsened when the target - singleton distractor separation was reduced, we observed improved target localization when the two singletons were contiguous. As discussed earlier, it is likely that the discrimination between singleton tactile frequencies and the selection of the target in the present study required the attentional processing of both singleton items. However, this observation does not explain the differences between the pattern of results observed in tactile and visual search studies. Indeed, evidence has shown hindered performance for reduced target-distractor separations in visual tasks both when participants had to completely ignore the singleton distractor (Hillmire et al., 2010) as well as when they had to compare it with the target, that is when both target and singleton distractor had to be attended (e.g. Yamani, McCarley, Mounts & Kramer, 2013; Bahcall & Kowler, 1999). Thus, impaired target selection in visual tasks was present at reduced target-distractor separations even when the distractor had to be endogenously attended. Together these findings suggest that different mechanisms mediate the attentional selection of task-relevant stimuli in vision and touch.

Furthermore, our results point to an intriguing dissociation between tactile selection mechanisms within and between the different hands. The effect of target-distractor separation on target selection has been primarily investigated in tactile distractor-interference tasks in which one target and one distractor were presented to fingers of the same or of different hands. In these tasks, performance improved when stimuli were presented to the different hands as compared to the same hands, that is, when the distance

between stimuli increased (e.g. Craig, 1985; Evans & Craig, 1991; 1992; Evans, Craig & Rinker, 1992). In line with these studies, performance worsened when a singleton distractor was presented to the same hand as the tactile target than to the opposite hand in an additional singleton task (including one target, one singleton distractor and two homogeneous distractors) (Mena et al., 2020). This confirmed stronger target-distractor interference when both singletons were delivered to the same hand, at reduced target-distractor separations. By contrast, the target-distractor interference between tactile stimuli *within the same hand* has been scarcely investigated (see Evans et al., 1992, for evidence of no effect of distance within the hand in one such manipulation). In the present study, the strongest interference between target and singleton distractor was observed for non-contiguous as compared to contiguous singletons, that is, when the within-hand separation between singletons was increased. Taken together these findings reveal different effects of target-distractor separation on target selectivity within and between the hands. In line with a growing body of evidence these findings suggest that different attentional selection mechanisms are engaged to solve the competition between tactile stimuli presented to the same hand (within-hand selectivity) and to different hands (between-hand selectivity) (c.f. Eimer & Forster, 2003; Gillmeister, Sambo & Forster, 2010; Overvliet et al., 2010).

To summarize, the present study demonstrated that the selection of a tactile target in an additional singleton tactile search task improved when the two singletons were delivered to contiguous rather than non-contiguous fingers and when the fingers of both hands were touching rather than splayed. Importantly, the mechanisms of tactile target selection indexed by the N140cc were modulated by the target-distractor separation within the search array. The larger N140cc amplitudes observed at increased target-distractor separations suggests a broader attentional focus or an increased numbers of within-hand attention shifts for non-contiguous than contiguous target and distractor singletons. In addition, the N140cc amplitude was also affected by the postural manipulation of external distance between the stimuli of the search array (fingers splayed vs. touching). We observed larger N140cc components when the fingers were touching rather than splayed, possibly suggesting a facilitation of the attentional spread across the hand. Together these evidences suggest that mechanisms of tactile selectivity (at least those responsible for the selection of relevant

stimuli presented on the same side of the body, i.e. within-hand selectivity) may be different from those reported in the visual domain.

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