Behavioral and Electrophysiological Evidence for Intertrial Priming of Pop-out in Touch

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Abstract

■ In mixed-features search tasks, the target-defining feature changes unpredictably across trials. Responses are faster when the same feature is repeated across successive trials. This effect, known as intertrial priming of pop-out (PoP), suggests that the selection of a perceptually salient singleton target is modulated by the properties of the preceding search array. To investigate whether PoP can be observed in touch, we developed a mixed-features search task in which a singleton target was presented simultaneously with three homogeneous distractors to the index and middle fingers of the left and right hands. The target-defining vibrotactile frequency varied across trials (either a high-frequency target among low-frequency distractors or vice versa) so that on half of the trials, the singleton frequency was repeated on successive trials, while on the other half, it was alternated. To investigate the presence and the mechanisms underlying PoP in touch, behavioral and ERPs were recorded. Specifically, the N140cc component was used as a marker of spatial selective attention in touch. In line with visual search studies, improved performance for both RTs and accuracy was observed when the singleton target feature was repeated across trials than when it was alternated. Importantly, the N140cc component showed larger amplitudes on repetition compared with change trials, demonstrating that the attentional selection of a tactile target was modulated by PoP. Results demonstrate for the first time that PoP effects emerge also during the search for a tactile target. ■

INTRODUCTION

In visual search tasks, participants have to find a relevant target among irrelevant distractors. The time necessary to find the target depends on several factors, including the physical salience of the items in the array, their number and the task requirements, and the constancy of their features across trials. For example, in "mixed-features search task," a singleton target is presented among homogeneous distractors. However, the target-defining feature is not fixed but swaps unpredictably with the distractors feature across trials (a red target among green distractors or a green target among red distractors; e.g., Bacon & Egeth, 1994; Bravo & Nakayama, 1992). In these tasks, participants prioritize the item that differs from the others along a specific dimension, directing attention to the location in the array with the strongest local feature contrast (singleton detection mode; e.g., Bacon & Egeth, 1994; Theeuwes, 1992). Larger distractors numbers are assumed to amplify the saliency of the target because of increased target-distractors local contrast (Wolfe, 1994; Bravo & Nakayama, 1992; Sagi & Julesz, 1987) and/or stronger spatial grouping between distractors (Bacon & Egeth, 1991), resulting in improved search performance.

In addition to bottom–up and top–down factors, search performance is impacted by selection history—the presentation of a particular sequence of trials—which increases the likelihood of attending to stimuli sharing the feature of a previously attended stimulus (e.g., Luck, Gaspelin, Folk, Remington, & Theeuwes, 2021; Failing & Theeuwes, 2018; Tseng, Glaser, Caddigan, & Lleras, 2014; Awh, Belopolsky, & Theeuwes, 2012; see Anderson et al., 2021, for a recent review). In mixed-features search tasks, performance is significantly improved when the target feature is repeated across consecutive trials, compared with when it changes (e.g., Maljkovic & Nakayama, 1994). This intertrial repetition effect known as priming of pop-out (PoP) has been observed across different tasks and stimulus features (e.g., Becker, 2008; Huang, 2004; Hillstrom, 2000; Maljkovic & Nakayama, 1994).

The mechanisms responsible for PoP and the specific processing stage(s) impacted by this priming effect have been widely debated. Many researchers support the view that PoP emerges from a facilitation of the target attentional selection driven by the repetition of the target feature across consecutive trials (visual selection accounts; e.g., Martini, 2010; Becker & Horstmann, 2009; Lee, Mozer, & Vecera, 2009; Müller & Krummenacher, 2006; Kristjánsson, 2006; Maljkovic & Martini, 2005; Wolfe, Butcher, Lee, & Hyle, 2003; Chun & Nakayama, 2000). Conversely, proponents of postselection accounts claim that PoP emerges after the target is found. Some posit that memory mediates PoP, specifically the retrieval from episodic memory of the search-relevant events on the

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previous trial (e.g., Huang, 2004; Hillstrom, 2000). Others suggest that PoP is determined by the repetition of the association between the target feature and a specific response (e.g., Theeuwes, Reimann, & Mortier, 2006; Mortier, Theeuwes, & Starreveld, 2005; Cohen & Magen, 1999). More recently hybrid accounts have tried to integrate both visual selection and postselection accounts, suggesting that PoP may impact both earlier and later stages of visual search (Yashar, 2013; Yashar & Lamy, 2011; Lamy, Yashar, & Ruderman, 2010; Meeter & Olivers, 2006).

Neuroimaging evidence shows that PoP modulates a network of areas associated with top–down attentional control—including the FEFs, the bilateral intraparietal sulci, the ACC, and the posterior parietal cortex—as well as visual areas involved in the processing of relevant features (Brinkhuis, Kristjánsson, Harvey, & Brascamp, 2020; Rorden, Kristjànsonn, Revill, & Saevarsson, 2011; Kristjánsson, Vuilleumier, Schwartz, Macaluso, & Driver, 2007). Importantly, direct evidence that the effects of PoP impact early visual processing stages comes from psychophysiological studies in humans measuring the N2pc component in PoP tasks (e.g., Tay, Harms, Hillyard, & McDonald, 2019; Christie, Livingstone, & McDonald, 2015; Eimer, Kiss, & Cheung, 2010; Olivers & Hickey, 2010). The N2pc is an enhanced negativity contralateral to the target side, considered the correlate of the attentional selection of visual targets. Specifically, it marks the moment when attention is focused on potentially task-relevant items after the initial preattentive processing of the array (e.g., Christie et al., 2015; Woodman & Luck, 1999; Eimer, 1996; Luck & Hillyard, 1994). In mixed-features search tasks, the N2pc component is elicited earlier and has larger amplitudes on repetition compared with change trials (Tay et al., 2019; Christie et al., 2015; Eimer et al., 2010; Olivers & Hickey, 2010), demonstrating that PoP effects already modulate early processing stages (see also Westerberg, Maier, Woodman, & Schall, 2020; Bichot & Schall, 2002, for converging physiological results in monkeys).

While this body of work shows that PoP facilitates the attentional selection of the target, the exact mechanisms through which priming modulates visual attention remain controversial (see Ramgir & Lamy, 2022; Westerberg & Schall, 2021, for reviews). For example, some researchers suggest that PoP impacts directly the relative priority weight assigned to different items in the search array (attentional guidance), biasing the weight of the repeated target feature (e.g., Wolfe, 2021; Theeuwes, 2018; Awh et al., 2012; Müller, Töllner, Zehetleitner, Geyer, & Rangelov, 2010; Kristjánsson, 2006; Huang, 2004; Hillstrom, 2000; Found & Müller, 1996; Müller, Heller, & Ziegler, 1995). According to others, PoP modulates the processing of the repeated target feature only after attention has been allocated based on attentional priority (cf. Ramgir & Lamy, 2022; Hillstrom, 2000). As such, PoP effects are contingent on the specific levels of target saliency, being reduced or eliminated with high-saliency targets (e.g., Meeter & Olivers, 2006). However, evidence from studies investigating interactions between PoP and the physical salience of the target—which is known to affect directly attentional priority (e.g., Gaspar & McDonald, 2014; Töllner, Zehetleitner, Gramann, & Müller, 2011; Itti & Koch, 2000, 2001)—is inconclusive, and results are largely dependent on the specific target feature considered (cf. Becker & Ansorge, 2013; Meeter & Olivers, 2006).

