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Long-term (statistically learnt) and short-term (inter-trial) distractor-location effects arise at different pre- and post-selective processing stages

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Abstract

A salient distractor interferes less with visual search if it appears at a location where it is likely to occur, referred to as distractor-location probability cueing. Conversely, if the current target appears at the same location as a distractor on the preceding trial, search is impeded. While these two location-specific "suppression" effects reflect long-term, statistically learnt and short-term, inter-trial adaptations of the system to distractors, it is unclear at what stage(s) of processing they arise. Here, we adopted the additional-singleton paradigm and examined lateralized event-related potentials (L-ERPs) and lateralized alpha (8–12 Hz) power to track the temporal dynamics of these effects. Behaviorally, we confirmed both effects: reaction times (RTs) interference was reduced for distractors at frequent versus rare (distractor) locations, and RTs were delayed for targets that appeared at previous distractor versus non-distractor locations. Electrophysiologically, the statistical-learning effect was not associated with lateralized alpha power during the pre-stimulus period. Rather, it was seen in an early N1pc referenced to the frequent distractor location (whether or not a distractor or a target occurred there), indicative of a learnt top-down prioritization of this location. This early top-down influence was systematically modulated by (competing) target- and distractor-generated bottom-up saliency signals in the display. In contrast, the inter-trial effect was reflected in an enhanced SPCN when the target was preceded by a distractor at its location. This suggests that establishing that an attentionally selected item is a task-relevant target, rather than an irrelevant distractor, is more demanding at a previously "rejected" distractor location.

KEYWORDS

distractor-location suppression, EEG, N1pc, N2pc, probability cueing, SPCN

1 | INTRODUCTION

Imagine you are in a central railway station. While you are searching for updated information on the information board, your attention is captured by an announcement broadcast via loudspeakers. But then you realize the announcement is not related to your schedule, and you return to your search task. This is a typical scenario depicting how our attention may be oriented to and captured by goal-relevant and irrelevant but salient stimuli, respectively. It is commonly agreed that attentional selection is determined interactively by top-down, that is, goal-driven or voluntary, and bottom-up, that is, stimulus-driven or involuntary, mechanisms (Awh et al., 2012; Egeth & Yantis, 1997; Orchard-Mills et al., 2013; Soto-Faraco et al., 2004; Wolfe et al., 1989).

Apart from explicit goal-driven guidance, top-down guidance can also be learned based on past experiences, such as the statistical spatial distribution of task-relevant targets or task-irrelevant salient distractors in the search scene (Geng & Behrmann, 2005; Goschy et al., 2014; Shaw & Shaw, 1977; Zhang et al., 2019). Attentional guidance based on statistical learning of the spatial distribution of target or salient distractor items has been referred to as *target-* or, respectively, *distractor-location probability cueing* (Geng & Behrmann, 2002; Miller, 1988; Müller & Findlay, 1987). Having learned the respective spatial distribution, observers can prioritize locations for attentional selection at which the searched-for target is encountered regularly (Geng & Behrmann, 2005; Shaw & Shaw, 1977), or deprioritize locations at which salient but irrelevant distractors appear frequently (Leber et al., 2016; Sauter et al., 2018; Wang & Theeuwes, 2018). In the latter case, which is the focus of the present study, distractors occurring at frequent (distractor) locations cause less interference than distractors occurring at rare locations.

This reduction of interference by distractors occurring at likely locations is partly attributable to (in Geng, 2014, terms) *proactive* distractor-location suppression, reducing the weight of signals at these locations in attentional-priority computations and thus reducing attentional capture; and partly to *reactive* suppression after attentional capture, placing inhibition on the distractor location so as to disengage attention from the distractor and reorient it to another (likely the target) location. Consistent with this, in oculomotor-capture studies, the power of distractors to attract the eye is reduced in frequent versus rare distractor regions (evidencing proactive suppression), and disengagement of the eye is expedited from distractors at frequent versus rare locations, consistent within the idea that less reactive suppression is necessary to reorient attention to another, likely the target, location (e.g., Sauter et al., 2021). Also, one proposal has been that proactive suppression (to avoid capture) is the cumulative result of reactive, post-capture suppression: When a distractor appears repeatedly at a particular location, it initially captures attention more frequently, and requires more effort to "reject," that is, reactively inhibit to redeploy attention; these reactive inhibitions act as training signals, making the priority computation system to learn over time and long-term reduce the selection weight allocated to distractor locations (Sauter et al., 2021; Zhang et al., 2022).

The effects of distractor-location reactive suppression manifest in short-term inter-trial effects (Goschy et al., 2014; Sauter et al., 2018; Wang & Theeuwes, 2018): search RTs are reduced when a distractor (on the current Trial *n*) occurs at the same location as a distractor on the preceding trial (*n*–1), as compared to a different location; while this *distractor-distractor* inter-trial effect is performance-enhancing, the downside is that a target appearing at the previous distractor location is responded to slower compared to a target at a different location (*distractor-target* inter-trial effect; for a detailed analysis of this effect pattern, including target-distractor and target-target effects, see the Supplementary in Sauter et al., 2018). A common interpretation of this distractor-distractor (and distractor-target) effect is that when a distractor at a particular location is rejected on the previous trial (on Trial *n*–1), this reactive rejection temporarily down-modulates the attention-capturing potential of a distractor (or, respectively, target) appearing subsequently at that location (on Trial *n*). This happens during the pre-attentive phase of attentional-priority computation. However, it is also possible that, rather than reflecting a short-term "inhibition-of-return" tag placed on the rejected distractor location, the rejection may change the criteria for the post-selective decision about whether an item encountered at that location is a target or a distractor: if the rejection biases towards a "distractor" decision (in a Ratcliff-type, (1979), two-boundary, distractor/target evidence accumulation/diffusion process), it would have multiple consequences: (i) it would speed up the identification of another distractor at that location as a "distractor," which would allow faster distractor rejection and reorientation of attention to the target at another location, leading to a faster search RT; and (ii) it would prolong the identification of a target appearing at the rejected distractor location, thus slowing search RTs on such trials (see similar conclusions in Allenmark et al., 2018). This alternative account could also fully explain the inter-trial distractor-distractor and distractor-target effects reported in the literature. In addition, due to the stochastic nature of the diffusion process, it would potentially have a third consequence: (iii) it might increase the rate of false "distractor" decisions at the post-selective (item-identification) stage when a target appears at the previous distractor location (i.e., the target

will be missed). Indirect evidence of such increased miss rates was recently provided by an eye-movement study of Allenmark, Gokce, et al. (2021): when the singleton target on (distractor-absent) trial *n* appeared at the rejected distractor location, observers (in particular, individuals with Asperger Spectrum Disorder, ASD) still directed their first saccade to the target, but then, instead of responding, went on to scan other locations before eventually making a return saccade to the target location and issuing the response. The effect was particularly striking (in individuals with ASD) when a distractor occurred at an unlikely location. In other words, the salient target still attracted (overt) attention to its location, but post-selective processing of the (target) item in the focus of attention failed, as a result of which the search proceeded to other (candidate) locations. A similar pattern had previously been described by Zhaoping and Guyader (2007) in a low-level feature-pop-out search task. Allenmark, Gokce, et al. (2021) interpreted their eye-movement pattern in terms of a predictive-coding framework (Auksztulewicz & Friston, 2016): rather than being attributable to inhibition of the distractor location itself that is carried over into the next trial (reducing the attentional priority of this location and, thus, oculomotor capture on that trial), it reflects a predictive bias as to the identity of the stimulus that is encountered at this location, that is: a post-selective bias towards a "distractor" decision. It should be noted that these alternative accounts are not necessarily mutually exclusive and may in fact coexist.

However, to what degree such looking-but-not-seeing depends on the long-term probability of the distractor and short-term inter-trial distractor-target coincidence remains elusive. Also, we have as yet a scant understanding of the underlying neural mechanisms, even though certain "brain" measures permit us to more directly distinguish between pre-attentive and post-selective processes compared to behavioral measures, in particular: EEG components associated with visuospatial item selection and, respectively, the processing of items in visual working memory (vWM). Accordingly, in the present study, we focused on lateralized event-related potentials (L-ERPs) related to visuospatial attention and working memory functions, in particular: the early posterior-contralateral negativity (N1pc), the posterior-contralateral positivity (Ppc or early Pd), the posterior-contralateral N2 (N2pc), and the (late) sustained posterior-contralateral negativity (SPCN) component.

The early posterior-contralateral negativity (N1pc), emerging 120 to 180 ms after stimulus onset, has been considered to reflect early sensory registration of and/or orienting to a salient object or (non-reportable) exogenous cue (Dodwell et al., 2021; Itthipuripat et al., 2014; Johannes et al., 1995; Schettino et al., 2016). However, in the same time window, a posterior-contralateral positivity (Ppc) may arise, for instance, when a salient stimulus (e.g., a square) that moves around a circle unexpectedly changes its shape (to a diamond) at the final, lateralized location, violating an "object-continuity" expectation[1] (Baker et al., 2022); or when, in the additional-singleton paradigm, a salient but task-irrelevant (and so to-be-ignored or "suppressed") distractor appears lateralized (in the presence of a non-lateralized target), in which case the positivity is referred to as P_D (Kerzel & Burra, 2020; Sawaki & Luck, 2010). Of note: while both the Ppc/Pd (positivity) and the negativity N1pc (negativity) reflect a lateralized bias in some early attention-related process, whether an L-ERP difference is considered a positivity, or a negativity depends on how the difference wave is referenced. Interestingly in this regard, Kerzel and Burra (2020) observed a (distractor-referenced) P_D which preceded a distractor-referenced negativity, indicative of the distractor being selected rather than suppressed; and this P_D was just the mirror image of the target-referenced negativity when the target appeared lateralized (with or without a distractor on the vertical midline). Given this, Kerzel and Burra (2020) reasoned that "*the initial 'P_D' is not a positivity to the distractor* [i.e., a positivity indicative of distractor suppression] *but rather a negativity … to the contralateral context element*" (p. 1170); in other words, the P_D is actually an early negativity referenced to the contralateral element (which, given the target occupied a location on the vertical midline, was a non-target item)—indicating that this item was selected first in the search process. Interestingly, in a study of "contextual cueing" of visual search (Chun & Jiang, 1998), Zinchenko et al. (2020) observed an N1pc/Ppc polarity shift with respect to statistically learnt target locations within repeated arrangements (or "contexts") of non-target items. Following an initial training phase in which participants acquired the search-guiding context cues, the target locations were switched to positions on the opposite side of the repeated non-target arrays in a test phase, abolishing the cueing effect. Electrophysiologically, Zinchenko et al. found an N1pc referenced to the initial target locations in the training phase, which was followed by a Ppc referenced to the relocated target positions in the test phase. Zinchenko et al. (2020) took this Ppc to be indicative of a persistent

[1]The movement of the object and its potential shape change was task-irrelevant (participants had to perform a central monitoring task), so the Ppc response to the changed shape would be an implicit effect. Of note, though, the shape changes also involved the change of the shape of the placeholder at the final location, potentially creating an additional (salient) local change signal (over and above that produced by the object's movement)—which may have contributed to the elicitation of the Ppc (in addition to the violation of the continuity expectation).

"misguidance" of attention (i.e., essentially a persistent N1pc referenced) to the initial, statistically learnt target location.

The N2pc component is commonly observed in salient pop-out search tasks, regarded as a signature of the allocation of focal attention to a target item in visual search (Eimer, 1996; Kiss et al., 2008; Luck & Hillyard, 1994; Sawaki & Luck, 2013; Töllner et al., 2012; Woodman & Luck, 1999). Its amplitude and latency are modulated by the target's feature contrast (or "saliency") relative to the non-target items (Luck et al., 1997), as well as by target repetition (van Moorselaar & Slagter, 2019). For example, when the target location repeats on consecutive trials, the amplitude of N2pc is reduced—reflecting more efficient guidance of attention to the target through positional intertrial priming (van Moorselaar & Slagter, 2019). However, with regard to distractor (location) inhibition in the context of distractor-location probability manipulations, the pattern of N2pc amplitude and latency effects is less clear. Wang et al. (2019) recently reported the N2pc to be delayed and reduced in amplitude when the target occurred at the (single) frequent relative to one of the rare distractor locations, potentially reflecting a lingering suppression component (such as the distractor positivity, Pd) at the frequent location. In contrast, van Moorselaar et al. (2021) failed to find any difference in the N2pc elicited by targets occurring at the frequent versus a rare distractor location. In an earlier study by Sauter et al. (2017), the distractor-elicited N2pc amplitude was actually larger for distractors appearing at locations in the frequent versus the rare (distractor) region in the midline-target/lateral-distractor condition; on the other hand, the target-elicited N2pc was delayed for targets appearing in the frequent versus the rare region, which Sauter et al. (2017) took to be indicative of a larger amount of attentional resources being required to detect a target stimulus in a region that is proactively suppressed as a result of distractor-location learning. In any case, the relevant literature provides no coherent picture of the N2pc effects, and new evidence is needed to resolve the inconsistencies.