Because most studies of PoP have been carried out in the visual domain, it remains unclear whether the mechanisms responsible for PoP are exclusively engaged during the selection of visual information or whether analogous processes can also impact the selection of information from different sensory channels. Intertrial feature priming effects have been recently described in the auditory domain (e.g., Klein & Stolz, 2015; Dyson, 2010; Dyson & Alain, 2008a, 2008b; see Addleman & Jiang, 2019, for a recent review). For example, the repetition of a nonspatial target feature such as pitch on consecutive trials resulted in faster responses compared with trials in which this feature changed across trials (Dyson & Alain, 2008b). However, evidence that auditory PoP effects modulate the attentional selection of the target is still lacking. Thus, questions about the modality-specific or modality-general nature of PoP remain open.

The aim of the present study was to investigate for the first time the presence of PoP in touch. We asked participants to report the location of a singleton target presented with three homogeneous distractors to the index and middle finger of their left and right hand (Figure 1). In this tactile mixed-features task, target and distractors were defined by different vibrotactile frequencies, which swapped unpredictably across trials (either one high-frequency vibration—"buzz"—with three low-frequency ones—"taps"—or vice versa). The presence of a tactile PoP effect should be reflected in the behavioral analyses by improved search performance on repetition compared with change trials.

Importantly, to investigate whether the repetition or change of the target feature (vibrotactile frequency) on consecutive trials directly impacted the attentional selection of the target, we measured the N140cc component, a reliable electrophysiological marker of target selection in touch (Forster, Tziraki, & Jones, 2016; Katus, Grubert, & Eimer, 2015), analogous to the N2pc in the visual modality. This lateralized ERP component is an enhanced negativity contralateral to the target side, elicited over central electrodes (close to somatosensory areas, e.g., C3/4) from about 120 msec post-array onset (Gherri, Fiorino, Iani, & Rubichi, 2023; Gherri, Zhao, & Ambron, 2021; Mena, Lang, & Gherri, 2020; Katus & Eimer, 2019; Ambron, Mas-Casadesús, & Gherri, 2018; Katus et al., 2015). If PoP effects in touch impact the attentional selection of the tactile target, we expect differences between the timing and/or amplitude of the N140cc elicited on repetition versus change trials.

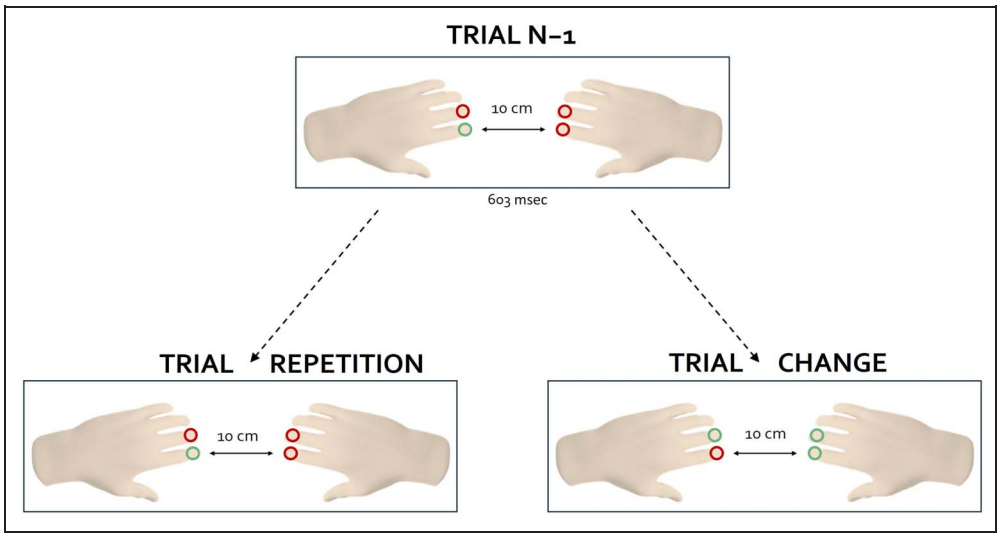

Figure 1. Illustration of the different types of trial sequences. Search arrays consisted of one target (either a buzz or a tap vibrotactile stimulus) presented with three homogeneous distractors (tap or buzz vibrotactile stimuli, respectively). The four-item search array was presented to the index and middle finger of the left and right hand. Across successive trials, target and distractors frequencies were either repeated (Repetition) or alternated (Change). Participants were instructed to determine the exact location of the target (middle vs. index finger location) by pressing one of two pedals under the same foot (the pedal under the toes to indicate the middle finger or the pedal under the heel to indicate the index finger).

Finally, previous studies in touch described search asymmetries between different search arrays (i.e., higher frequency target surrounded by lower frequency distractors vs. the opposite pairing; Mena et al., 2020), suggesting differences in target saliency based on specific vibrotactile frequencies. To shed further light on the attentional mechanisms responsible for PoP in touch, we exploited these search asymmetries to investigate whether the N140cc is jointly modulated by target salience and PoP.

METHODS

Participants

The behavioral PoP effect (difference between RTs on repetition vs. change trials) reported in visual search tasks is a relatively large and robust phenomenon (dz ≥ 0.7; e.g., Lamy et al., 2010; Meeter & Olivers, 2006). An a priori power analysis using G*Power 3.1 (Faul, Erdfelder, Buchner, & Lang, 2009) indicated that 18 participants are sufficient to detect an effect of similar size (dz = 0.7, two-tailed, alpha = .05, power = .80). Fewer studies have investigated PoP with ERP measures. The effect size reported for PoP modulations of the N2pc component (both in terms of timing and amplitudes) appears to be somehow smaller than the behavioral effect. Calculations based on the results of Eimer et al. (2010) and Olivers and Hickey (2010) suggest that the effect of PoP on the N2pc is closer to dz = 0.5/dz = 0.6, which would require a sample ranging between 23 and 33 participants (two-tailed, alpha = .05, power = .80). Given that this is the first study to investigate PoP in the tactile modality and considered that this type of tactile search tasks tends to be quite challenging for participants (with many excluded based on overall performance; e.g., see Gherri et al., 2023), we tested a sample of 42 participants. Eleven participants were subsequently excluded from the analyses due to low accuracy rates in the behavioral task (overall accuracy rates < 60%). In the final sample, task accuracy ranged between 60% and 92%, with a mean accuracy of 78%. Following the ERP data processing procedure, one further participant was excluded due to a low number of trials (less than 60% of trials left after the rejection of ERP artifacts for at least one of the conditions). Thus, the final sample included 30 participants (14 female and 16 male, *M* age = 21.06 years, *SD* age = 1.81 years; 22 right-handed and eight ambidextrous; Oldfield, 1971). All participants had normal or corrected-to-normal vision and no history of neurological disorders.

This project was approved by the Comitato di Bioetica of the University of Bologna (prot. no. 0094164, 04-04-2023) and followed the Helsinki Declaration principles. All participants signed an informed consent before starting the experiment.