The sustained posterior-contralateral negativity (SPCN) is a relatively late component (>300 ms; for example, 500 to 1000 ms post-stimulus), which is regarded as attentional selection of cued memory items or stored visual working memory representations (Eimer & Kiss, 2010). For example, the SPCN has been observed in visual discrimination tasks requiring detailed analysis of selected target items (Mazza et al., 2007, 2009), as well as complex choice or visuospatial configuration judgment tasks that require a great involvement of attention and visual working memory (Jolicoeur et al., 2008; Maheux & Jolicœur, 2017). Given this, we considered the SPCN to potentially provide a useful indicator of the processing demands posed by the analysis of a critical item, such as a target appearing at a previous distractor location that participants first look at but initially fail to recognize.

In addition to examining the above L-ERP components, frequency analysis may also be useful for understanding statistical learning of distractor-location suppression. For example, enhanced lateralized alpha-band (8–12 Hz) oscillations have been reported over the occipital cortex contralateral to the to-be-ignored location prior to the onset of the to-be-attended target (Jensen & Mazaheri, 2010; Kelly et al., 2006; Worden et al., 2000). A recent study of distractor-location probability cueing found pre-stimulus alpha-band oscillations in the parieto-occipital visual region to be enhanced for frequent relative versus rare distractor locations (Wang et al., 2019). It should be noted, though, that such findings consistent with anticipatory suppression have not always been replicated in other studies using a probability-cueing paradigm. In fact, several recent studies (Noonan et al., 2016; van Moorselaar et al., 2020, 2021; van Moorselaar & Slagter, 2019) failed to find any evidence that a bias in the spatial distractor distribution induces changes in pre-stimulus alpha-band activity in visual regions.

Thus, more work is needed to advance our understanding of the neural dynamics underlying statistical distractor-location learning and inhibitory intertrial effects in visual attention. Given this, the present study aimed to investigate (1) how the long-term probability of distractor location and the short-term inter-trial coincidence of the distractor and target locations modulate attentional selection across trials at the neural level, by examining the early posterior-contralateral components (N1p, Ppc, and N2pc) and the late SPCN component when the target (Trial *n*) occurs at the previous distractor (Trial *n*–1) location; and (2) whether any anticipatory suppression occurs prior to search display onset, by examining the pre-stimulus alpha activity. Concerning issue (1): Based on Kerzel and Burra's (2020) reasoning that the early components' polarity (positivity or negativity) depends on the display "context" to which they are referenced, and on Baker et al.'s (2022) finding that these components may already be sensitive to expectations about upcoming stimulus events (see also Zinchenko et al., 2020), we hypothesized that the early posterior-contralateral components may also be determined by statistical learning (i.e., acquired "priors") of where the most salient and behaviorally most significant items are likely to appear in the search display. In our study, the most likely location to contain the most salient display item across all (distractor-present and -absent) trials was the frequent distractor location. Examining the early components referenced to this "context" location is also of interest in light of the conflicting reports (mentioned above)

according to which the N2pc does (Wang et al., 2019) or does not (van Moorselaar et al., 2021) differ between targets at the frequent and rare distractor locations. Further, if the behavioral *distractor-target inter-trial effect* is attributable to impaired identification of a selected target (Trial *n*) at the previous (Trial *n*–1) distractor location, we would expect the SPCN to be increased in amplitude, reflecting the increased demands to post-selectively recognize the target as the task-critical (vs. an irrelevant) item in the coincident condition. Concerning issue (2): If anticipatory suppression exists, we expect alpha power (8–12 Hz) to be increased in the contra- versus the ipsilateral parietal-occipital region with reference to the frequent distractor location. To test these predictions, we adopted the additional-singleton search paradigm (Allenmark et al., 2019; Theeuwes, 1992; Zhang et al., 2019), in which participants look for and respond to a unique shape-defined target (e.g., a circle among diamonds, or vice versa) while ignoring a salient color-defined distractor (e.g., a red or green singleton different in color from other, non-distractor items). Importantly, when present in the search display, the salient distractor singleton appeared with high probability at one "frequent" location and with low probability at one of the "rare" locations, providing for statistical learning of the distractor-location distribution (see Figure 1).

2 | MATERIALS AND METHODS

2.1 | Participants

Twenty-four participants (mean age 26.79 years, age range 18 to 40 years; 9 females) were recruited at Ludwig-Maximilians-University (LMU) Munich for this experiment. They were paid 9 Euro per hour for their participation or received course credits. The sample size was determined based on the crucial target-location effect reported in previous studies (Liesefeld et al., 2017; Wang & Theeuwes, 2018; Zhang et al., 2019), which is sufficient to detect effects of size $d_z = 0.65$ and above with a power of 0.8 ($\alpha = 0.05$, one-tailed).