Apparatus, Stimuli, and Procedure

Participants were tested in a dimly lit room. They sat at a table, resting their hands palms down on it (with a distance of 10 cm between right and left indexes). The hands were rotated medially (at an angle of approximately 45°) until the index and middle fingers of each hand were approximately aligned and parallel to each other, so that the middle fingers were spatially on top and the index fingers were spatially on the bottom (Figure 1). To hide the hands from view, a black cardboard panel (50 × 70 cm) was placed above the hands. A white pin in the middle of the cardboard panel was used as fixation point. To mask the sounds made by the tactile stimulators, one speaker was positioned on the table between the hands under the

cardboard panel and presented white noise (65 dB SPL) throughout the experimental blocks. When explicitly asked, no participant reported perceiving any sounds associated with the activation of the tactile stimulators. Tactile stimuli were presented using 12 V solenoids (Heijo Research Electronics) driving a metal rod with a conical tip. The tip of the tactile stimulators touched the skin whenever a current passed through the solenoid. Four solenoids were attached with adhesive medical tape to the inner side of the top phalanx of the left and right index and middle fingers. Participants responded using two pedals vertically arranged and positioned under the same foot (top and bottom pedals).

The singleton target was either a buzz vibration (high frequency) presented simultaneously with three homogeneous tap distractors (low frequency), or a tap vibration presented with three buzz distractors. Buzz vibrations consisted of a 3-msec single tap every 17 msec. This cycle was repeated 10 times during the 603-msec array duration. Taps consisted of a 20-msec single tap every 280 msec. This was repeated two times during the 603-msec stimulus duration (Forster et al., 2016).

Each trial started with a 300-msec empty interval, which was followed by the presentation of the four-item search array (603-msec duration), simultaneously delivered to the index and middle fingers of the left and right hand. The search array started and ended with all the stimulators touching the skin simultaneously to avoid participants using the offset of the stimuli to complete the task. Stimulus presentation was followed by a 1800-msec interval, which was used to collect foot responses.

Each participant completed 12 blocks of 64 trials (in total 768 trials). In each block, on half of the trials, the target was a buzz vibration, while on the remaining half, it was a tap vibration. Furthermore, the target was equally likely to be presented at one of the four possible locations within the array: to the middle or to the index of the left or right hand (16 times per block). Therefore, on 32 trials, the target was delivered to the middle finger (top location) and required a top pedal response (toes), while on the remaining 32 trials, it was presented to the index fingers (bottom location), requiring a bottom pedal response (heel). Trials were presented in a pseudorandom sequence such that each array type (singleton buzz target or tap target) was equally likely to be preceded by a trial (trial $N - 1$) with the same target and distractor frequency (repetition condition) or by a trial where the frequency of target and distractors was reversed (change condition).

Participants were instructed to always keep their eyes on the central fixation and to respond to the target location (target presented to the middle or index finger, regardless of stimulated hand) by pressing the pedal as fast and as accurately as possible. This compound task was developed to dissociate the response-relevant feature (target finger location) from the target-defining feature (frequency) to control for the effects of stimulus–response S-R repetition versus alternation in the sequential analysis (e.g., Hommel, 2004). To avoid ERP contamination from motor responses, the responding foot operating the top and bottom pedals was changed after six consecutive blocks of trials, so that, overall, participants completed six blocks with their left foot and six with their right foot (the starting foot—left vs. right—was counterbalanced across participants). Prior to the beginning of the experiment, participants completed a practice session in which their average accuracy had to reach 60% before completing the experimental session. Whenever needed, further blocks of training were delivered until the required accuracy rate was reached. At the end of each block, participants received feedback about their performance (average response time and accuracy).

EEG Recording and Data Analysis

EEG was recorded with a BrainAmp amplifier system (500 Hz sampling rate) from 64 active electrodes positioned according to 10–20 system. EEG data were analyzed using Brain Vision Analyser (Version 2.3.0.8300). EEG was digitally re-referenced to the average of the left and right earlobe and was digitally filtered offline (band-pass filtered 0.1–40 Hz and notch filter 50 Hz). The EEG was epoched into 600-msec intervals, starting 100 msec before and ending 500 msec after the search-array onset. Trials with eye blinks, horizontal eye movements, and other artifacts (voltage exceeding $\pm$ 80 mV at any electrode sites) were excluded from further analysis. Participants with less than 60% of the trials in at least one of the repetition or change conditions were excluded from the analyses. This led to the exclusion of one participant. The average number of trials included in each condition for the remaining participants was 341 for the repetition condition (89% of the trials) and 339 for the change condition (88.3% of the trials).

ERPs elicited by the presentation of the search array were averaged relative to a 100-msec prestimulus baseline separately for all conditions (repetition and change) and target side (left vs. right side). The N140cc was quantified for each participant and for each experimental condition based on ERP mean amplitudes obtained at lateral central electrodes C3/4 (where this component was maximal, in line with previous studies; e.g., Forster et al., 2016) over the hemisphere contralateral and ipsilateral to the target side. ERP analyses in previous N140cc studies considered two consecutive time windows to characterize the functional significance of this long-lasting lateralized component, identifying an earlier and a later phase of the N140cc (cf. Gherri et al., 2021, 2022; Mena et al., 2020; Katus & Eimer, 2019; Ambron et al., 2018; Forster et al., 2016). Increasing evidence suggests that the N140cc component is likely to include more than a single attentional process, not only because of its long duration but also because the early and late phases are sensitive to different experimental manipulations (e.g., Gherri, White, & Ambron, 2022; Gherri et al., 2021; Mena et al., 2020; Ambron et al., 2018). Accordingly, mean amplitude values

in the present study were computed within two consecutive time windows, 140–250 and 250–360 msec post-array onset. These time windows were chosen based on previous studies using stimuli (Forster et al., 2016) and task (Mena et al., 2020) similar to those of the present study. To investigate whether intertrial PoP effect modulates the amplitude of the N140cc component, repeated-measures ANOVAs were conducted on the mean amplitude values measured at electrodes pair C3/4 for the factors Trial Type (repetition vs. change), Laterality (hemisphere contralateral vs. ipsilateral to the target side), and Target Frequency (buzz vs. tap). In these analyses, the statistical presence of the N140cc lateralized components is reflected by the main effect of the factor Laterality, indicating significant differences between the ERP waveforms measured over the hemispheres contralateral and ipsilateral to the target side/hand. Importantly, two were the results of interest in this omnibus ANOVAs. First, we were interested in Trial Type × Laterality interactions to investigate whether the repetition or change of the target feature (vibrotactile frequency) across consecutive trials modulated the N140cc amplitude. Following significant Trial Type × Laterality interactions, follow-up pairwise comparisons were carried out separately for each trial type (repetition and change) to determine whether statistically reliable N140cc components were present for both repetition and change trials. In addition, to investigate whether PoP effects on the N140cc differed across target frequencies, we were also interested in the three-way interaction between Target Frequency, Trial Type, and Laterality. To determine whether modulations of the N140cc component by trial type (that is Trial Type × Laterality interactions) were present for each target frequencies (buzz vs. tap), follow-up analyses were carried out separately for buzz and tap targets including the factors trial type and laterality.

Because visual inspection of the ERP waveforms showed the presence of an early lateralization partly overlapping with the P45 and N80 components (observed between 50 and 80 msec post-array onset), additional exploratory analyses were included in the Results section. These analyses aimed to investigate the presence and characteristics of this early lateralization. Analogous to the analyses conducted for the N140cc, this exploratory ANOVA included the factors Trial Type (repetition vs. change), Laterality (hemisphere contralateral vs. ipsilateral to the target side), and Target Frequency (buzz vs. tap).