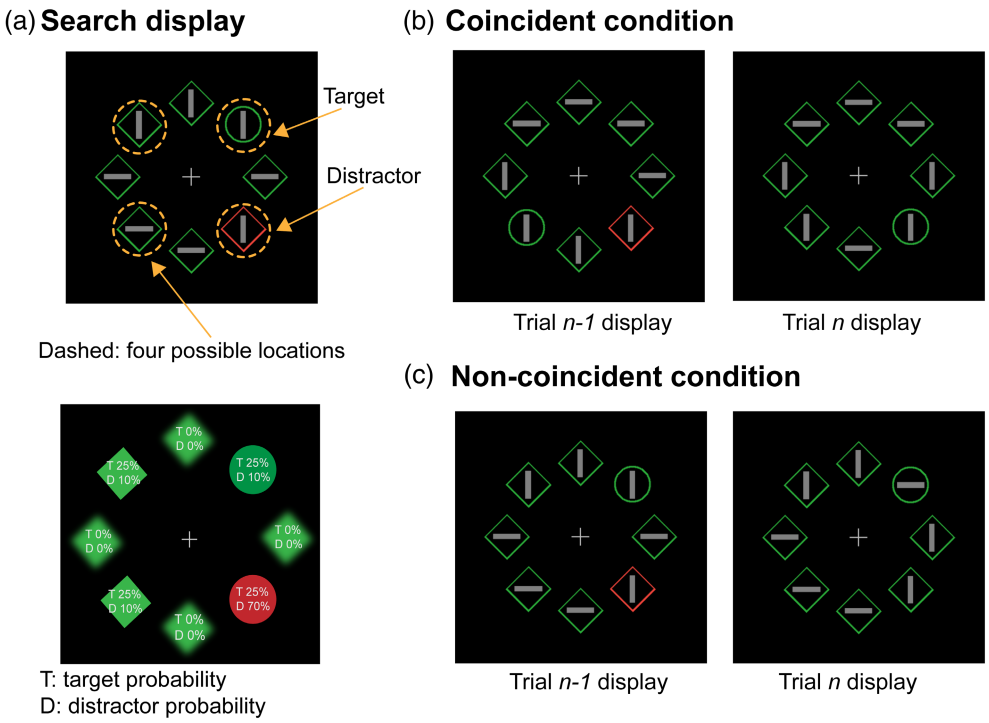

FIGURE 1 Visual search display and design. (a) An example of the search display with the labeled singleton-shape target, singleton-color distractor, and non-target items is shown in the upper panel. On each trial, participants had to find the shape-defined target singleton (here the circle) and discriminate (and respond to) the orientation of the line segment inside it (horizontal or vertical), while ignoring a salient but task-irrelevant color-defined singleton distractor (colored either red or green, depending on the color of the non-distractor items) of the same shape as the other non-target items. The dashed circles (not presented in the real trial displays) denote the four possible locations at which the target and distractor could appear in a given search display. The lower panel illustrates the probability of the target and distractor at each location. The high-probability location was fixed for each participant, and counter-balanced over the four possible locations across participants. (b) The *coincident* condition (illustrating a trial sequence with distractor-present Trial *n*–1 being followed by a distractor-absent Trial *n*): critically, the target on Trial *n* appears at the same location as the singleton distractor on Trial *n*–1. (c) The *non-coincident* condition: the target on Trial *n* does not appear at the location of the singleton distractor on Trial *n*–1.

All participants were right-handed and had normal or corrected-to-normal visual acuity and (self-reported) normal color vision. The study protocol was approved by the Ethics Committee of the LMU Faculty of Psychology and Pedagogics. Informed consent was obtained from all participants before the experiment. To reduce the COVID-19 risks for both experimenters and participants (Simmons & Luck, 2020), we filled out a short coronavirus checklist for each participant, following the approved hygiene concept of the LMU Central Administration and the Department of Psychology out laboratory-based research, and participants signed the coronavirus regulations consent form.

Four participants were excluded for further analysis because three of them had large artifacts after EEG preprocessing, and another participant had a high error rate of 49.53%.

2.2 | Apparatus and stimuli

The experiment was performed in a dimly lit, sound-attenuated, and electrically shielded experimental booth. Stimuli were generated by Psychophysics Toolbox Version 3 (PTB-3) (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997) based on MATLAB R2019b (The MathWorks® Inc., Natick, MA USA). Stimuli were presented on a VIEWPixx/3D 24-inch monitor at 1920×1080 pixels screen resolution and a refresh rate of 120 Hz. Participants viewed the monitor from a distance of 60 cm (eye to screen). They were instructed to sit as relaxed as possible to minimize muscle activity and other "noise" that could appear in the EEG signal during task performance. They issued manual responses by pressing the left- ("horizontal") or upward-pointing ("vertical") arrow key on the keyboard with their right-hand index or middle fingers, respectively.

The visual search display (see Figure 1) consisted of eight colored outline shapes (circles or diamonds) equidistantly arranged around an imaginary circle (radius: 4° of visual angle). The circle shapes were 2° of visual angle in diameter, and the diamond shapes were 2°×2° in size. The display items consisted of either one circle (the response-critical singleton-shape target) and seven diamonds (non-targets) or, alternatively, one diamond (the target) and seven circles (non-targets). Each shape contained either a vertical or a horizontal gray line (0.3°×1.5°) inside; that is, there were four vertical and four horizontal lines randomly distributed across the eight shapes on a given trial. On some trials (see Section 2.3), one of the non-target shapes (the additional-singleton distractor) differed in color from all the other shapes, being either green (CIE [Yxy]: 29.5, 0.17, 0.55) among homogeneous red shapes (CIE [Yxy]: 29.6, 0.63, 0.32) or red among homogeneous green shapes. All search displays were presented on a black screen background (3.58 cd/m^2), with a white fixation cross (1°×1°) in the center.

2.3 | Design and procedure

A target—a shape-defined singleton (either a circle among diamond non-targets or a diamond among circular non-targets, equally likely and randomly assigned on each trial)—was present on all trials. A salient distractor—a color-defined singleton (either red among green or green among red non-distractors, equally likely and randomly assigned on each trial)—appeared in 50% of trials. The target and the distractor singleton could appear only at four possible locations: the top-right, bottom-right, bottom-left, and top-left positions (marked by dashed outline shapes in Figure 1a); they never appeared on the horizontal or vertical midline positions (i.e., the 3 and 9 o'clock and, respectively, the 12 and 6 o'clock positions). If a distractor was present, it appeared with a likelihood of 70% at one consistent location (the frequent distractor location) and with a likelihood of 10% at each of the other three locations (the rare distractor locations). On distractor-absent trials, the target was equally likely to appear at all four possible locations; and on distractor-present trials, it was equally likely to appear at each of the three non-distractor locations (i.e., within a given trial display, the target and distractor never appeared at the same location). The frequent distractor location was fixed per participant and counter-balanced across participants.

To ensure sufficient cross-trial sequences of target-only (i.e., distractor-absent) displays following target-plus-distractor (i.e., distractor-present) displays—necessary for examining how a target falling versus not falling at a previous distractor location is processed[2] – distractor-absent and distractor-present trials (including the critical "long-exposure" trials; see below) alternated in a row; that is, a given distractor-present trial (Trial $n-1$) with a singleton distractor appearing at one of the locations was followed by a distractor-absent trial (Trial n). As regards the latter (distractor-absent) trials n, there were then two possibilities: the target appeared either at the location of the preceding distractor (hereafter, the *coincident* condition; see Figure 1b), or at a different location (hereafter, the

[2]In principle, this question could also be addressed by examining successive distractor-present trials (i.e., both Trial $n-1$ and Trial n contain a distractor, but the target on Trial n either does or does not fall at the location of the distractor on Trial $n-1$; see also Sauter et al. (2018), for a behavioral analysis of such sequences). Arguably, however, given that the presence of a distractor calls upon various distractor-handling strategies, the carry-over of inhibitory tags is best investigated by examining pure target-only trials (uncontaminated by effects of a salient distractor in the display).

non-coincident condition, see Figure 1c). Thus, with the type of positional distractor-target coincidence (coincident, non-coincident) and appearance of the target at a frequent or rare distractor location as the two main factors, the present study implemented a 2 × 2 (Distractor-Target Coincidence × Target-Location) within-subject design.