To investigate the onset of the N140cc component on repetition and change trials, we carried out two separate onset analyses. The classic method to measure the onset of a lateralized component is the fractional peak latency obtained from jackknife-averaged ERPs (e.g., Kiesel, Miller, Jolicœur, & Brisson, 2008; Ulrich & Miller, 2001; Miller, Patterson, & Ulrich, 1998) within the time window of interest. However, the absence of clear peaks in the N140cc components, typical of tactile search tasks with vibrotactile frequencies, makes this approach prone to distortions. Thus, in addition to the classic jackknife procedure, we also analyzed the data following the procedure described by Smulders (2010), which estimates individual onset latencies and has already been used to measure the onset of components such as the N400, which is typically lacking a clear peak. Because the peak of the N140cc observed on tap target trials emerged earlier than the one on buzz target trials (see Figure 5), differences in the N140cc onset were measured separately for tap and buzz target trials. Two separate time windows were used for peak detection for each target frequency, the 145–185 msec time window for tap target trials and the 180–240 msec time window for buzz target trials.

To assess the effect of PoP on behavioral data, mean RTs and error rates were analyzed separately. Only trials in which participants responded correctly in the preceding trial ($N - 1$) were included in the RT and error rate analyses. In addition, only responses recorded on accurate current trials (N) were included in the RT analysis. RTs exceeding 2.5 standard deviations above or below the mean (calculated separately for each participant and trial type) were excluded from the RT analysis. A total of 12,931 trials (6077 change trials and 6854 repetition trials) was included in the RT analysis (M = 431 trials per participant). Mean RTs and error rates were then submitted to separate repeated-measures ANOVAs with Trial Type (repetition vs. change) and Target Frequency (buzz vs. tap) as a within-subject factors. Where appropriate pairwise comparisons were performed with paired sample t tests, and all resulting p values were corrected using the Holm method.

RESULTS

Behavioral Results

The analysis of error rates (Figure 2, bar graph) revealed a main effect of Trial Type, $F(1, 29) = 13, p = .001, \eta_p^2 = .309$). Participants made more errors on change trials (M_{error} = 23.4%, SE = 1.7) than on repetition trials (M_{error} = 20.3%, SE = 1.4). Furthermore, the main effect of Target Frequency, $F(1, 29) = 18, p < .000, \eta_p^2 = .383$, revealed fewer errors for buzz targets (M_{error} = 15.5%, SE = 1.8) than for tap targets (M_{error} = 28.3%, SE = 2.4). No Trial Type × Target Frequency interaction emerged, $F(1, 29) = 0.267, p = .60, \eta_p^2 = .009$.

The analysis of RTs (Figure 2, line graph) revealed a significant main effect of Trial Type, $F(1, 29) = 475, p < .001, \eta_p^2 = .621$. Participants were faster when the target was repeated across successive trials (M = 881 msec, SE = 15.3) than when it changed (M = 911.4 msec, SE = 16.4). Furthermore, there was also a main effect of Target Frequency, $F(1, 29) = 71.2, p < .001, \eta_p^2 = .711$, with faster responses to buzz targets (M = 859.3 msec, SE = 16.4) than to tap targets (M = 933 msec, SE = 16.2). Results revealed also a significant Trial Type × Target Frequency interaction, $F(1, 29) = 78.35, p = .000, \eta_p^2 = .730$. Pairwise comparisons carried out separately for each target frequency showed faster responses for target repetition

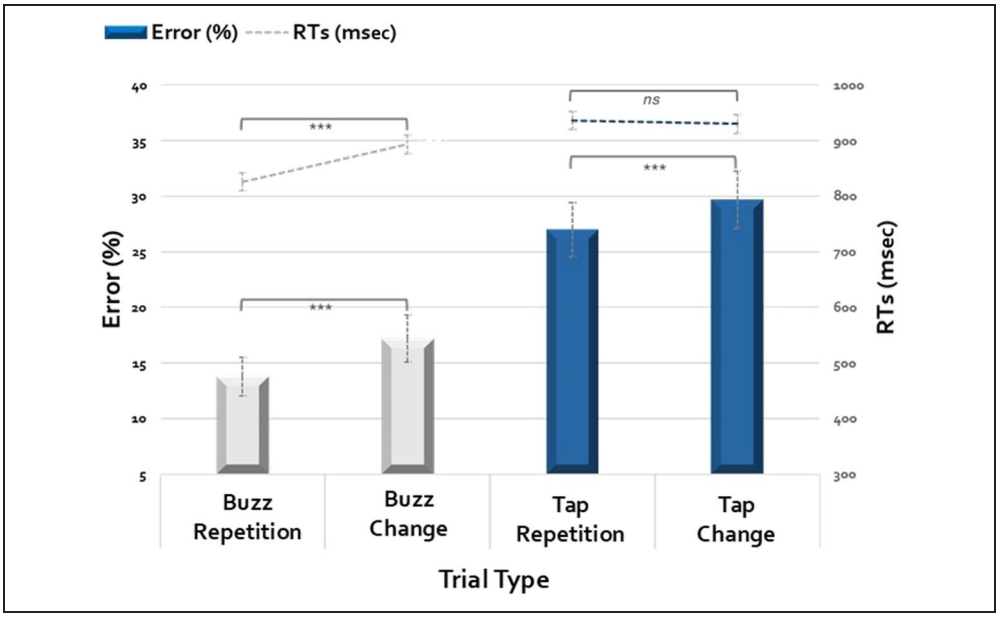

Figure 2. Behavioral results. Mean error rates (bar graph) and mean RTs (line graph) shown for the Trial Type × Target Frequency interaction. Error bars represent the *SEM*s.

(M = 825.5 msec, SE = 16.5) than for target change (M = 893 msec, SE = 16.8) when the target was a buzz, $t(29) = -11.44, pc < .001, d = -2$. No difference emerged when the target was a tap, $t(29) = 2, pc = .28, d = 0.2$.

ERP Results

Early Lateralization (50–80 msec)

As discussed earlier, increasing evidence has shown that PoP improves the attentional selection of the target (as demonstrated by evidence from N2pc studies in the visual domain, e.g., Tay et al., 2019; Eimer et al., 2010; Olivers & Hickey, 2010). However, it remains debated whether PoP impacts directly the processes preceding attentional selection, such as attentional guidance (i.e., the target is localized faster on repetition trials) or whether it helps the target processing after the target has been localized (see Ramgir & Lamy, 2022, for a recent review). To demonstrate that PoP impacts directly attentional guidance, some researchers have argued that ERPs elicited before the N2pc component should be modulated by PoP (e.g., Ramgir & Lamy, 2022; Olivers & Hickey, 2010). However, only one study to date has demonstrated PoP modulations of the earlier P1 component in a visual search task in which participants had to keep the target feature in working memory (Olivers & Hickey, 2010).

Because visual inspection of ERP waveforms (Figure 5, right panel, top) suggested the presence of early lateralizations modulated by trial type and target frequency, we tested whether early stages of processing (preceding the N140cc) were impacted by PoP. To this aim, an exploratory statistical analysis was carried out on ERP mean amplitude values measured between 50 and 80 msec post-array onset.

Results showed no significant main effects for Trial Type, $F(1, 29) = 1.635, p = .21, \eta_p^2 = .053$; Target Frequency, $F(1, 29) = 2.146, p = .15, \eta_p^2 = .069$; or Laterality, $F(1, 29) = 0.9, p = .35, \eta_p^2 = .03$. However, the interaction between Target Frequency × Laterality was significant, $F(1, 29) = 13.2, p < .001, \eta_p^2 = .313$. Pairwise comparisons between ipsilateral and contralateral ERPs carried out separately for each target frequency showed a reliable lateralization for buzz target trials, $t(29) = -3.6, pc < .001, d = -0.6$ (M = 0.3 μV, SE = 0.044), which only approached significance for tap target trials, $t(29) = 1.9, pc = .067, d = 0.3$ (M = −0.24 μV, SE = 0.063). As shown in Figure 5, the polarity of this early lateralization was determined by target frequency. On higher saliency (buzz) target trials, this component was elicited contralateral to the target side (i.e., the hemisphere contralateral to the target was more positive than the ipsilateral one). By contrast, when the target was less salient (tap) than the distractors, this early lateralization was ipsilateral to the target (contralateral to the side of the two salient distractors). Based on the observation that the following N140cc was elicited contralateral to the target side regardless of target saliency, this early lateralization may reflect an early representation of salient items in the array.

Although visual inspection of these waveforms suggested that both these lateralizations were further modulated by PoP with reduced amplitudes when the target-defining feature repeated across trials compared with when it changed, these amplitude differences were not statistically reliable, as shown by the absence of a significant three-way interaction between Trial Type × Target Frequency × Laterality, $F(1, 29) = 0.56, p = .46, \eta_p^2 = .019$. Therefore, it remains to be established whether lateralized ERP components elicited before the N140cc

can be considered an index of attentional guidance and whether these can be directly modulated by PoP. The exact functional meaning of early lateralizations observed before the N140cc onset in vibrotactile search tasks (cf. Gherri et al., 2023) remains to be clarified in future studies.

N140cc Amplitude

Statistical analyses of the N140cc mean amplitude values measured between 140–250 and 250–360 msec post-array onset showed significant main effects of Laterality for both time windows (140–250 msec: $F(1, 29) = 82.76, p < .001$, $\eta_p^2 = .74$; 250–360 msec: $F(1, 29) = 38, p < .001$, $\eta_p^2 = .567$), demonstrating the reliable presence of the lateralized N140cc component. Results also showed main effects of Target Frequency in both time windows (140–250 msec: $F(1, 29) = 12.47, p = .001$, $\eta_p^2 = .301$; 250–360 msec: $F(1, 29) = 26.18, p = .000$, $\eta_p^2 = .474$). Nonlateralized ERP amplitudes were reduced for tap compared with buzz targets (140–250 msec: M tap $= -5.67$ μV, $SE = 0.767$ vs. M buzz $= -6.49$ μV, $SE = 0.756$; 250–360 msec: M tap $= -2.48$ μV, $SE = 0.450$ vs. M buzz $= -3.72$ μV, $SE = 0.452$).

The N140cc amplitude was reduced when the target was a tap compared with a buzz (see Figure 5, black vs. gray lines, respectively), as demonstrated by significant Target Frequency × Laterality interactions in both time windows (140–250 msec: $F(1, 29) = 30.69, p = .000$; $\eta_p^2 = .514$; 250–360 msec: $F(1, 29) = 38.83, p = .000$, $\eta_p^2 = .573$).

The interaction of interest, Trial Type × Laterality, was significant in both time windows (140–250 msec: $F(1, 29) = 23.92, p = .000$, $\eta_p^2 = .452$; 250–360 msec: $F(1, 29) = 11.30, p = .002$, $\eta_p^2 = .280$), revealing that the N140cc amplitude was larger when the target feature was repeated across trials than when it was changed. Pairwise comparisons between ipsilateral and contralateral ERP amplitudes carried out separately for each Trial Type confirmed the presence of statistically reliable N140cc components on repetition trials (140–250 msec: $t(29) = 7.85, pc < .001, d = 1.4, M$ repetition $= -0.926$ μV, $SE = .093$; 250–360 msec: $t(29) = 6.54, pc < .001, d = 1.2$, M repetition $= -0.693$ μV, $SE = 0.112$), as well as on change trials in both time windows (140–250 msec: $t(29) = 6.341$, $pc < .001, d = 1.4, M$ change $= -0.522$ μV, $SE = 0.087$; 250–360 msec: $t(29) = 5.33, pc < .001, d = 0.9$, M change $= -0.552$ μV, $SE = 0.09$. This interaction is shown in Figure 3 (left panels) in which ERP waveforms elicited over the hemisphere ipsilateral (red lines) and contralateral (blue lines) to the side of the tactile target (electrodes C3/4) are depicted separately for trials in which the target was repeated and trials in which the target changed across trials. The corresponding difference waveforms (Figure 3, right panel) were obtained by subtracting ERPs elicited at electrodes ipsilateral to the target from contralateral ERPs. Finally, the scalp distributions of the N140cc observed in the 140–250 and 250–360 msec post-array intervals are shown in Figure 4.

Finally, the interaction of interest between trial type and laterality was further modulated by target frequency in the early time window (140–250 msec: $F(1, 29) = 4.44, p = .044$, $\eta_p^2 = .133$) but not in the late one (250–360 msec: $F(1, 29) = 2.22, p = .15$, $\eta_p^2 = .068$; see Figure 5). To

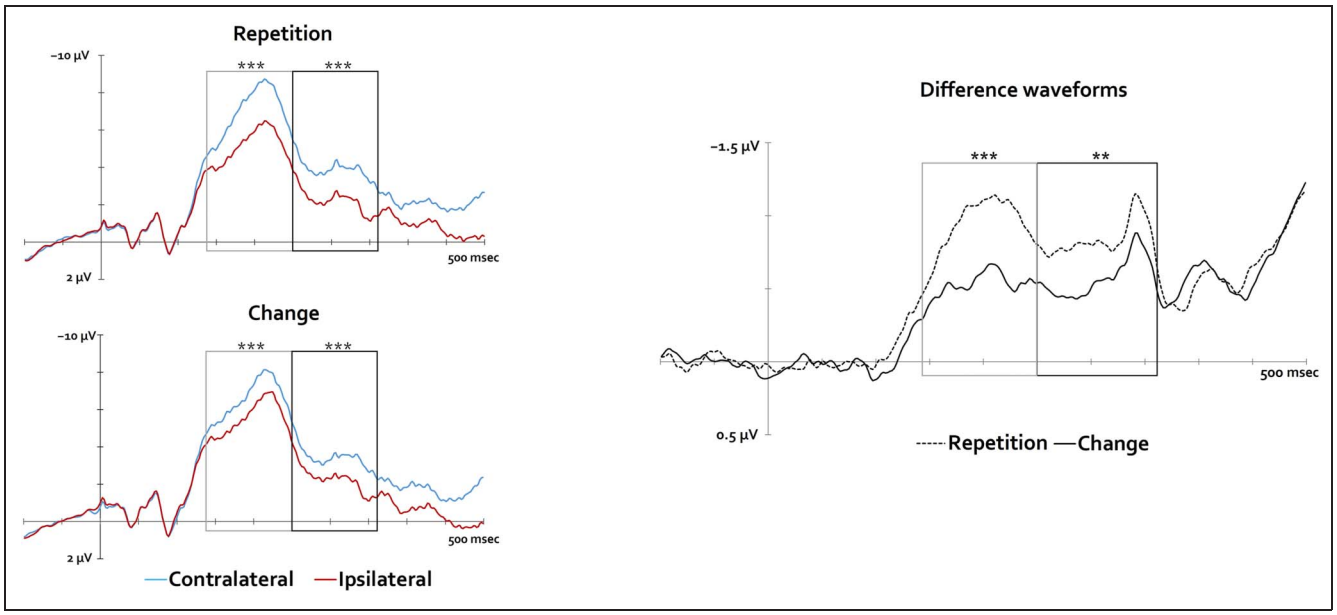

Figure 3. Left: Grand-averaged waveforms obtained in the 500-msec interval after search array onset at lateral central electrodes C3/4 contralateral (blue line) and ipsilateral (red line) to the target side. ERP waveforms are shown separately for trials in which the target frequency was repeated (top) and when it changed (bottom) across consecutive trials. Right: Difference waveforms obtained in the 500-msec interval after search array onset by subtracting ERPs elicited at electrodes C3/4 ipsilateral to the side of the target from contralateral ERPs. Difference waveforms are shown separately for trials in which the target frequency repeated (dashed line) and changed across consecutive trials (solid line). Line boxes represent the consecutive time windows considered for the amplitude analyses (140–250 and 250–360 msec post-array onset).