Participants were instructed to search for the singleton-shape target and respond to the orientation of the line inside it (vertical or horizontal), as fast and accurately as possible. For a vertical line, participants pressed the upward-pointing arrow key on the keyboard, and for a horizontal line the leftward-pointing arrow key. Participants were told that the odd-one-out colored item (i.e., the singleton distractor) was task-irrelevant, and so could be ignored. However, they were not informed that this item would appear more frequently at one location, and they were not expressly informed that distractor-absent trials would alternate with distractor-present trials. After they had completed the experiment, participants were asked whether the distractors had appeared equally often at all four critical locations or more often at one location. If they noticed the unequal distractor distribution, they were further asked to indicate exactly at which location the distractor had appeared most frequently. In total, 20 participants reported the distribution of the distractor locations was unequal, but only five of them went on to indicate the correct location of the frequent distractor.

Each trial began with a fixation cross for 1300 ms, followed by the search display (with the fixation marker remaining visible). In order to balance the need for sufficient trials for the four conditions of interest (2 Distractor-Target Coincidence × 2 Target-Location) and a reasonable overall duration for conducting an EEG experiment, we split the trials into two types regarding their exposure roughly equally: long-exposure (52.48% of all trials) and short-exposure (47.52% of all trials) trials. The critical inter-trial sequences, which determined the four conditions that we investigated, were always presented as long-exposure trials (71.38% of the long-exposure trials), that is: a long-exposure distractor-present trial (Trial $n-1$) was followed by long-exposure a distractor-absent trial (Trial n). On such long-exposure trials, the search displays were presented until the participant responded or for a maximum of 2500 ms, followed by response feedback, the word "correct" or "error" in the display center for 300 ms. On short-exposure trials, search displays were shown for 300 ms, and the window for issuing a response was curtailed at 900 ms (measured from search-display offset)[3]; search-display termination was then followed by a feedback display with a neutral white dot in the center shown for 300 ms. The next trial started after a random inter-trial interval (ITI) varying between 0 and 350 ms. Participants were instructed to maintain fixation on the central cross throughout each trial. They could take a break of a self-determined length between blocks, starting the next block by pressing any key on the keyboard. The experiment consisted of 1920 trials in total, subdivided into 16 blocks of 120 trials each. Prior to the formal experiment, participants completed one block of 120 trials to become familiar with the task. Overall, the 1920 trials took around 80 min to complete.

2.4 | Electrophysiological recording and preprocessing analysis

The electroencephalogram (EEG) was sampled at 1 kHz from 64 Ag/AgCl active electrodes (actiCAP system; Brain Products, Munich, Germany). Electrodes were mounted on an elastic cap (Easy Cap, FMS, Munich, Germany) placed according to the international 10–20 System (American Electroencephalographic Society, 1994). To monitor for potential eye movements, horizontal eye movements were recorded from electrodes F9 and F10, and vertical eye movements from Fp1 and an electrode placed at the inferior orbit of the left eye. All electrophysiological signals were amplified using BrainAmp amplifiers (Brain Products) with a 0.1 Hz to 250 Hz band-pass filter. During data acquisition, all electrodes were referenced to FCz and re-referenced offline to the average of both mastoids. All electrode impedances were kept below 5 kΩ prior to the experiment.

Data analysis was performed using the Brain Vision Analyzer II (Brain Products, Munich, Germany). Firstly, the continuous EEG data were manually inspected to remove apparent noise, such as electromyographic (EMG) bursts or wireless signal interference. Subsequently, the raw data was band-pass filtered using a 0.1 Hz to 30 Hz Butterworth infinite-impulse-response (IIR) filter (24 dB/Oct). Next, an ocular infomax independent-component analysis (ICA) was performed to remove eye blinks and horizontal eye-movement artifacts.

After the preprocessing of the continuous EEG, data were epoched from −200 to 800 ms relative to search display onset and baseline-corrected using the prestimulus interval. Next, incorrect trials and trials with large artifacts, such as any absolute amplitude exceeding ±60 μV, bursts of electromyographic activity as defined by voltage steps larger than 50 μV per sampling point, and activity changes lower than 0.5 μV within an interval length of 500 ms (indicating dead channels),

[3]These settings were taken over from a previous (fMRI) study, in which we obtained a significant distractor-location probability-cueing effect with a search-display exposure time limited to 300 ms and a response time window of 900 ms (Zhang et al., 2022).

were removed on an individual-channel basis before further ERP averaging. Among the 23 participants, three had more than 30% of the total trials with large artifacts. These participants were excluded from further analysis (including the behavioral analysis). Across the remaining 20 participants, the preprocessing procedure left 90.09% of the critical—inter-trial condition—trials for analysis.

2.4.1 | L-ERP analysis

To examine the three L-ERP components of interest (N1pc, N2pc, SPCN) on critical trials, EEG epochs were averaged separately for contralateral and ipsilateral parieto-occipital electrodes (PO7 and PO8) relative to the target location for each condition. These ERPs were then used to calculate the L-ERP components by subtracting the ipsilateral from the contralateral waveforms. We adopted the mean amplitude (rather than the peak-amplitude) approach to provide a metric for the components of interest, as it is less affected by noise (e.g., Larson et al., 2013).[4] Based on the literature (Mazza et al., 2009; Tay et al., 2019; van Moorselaar & Slagter, 2019) and the L-EPRs we observed, the N1pc and N2pc were quantified by the mean amplitude of the difference waveforms (at the lateral occipital electrodes PO7/PO8) in the 120–180 ms and, respectively, 180–350 ms time windows post-stimulus onset. To quantify the SPCN, the mean amplitude was calculated across the 350–500 ms time window, following the criteria used in previous studies (Geib et al., 2020; Gokce et al., 2014; Kiss et al., 2008).

2.4.2 | Time-frequency analysis

To study frequency-specific activity over time, a time-frequency analysis (Mallat, 2009) was performed on individual epochs. This was done by transforming epochs into power values using a continuous wavelet transform (CWT) in the time domain (t) to different frequencies (f). These modulated Gaussian sine functions are defined as: $W(t,f) = Ae^{\frac{-t^2}{2\sigma_t^2}} e^{i2\pi ft}$ where W denotes the complex convolution with the wavelet function, t is the time, and f is the frequency which increased from 1 to 30 Hz in 30 logarithmically spaced steps. To keep a good trade-off between temporal and frequency precision, the Morlet parameter c: $c = f_0(2\pi\sigma_t)$, or $c = f_0/\sigma_f$, was set to 7 cycles, as suggested previously (Cohen, 2014; Rommerskirchen et al., 2021), where f_0 is the central frequency, σ_f is the width of the Gaussian shape in the frequency domain, and σ_t represents the standard deviation of the Gaussian bell function (Tallon-Baudry et al., 1998). For different f_0, time and frequency resolutions can be calculated as $2\sigma_t$ and $2\sigma_f$, respectively (Tallon-Baudry et al., 1997). We extracted wavelet layers corresponding to our interest in alpha-band (8–12 Hz) activity. The time and frequency resolution for the lowest (8 Hz) and highest (12 Hz) frequency were determined by Morlet transform functions, which yielded the center of each frequency layer of 8.26 Hz and 11.74 Hz, time resolutions of 269.85 ms and 189.81 ms, and frequency resolutions of 2.40 Hz and 3.35 Hz, respectively. To ensure a reliable analysis with sufficient temporal distance to the stimulus onset and to avoid edge and smearing effects, a 2950 ms long segmentation (i.e., −1950 to 1000 ms relative to the onset) was used for time-frequency decomposition. We assumed that any anticipatory suppression would be detectable within the pre-stimulus time window [−1950, 0 ms]. The resulting power was baseline-corrected using a time window of −1300 to −1000 ms: a time window without any task-related processing and distant from the stimulus onset. The assumption underlying this choice of the baseline is that proactive suppression would be effectively activated only some time before the expected onset of the search display, rather than being maintained in active state throughout the pre-stimulus period. This procedure differs from previous research that did not implement any baseline correction (see van Moorselaar et al., 2020, 2021; Wang et al., 2019). The results of the wavelet transformations were then averaged across participants and conditions to obtain a measure of total power (Cohen, 2014). Finally, the time-frequency power was quantified as mean power within 8–12 Hz for further statistical analysis.

Given that the pre-stimulus lateralized alpha power could reflect anticipatory location suppression prior to display onset (Kelly et al., 2006; Wang et al., 2019), we further calculated the lateralized alpha power from a parieto-occipital electrode cluster (O1/2, PO3/4, and PO7/8), separately for the three types of distractor condition on the previous Trial n–1 (i.e., distractor absent, distractor present at the frequent location, distractor present at the rare location). Note that, for the lateralization index, the contra- and the ipsilateral alpha power were defined based on the side of the distractor on the preceding (distractor-present) trial; if there was no distractor on the preceding (distractor-absent) trial, the lateralization index was defined based on the side of the frequent distractor location. Further, to obtain a full

[4] Of note, in Appendix S2, we also provide the peak-amplitude metric for the N2pc analysis.

picture of any anticipatory suppression based on statistical distractor-location learning, we also calculated the lateralization index solely based on the frequent distractor "side" across all (i.e., both distractor-absent and -present) trials. That is, we calculated the lateralization index—contralateral-minus-ipsilateral alpha power—for the 8–12 Hz wavelet layer (with the center at 10 Hz) from the parieto-occipital cluster within the pre-stimulus window [−1950, 0] ms. According to the literature (Kelly et al., 2006; van Moorselaar et al., 2020), if the previous distractor location or the frequent distractor location is suppressed prior to display onset, we would expect alpha power to be higher over the contralateral relative to the ipsilateral parietal-occipital region.

3 | RESULTS

Given that the main manipulations were in those long-exposure trials, we reported the results on those long-exposure trials here and the results on those short trials in Appendix S1.

3.1 | Behavioral data

3.1.1 | Error rates

On average, the error rate was 12.20%.[5] The mean error rates for three different distractor conditions (distractor absent, at frequent location, at rare location) are shown in Figure 2a (bottom panel). A repeated-measures ANOVA revealed the Distractor condition main effect to be significant, $F(2, 38) = 15.9$, $p < .05$, $\eta_p^2 = .46$: the error rate was lower on distractor-absent trials relative to the two types of distractor-present ($\Delta = 5.30\%$; $ts(19) > 4.52$, $ps < .001$, Bonferroni-corrected), with numerically higher error rates caused by distractors occurring at the frequent versus the rare locations (13.6% vs. 16.8%, $t(19) = 2.60$, $p = .05$, Bonferroni-corrected).

[5]This error rate is relatively high, likely owing to the pressure to respond fast was introduced by the fact that the display was presented only briefly and required a response within 900 ms in nearly 50% of the trials (the error rate was similar in Zhang et al.'s (2022), fMRI study, under 300 ms display-presentations and 900 ms response-deadline conditions). Note that in the slowest—that is, the distractor at rare location—condition, the mean RT was around 900 ms, indicating that participants attempted to respond within the 900 ms deadline even though there was no externally imposed pressure to respond fast on long-exposure trials (on which the response deadline was extended to 2500 ms).

3.1.2 | Mean RTs

For the analysis of the correct mean RTs, we excluded the error trials (12.20%) as well as outliers (1.06%), defined as RTs outside 1.5 interquartile differences above the third or below the first quartile of the respective RT distribution. The mean RTs for three different distractor conditions (distractor absent, at frequent location, at rare location) are depicted in Figure 2a (top panel). A repeated-measures ANOVA revealed a significant main effect of Distractor Condition, $F(2, 38) = 36.1$, $p < .001$, $\eta_p^2 = .66$: responses were faster in the distractor-absent condition relative to the distractor-present conditions ($\Delta = -106.5$ ms; $ts(19) > 4.39$, $ps < .001$, Bonferroni-corrected), evidencing significant distractor interference. And, crucially, distractors that appeared at the frequent location caused substantially less interference than distractors at rare locations (873.26 ms vs. 938.83 ms, $t(19) = 4.11$, $p < .001$, Bonferroni-corrected). The error rate pattern mirrored the RT pattern, effectively ruling out speed-accuracy trade-offs.

Of note, on distractor-absent trials (see Figure 2a), when the target appeared at the frequent distractor location relative to the rare locations, RTs were slightly increased by 10 ms (805 vs. 795 ms), associated with a numerically lower error rate (9.6% vs. 10.2%), though this increase was not significant, $t(19) = .99$, $p = .33$. The absence of a (significant) target-location effect is at variance with, for instance, Wang and Theeuwes (2018), who found RTs to be prolonged to targets at the frequent location on trials without a competing color distractor in the display; but it is consistent with other recent studies that found no reliable target-location effect (Allenmark, Shi, et al., 2021; van Moorselaar et al., 2021).