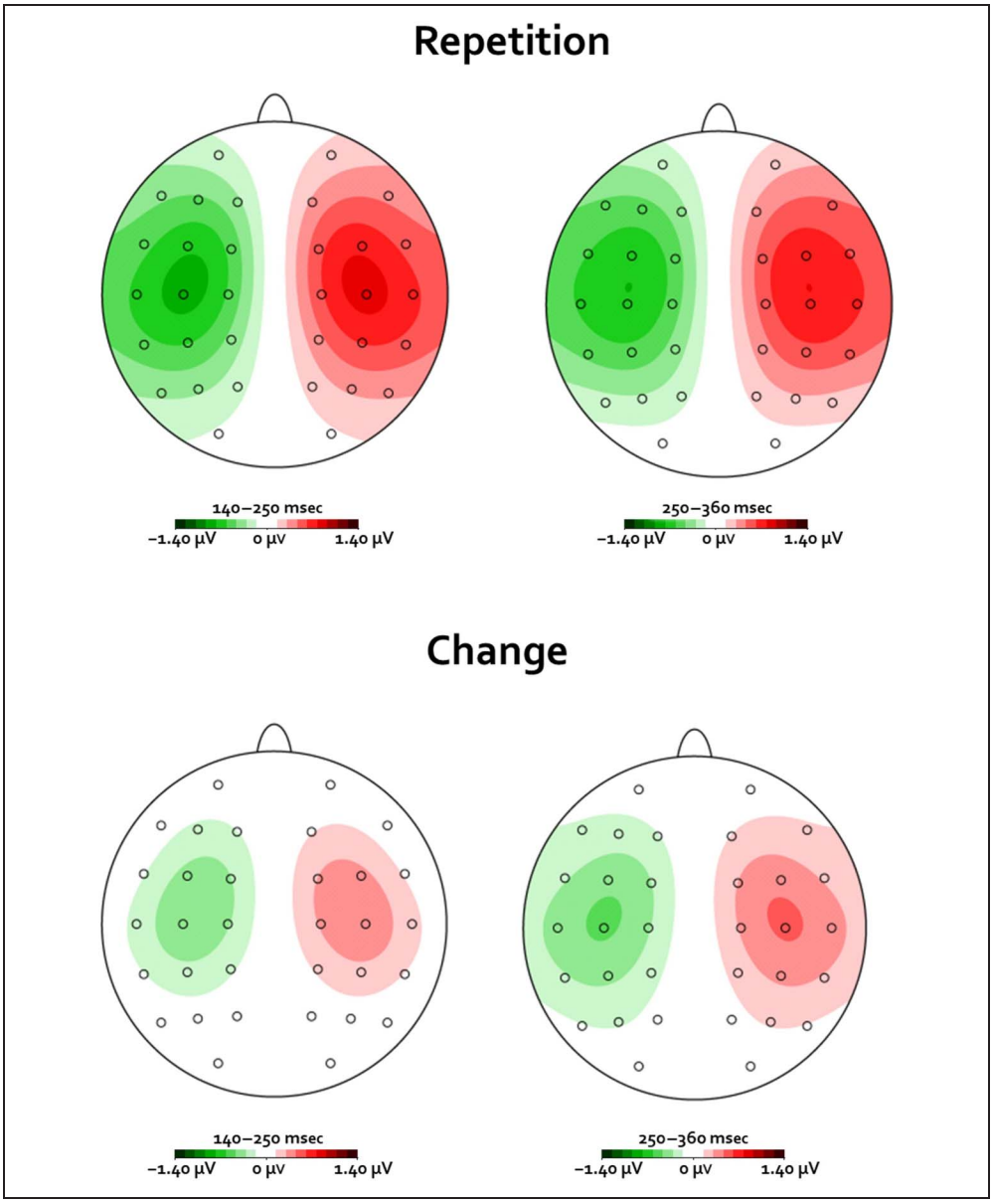

Figure 4. Topographical maps of the scalp distribution of the N140cc component obtained in the 140–250 and 250–360 msec time intervals after the array onset. These maps were constructed by spherical spline interpolation (see Perrin, Pernier, Bertrand, & Echallier, 1989) after mirroring the ipsilateral–contralateral difference waveforms to obtain symmetrical voltage values for both hemispheres. Top panels represent repetition trials, while bottom panels represent change trials.

further investigate this three-way interaction, separate analyses were carried out for buzz and tap targets in the early time window. Reliable Trial Type × Laterality interactions were observed for buzz, $F(1, 29) = 22.47$, $p = .000$, $\eta_p^2 = .437$, but not for tap targets, $F(1, 29) = 3.58$, $p = .068$; $\eta_p^2 = .110$, suggesting that PoP modulations of the N140cc component were present on buzz target trials only. Figure 5 (left and middle panels) shows ERP waveforms elicited over the hemisphere ipsilateral (red lines) and contralateral (blue lines) to the side of the tactile target (electrodes C3/4) separately for trials in which the target was repeated and trials in which the target changed across trials as well as for buzz and tap trials. The corresponding difference waveforms (Figure 5, right panel top) are shown separately for trials in which the target frequency repeated (dashed lines) and changed across consecutive trials (solid lines) and for buzz (gray lines) and tap target trials (black lines). Furthermore, the modulatory effect of PoP on the N140cc component obtained by subtracting the difference waveforms (contra − ipsi) elicited on frequency change trials from those elicited on frequency repeat trials, is shown separately for buzz target trials (gray lines) and tap target trials (black lines; Figure 5, right panel, bottom).