3.1.3 | Coincidence effect

Next, we examined the critical positional (inter-trial) inhibition effects induced by a distractor (on distractor-present Trial n–1) onto the processing of a target (on distractor-absent Trial n) falling either at the same (coincident) or a different (non-coincident) location relative to the distractor on the preceding trial, separately for distractors (Trial n–1) and targets (Trial n) at the frequent and, respectively, one of the rare locations. Figure 2b depicts the corresponding RT (upper panel) and error rate (lower panel) results. A 2 (Distractor-Target Coincidence: coincident, non-coincident) × 2 (Target-Location: frequent, rare) repeated-measures ANOVA revealed only the Coincidence main effect to be significant, $F(1, 19) = 5.83$, $p < .05$, $\eta_p^2 = .23$. There were no significant effects involving Target Location; Target-Location main effect, $F(1, 19) = .09$, $p = .76$, $\eta_p^2 = .004$; Coincidence ×

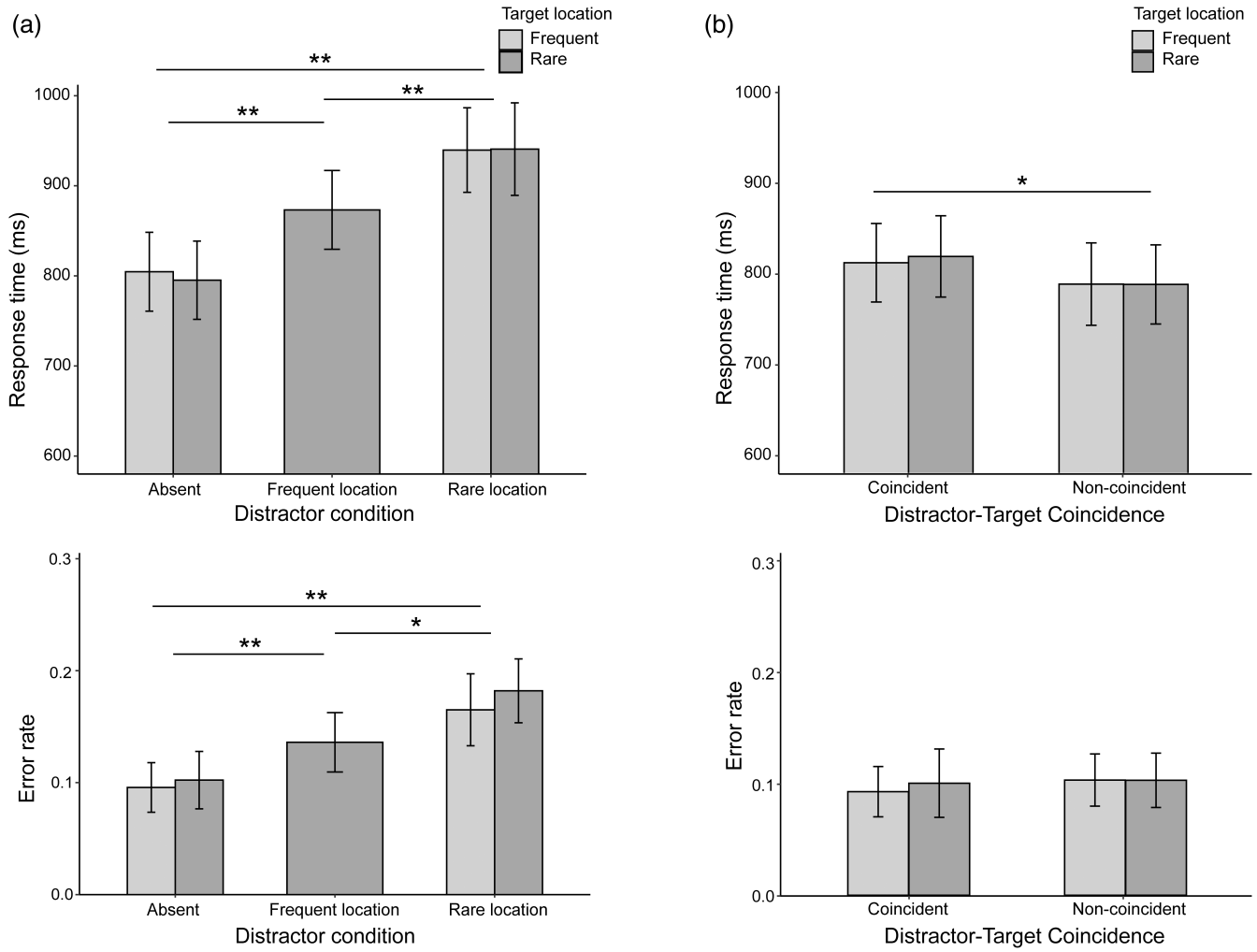

FIGURE 2 Behavioral results. (a) Mean RTs and error rates (on long-exposure trials) for the three distractor conditions: "Absent" denotes the distractor-absent condition, "Frequent location" that the distractor occurred at the frequent location, and "Rare location" that the distractor occurred at one of the rare locations. (b) Mean RTs and error rates on (long-exposure) distractor-absent trials, separately for the Distractor-Target Coincidence (coincident vs. non-coincident location of the target relative to the preceding distractor) × Target-Location (at frequent vs. rare distractor location) conditions. Significant differences between two means are indicated by one ($p < .05$) or two asterisks ($p < .001$). Error bars depict the one standard error of the mean.

Target-Location interaction, $F(1, 19) = .24$, $p = .63$, $\eta_p^2 = .01$. The coincidence effect was due to RTs being significantly slower when the target appeared at the same location as the distractor on the preceding trial (814.93 ms), as compared to a different location (787.77 ms)—indicative of (reactive) distractor-location inhibition being carried over across consecutive trials. Interestingly, this carry-over-of-inhibition effect, of some 27 ms, was only little influenced by whether the distractor and target occurred at the frequent distractor location (23 ms) or a rare location (30 ms). In previous studies, the carry-over of inhibition had been found to be significantly reduced for frequent (vs. rare) distractor locations (Allenmark, Shi, et al., 2021).