N140cc Onset Latency

The onset latencies of the N140cc components were calculated on the grand averages of each subsample obtained by excluding one participant at a time from the original sample. For each subsample, an onset latency measure was obtained at the time point in which the voltage value

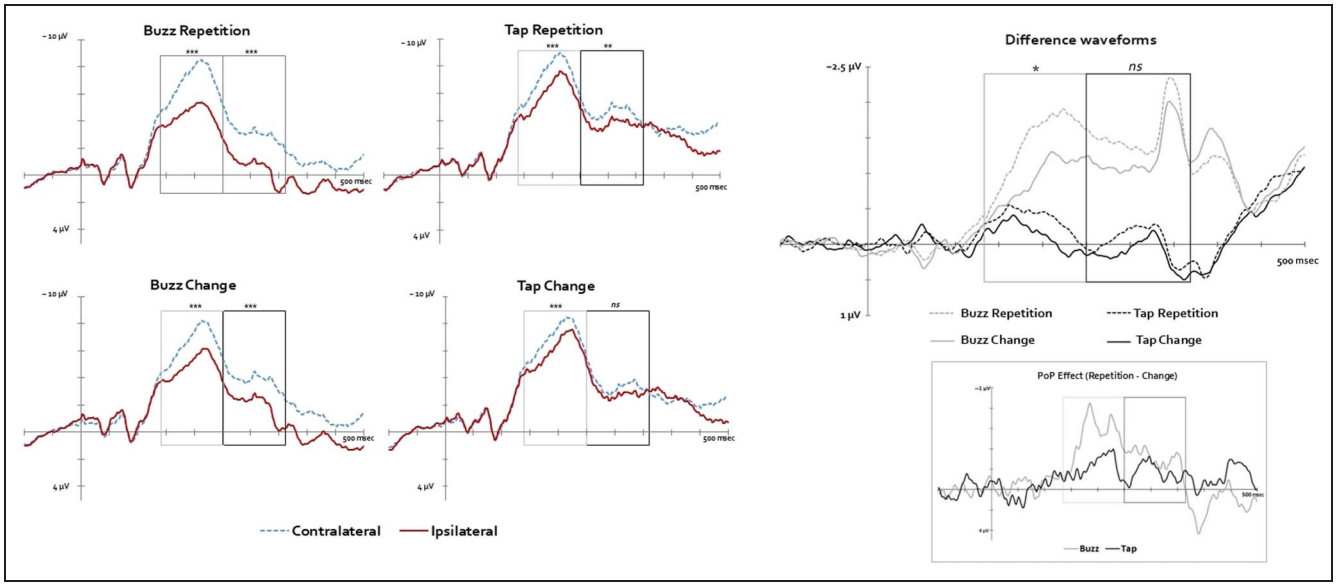

Figure 5. Left and middle: Grand-averaged waveforms obtained in the 500-msec interval after search array onset at lateral central electrodes C3/4 contralateral (blue line) and ipsilateral (red line) to the target side. ERP waveforms are shown separately for trials in which the target frequency was repeated (top) and when it changed (bottom) across consecutive trials, and separately for buzz target trials (left) and tap target trials (middle). Right (top): Difference waveforms obtained in the 500-msec interval after search array onset by subtracting ERPs elicited at electrodes C3/4 ipsilateral to the side of the target from contralateral ERPs. These difference waveforms are shown separately for trials in which the target frequency repeated (dashed lines) and changed across consecutive trials (solid lines), and for buzz target trials (gray lines), and tap target trials (black lines). Right (bottom): Difference waveforms illustrating the modulatory effect of PoP on the N140cc component obtained by subtracting the difference waveforms (contra − ipsi) elicited on frequency change trials from those elicited on frequency repeat trials, separately for buzz target trials (gray lines) and tap target trials (black lines). Line boxes represent the consecutive time windows considered for the amplitude analyses (140–250 and 250–360 msec post-array onset).

corresponded to 50% of the N140cc peak's amplitude. The jackknife procedure was carried out separately for buzz and tap targets, as well as for repetition and change trials. ANOVAs were performed on the onset values obtained on repetition and change trials, separately for buzz and tap targets. The corresponding F values were corrected (label Fc) according to the formula suggested by Ulrich and Miller (2001). On tap target trials (Figure 5, top right panel, black lines), the N140cc onset time, calculated with a 50% amplitude criterion, was earlier for repetition (132 msec) than change tap target trials (146 msec; peak latency values of 162 msec, −0.55 μV, on repetition trials and 166 msec, −0.41 μV, on change trials). However, the main effect of Trial Type for tap targets did not survive corrections, $Fc(1, 29) = 1.849$, $pc = .184$. On buzz target trials (Figure 5, top right panel, gray lines), the N140cc onset time, calculated with a 50% amplitude criterion, was earlier for repetition (157 msec) than change tap target trials (165 msec) (peak latency values of 222 msec, −1.92 μV, on repetition trials and 210 msec, −1.30 μV, on change trials). The main effect of Trial Type for buzz targets did not survive corrections, $Fc(1, 29) = 0.326$, $pc = .57$. Analogous results were obtained with the procedure described by Smulders (2010). No statistically significant PoP onset difference emerged for tap target trials, $F(1, 29) = 0.849$, $p = .184$, $\eta_p^2 = .060$, nor for buzz target trials, $F(1, 29) = 0.326$, $p = .57$, $\eta_p^2 = .011$.

DISCUSSION

To investigate whether the mechanisms responsible for PoP in vision can generalize to touch, we assessed the presence of intertrial priming effects in a tactile search task in which target and distractors' vibrotactile frequencies (buzz vs. tap) swapped unpredictably from trial to trial. Results showed faster and more accurate responses when the target frequency was repeated on consecutive trials than when it was changed. These behavioral findings demonstrate for the first time that PoP effects modulate the selection of the (nonspatial) target-defining feature in touch. Importantly, behavioral differences between repetition and change trials were accompanied by modulations of the N140cc component, the correlate of attentional target selection (e.g., Forster et al., 2016). The N140cc was reliably elicited between 140 and 360 msec post-array onset, contralateral to the target hand (e.g., Mena et al., 2020; Ambron et al., 2018; Forster et al., 2016). Crucially, increased N140cc amplitudes were observed for repetition compared with change trials. These findings offer initial evidence that PoP impacted earlier stages of somatosensory processing, in line with evidence from the visual domain (e.g., Tay et al., 2019; Christie et al., 2015; Eimer et al., 2010; Olivers & Hickey, 2010). In recent tactile search studies, the observation of improved behavioral performance in experimental conditions with larger

amplitude N140cc components was suggested to reflected higher certainty about the location of the target candidate in the array, resulting in improved target attentional processing (e.g., Gherri et al., 2023; Mena et al., 2020). Accordingly, the increased N140cc amplitudes observed on repetition trials of the present study suggest that the repetition of the same target-defining feature across consecutive trials boosted the certainty with which attention was engaged in the target candidate. In turn, this resulted in more efficient processing of the task-relevant feature (target finger location) during subsequent processing stages and in faster and more accurate responses.

In visual PoP studies, the N2pc components emerged earlier and showed larger amplitudes on repetition than change trials, suggesting that the target feature repetition sped up the perceptual analysis of the search array and facilitated the attentional selection of the target (e.g., Tay et al., 2019; Christie et al., 2015; Eimer et al., 2010; Olivers & Hickey, 2010). Results of the present study did not show reliable N140cc onset time differences between repetition and change trials, as measured by the jackknife procedure. While it is possible that the duration of the preattentive perceptual analysis of the search array was not affected by the target feature repetition/change across trials, conclusions based on null results should be treated with caution. Indeed, it is particularly difficult to demonstrate N140cc onset differences when the target-defining feature changes over time (i.e., vibrotactile frequency), due to the high trial-by-trial temporal variability of target selection processes in these tasks (e.g., Gherri et al., 2023; Mena et al., 2020). Future studies could assess the presence of N140cc onset modulations by PoP in tactile search tasks in which the stimuli impinge upon mechanoreceptors at once (e.g., tactile stimuli defined by different shape, orientation, etc.).

As expected, target selection was also modulated by salience in the present study. Larger N140cc amplitudes, lower error rates, and faster RTs were observed on higher saliency trials (buzz target presented among tap distractors) compared with lower saliency trials (tap target among buzz distractors), in line with previous studies in touch using similar stimuli features and tasks (e.g., Mena et al., 2020; Whang, Burton, & Shulman, 1991). These search asymmetries suggest that increased attentional resources were deployed toward the target when it was the most salient item in the array, resulting in larger N140cc components and reduced RTs and error rates. This pattern is similar to the one observed in visual search studies in which targets with higher salience were identified faster and more accurately (e.g., Itti & Koch, 2000, 2001), leading to larger and earlier N2pc components (e.g., Luck et al., 2021; Gaspar & McDonald, 2014; Töllner et al., 2011).[1]

Importantly, results revealed reliable interactions between PoP and target salience. As shown in Figures 5 and 2, differences between repetition and change trials were more pronounced on higher saliency compared with lower saliency target trials on both N140cc amplitudes and RTs. No such PoP difference emerged for accuracy rates. This pattern of PoP modulations by salience is different from the one usually observed in visual search studies with reduced PoP effects for higher saliency compared with lower saliency target trials (e.g., Leonard & Egeth, 2008; Meeter & Olivers, 2006). These visual PoP modulations are assumed to depend on the level of ambiguity between the target and other potentially salient items in the display (i.e., on their level of competition, ambiguity account [Meeter & Olivers, 2006], or on the level of uncertainty remaining after a candidate target has been located [Ramgir & Lamy, 2022]). Stronger visual PoP effects were present with lower saliency targets—characterized by higher target-distractor ambiguity/uncertainty—because the weaker target representation benefited from the attentional selection of the same feature on consecutive trials. Conversely, when the ambiguity between stimuli was lower, feature repetition across trials did not improve target selection because the target was already sufficiently salient to be selected (e.g., Rangelov, Müller, & Zehetleitner, 2017; Leonard & Egeth, 2008; Meeter & Olivers, 2006).

Most evidence supporting the ambiguity account comes from color pop-out tasks, and it remains unclear whether analogous PoP modulations by saliency emerge when participants search for targets defined along different visual dimensions (e.g., Becker & Ansorge, 2013). Importantly, only few studies to date have investigated PoP in asymmetric visual search tasks in which the target does not pop out from the array (e.g., Amunts, Yashar, & Lamy, 2014; Lamy, Amunts, & Bar-Haim, 2008). In these studies, in which participants searched for a singleton emotional facial expression or for a singleton shape, larger priming effects were observed for higher saliency compared with lower saliency targets (Amunts et al., 2014; Lamy et al., 2008). This pattern of PoP modulations by salience is comparable to the one observed in the present study. It is worth noting that vibrotactile search tasks—similar to the one of the present study—are not only asymmetric and inefficient (cf. Gherri et al., 2023; Halfen, Magnotti, Rahman, & Yau, 2020) but also characterized by high levels of uncertainty, as shown by high error rates.

A possible resolution between the pattern of PoP modulation by salience observed in the present study and the one predicted by the ambiguity account may be found in the different levels of ambiguity/uncertainty across tasks. Under the high-uncertainty conditions of the present study, it is conceivable that both higher and lower saliency target trials benefitted from priming because the singleton target was not sufficiently salient to be selected. Importantly, although indications of PoP advantages were present for both higher and lower saliency trials, results showed stronger PoP effects on higher than lower saliency target trials. We argue that the repetition of the target-defining feature across consecutive trials facilitated performance only following trials in which the candidate target

had been located/selected with sufficient certainty, allowing the formation of the memory trace necessary to facilitate the target identification on the next trial (cf. Amunts et al., 2014, for a similar argument in vision). Indeed, in the visual modality, the emergence of PoP effects is contingent upon the conscious perception of the target (Peremen, Hilo, & Lamy, 2013). Although stimuli in the present study were suprathreshold, the simultaneous presentation of different vibrotactile frequencies can cause distortions in the sensory representation of these stimuli (i.e., masking effects; e.g., Gilson, 1969). We speculate that following trials in which participants were highly uncertain about the target—despite having responded correctly—the memory trace required for the emergence of PoP was not formed, resulting in no advantage for the target feature repetition. If this were the case, the reduced PoP effects observed on lower compared with higher saliency target trials may be driven by a larger number of high-uncertainty trials in which no PoP effect emerged.

Finally, ERP differences between PoP effects on lower and higher saliency target trials were particularly evident in the early N140cc time window, suggesting that this interaction selectively impacted the initial phase of attentional selection (cf. Dolci et al., 2024). For lower saliency targets, the deployment of attention to the target candidate was likely characterized by increased temporal and spatial variability across trials (e.g., increased number of attentional shifts toward either side of the array to identify the singleton), which resulted in reduced/absent PoP modulations of N140cc amplitudes compared with higher saliency target trials. Overall, the present results suggest that the size of PoP modulations in touch is determined not only by the saliency of the target but also by the certainty with which it is selected on a trial-by-trial basis.

To conclude, the findings of the present study demonstrate for the first time the presence of PoP effects in a tactile search, confirming that the repetition of the target-defining (nonspatial) feature can facilitate search performance. Larger N140cc amplitudes on repetition compared with change trials suggest that the target was selected with a higher degree of certainty when its defining feature was repeated across consecutive trials. Together, these findings show that also in tactile domain PoP effects impact the attentional selection of the target. More generally, results of the present study align well with initial observations from the auditory domain showing search improvements when the same target feature is repeated on subsequent trials (e.g., Addleman & Jiang, 2019; Klein & Stolz, 2015; Dyson, 2010; Dyson & Alain, 2008a, 2008b). Together, these findings reveal the existence of similar influences of selection history, specifically PoP, on search performance across different sensory modalities. However, future studies should further investigate the extent to which the attentional system is governed by modality-general principles across different sensory modalities.

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Data Availability Statement

Data sets are available on request. The data supporting the conclusions of this article have been made available by the authors, without undue reservation. Supplemental Material can be accessed on this article's homepage: https://doi.org/10.1162/JOCN.a.2400.

Author Contributions

Fabiola Rosaria Fiorino: Data curation; Formal analysis; Investigation. Cristina Iani: Funding acquisition; Project administration; Resources; Supervision; Writing—Review & editing. Sandro Rubichi: Funding acquisition; Writing—Review & editing. Elena Gherri: Conceptualization; Funding acquisition; Methodology; Project administration; Supervision; Writing—Original draft; Writing—Review & editing.

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Diversity in Citation Practices

Retrospective analysis of the citations in every article published in this journal from 2010 to 2021 reveals a persistent pattern of gender imbalance: Although the proportions of authorship teams (categorized by estimated gender identification of first author/last author) publishing in the *Journal of Cognitive Neuroscience* (*JoCN*) during this period were M(an)/M = .407, W(oman)/M = .32, M/W = .115, and W/W = .159, the comparable proportions for the articles that these authorship teams cited were M/M = .549, W/M = .257, M/W = .109, and W/W = .085 (Postle and Fulvio, *JoCN*, 34:1, pp. 1–3). Consequently, *JoCN* encourages all authors to consider gender balance explicitly when selecting which articles to cite and gives them the opportunity to report their article's gender citation balance.

Note

1. It is worth noting that the search arrays presented on higher and lower saliency target trials of the present study were

physically different. While the target side in the array always included one tap and one buzz regardless of saliency, the other side included two identical stimuli (both taps on higher saliency trials or both buzzes on lower saliency trials). Therefore, the comparison of lateralized ERPs (waveforms ipsilateral and contralateral to the target) elicited on higher and lower saliency target trials is likely to reflect—in addition to the attentional processes responsible for target selection—also residual sensory differences driven by stimulation imbalances across hemispheres.

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