Given that some priming effects, such as "priming of pop-out" (Allenmark, Gokce, et al., 2021; Maljkovic & Nakayama, 1994, 1996), have been reported to involve longer-lasting memory traces, we also examined the Coincidence effect on Trial n with respect to Trial $n-2$. Neither the Coincidence effect ($F(1, 19) = 3.96$, $p = .06$, $\eta_p^2 = .17$) nor the Target-Location effect ($F(1, 19) = 3.88$, $p = .06$, $\eta_p^2 = .17$) turned out significant (interaction, $F(1, 19) = .83$, $p = .37$, $\eta_p^2 = .04$). In fact, the mean RT was numerically faster (by 16.60 ms) when the current target appeared at the location of the distractor on Trial $n-2$ compared to a non-coincident location. Thus, the coincidence effect did not persist beyond one trial back.

3.2 | Electrophysiological data

To investigate the short-term inter-trial distractor interference, we calculated the N1pc/Ppc, N2pc, and SPCN

components. For the target-only (distractor-absent, long-exposure) trials, the lateralized waveforms were calculated relative to the target side, separately for each combination of Distractor-Target Coincidence (coincident vs. non-coincident) and Target Location (frequent vs. rare). For the distractor-plus-target (distractor-present long-exposure) trials, the lateralized waveforms were calculated relative to the distractor side, but only for trials on which the target appeared on the side opposite to the distractor. We omitted trials on which the target and distractor appeared on the same side, as those trials do not allow the distractor-related L-ERPs to be distinguished from the target-related L-ERPs. Further, to obtain an unconfounded measure of the L-ERPs for distractors at rare locations, we ignored trials on which the distractor or target occurred at the one rare location on the same side as the frequent location.

Figure 3 shows the lateralized ERPs for the (four critical) target-only conditions (Figure 3a,b) and the (two) distractor-present conditions (Figure 3c,d). By visual inspection, all waveforms exhibit a more negative-going deflection in the 100–250 ms time window (N2) over the

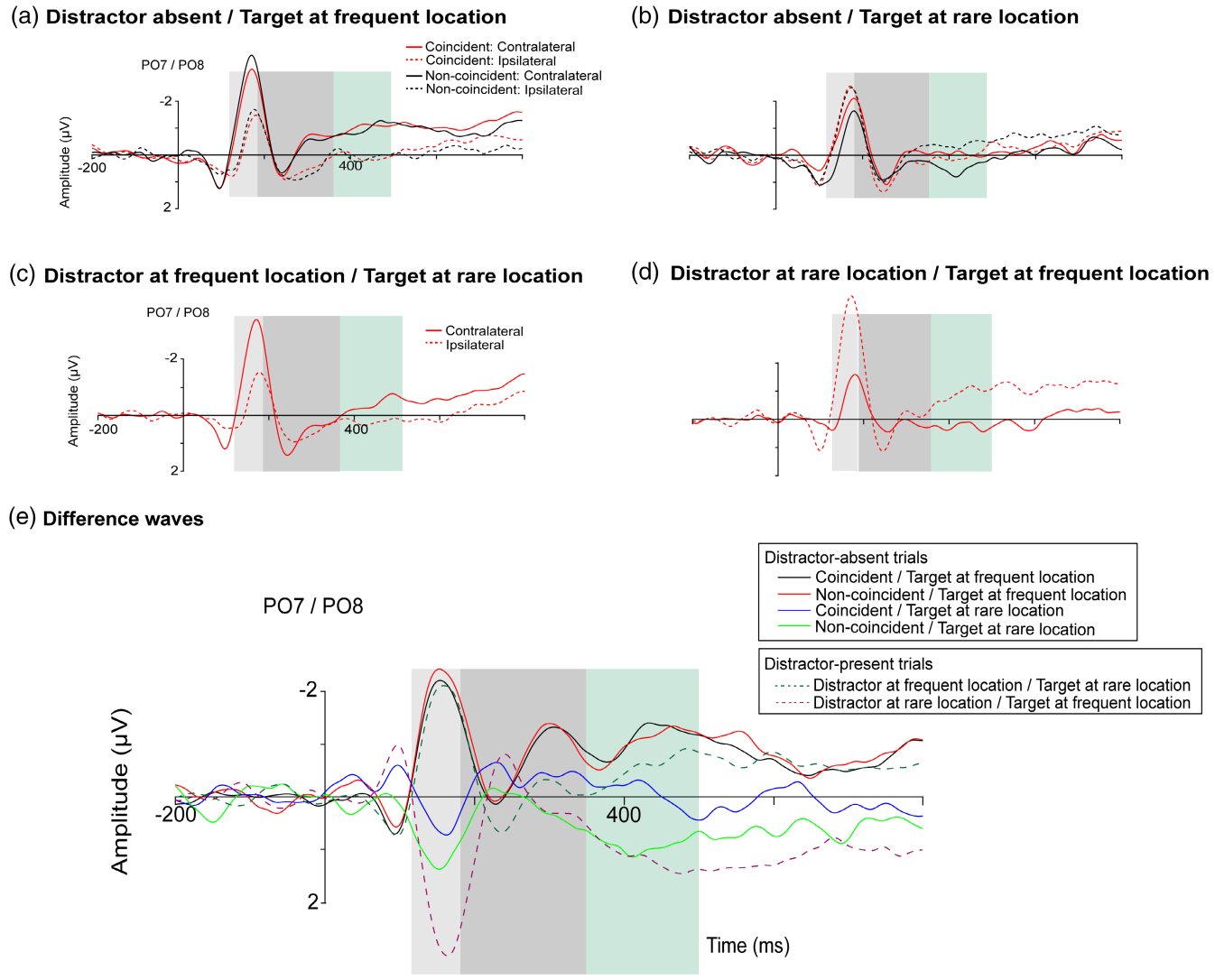

FIGURE 3 Grand-average ERP waveforms. Subpanels A and B show the *target-related* contra- and ipsilateral waveforms, at electrodes PO7/PO8, from 200 ms pre-stimulus to 800 ms post-stimulus for targets that appeared at the frequent location (a) and, respectively, a rare location (b). The red waveforms indicate the coincident condition, in which the target appeared at the same location as the distractor on the previous trial; the black waveforms denote the non-coincident condition, in which the target occurred at a different location from the previous distractor. The solid lines represent the contralateral waveforms, the dashed lines the ipsilateral waveforms. Subpanels C and D show the *distractor-related* waveforms for the distractor at the frequent location, with the target at the rare location on the opposite side (c); and, respectively, the distractor at a rare location, with the target at the frequent location on the opposite side (d). Panel (e) shows the ERP difference waves (contralateral minus ipsilateral) for the six experimental conditions. The light gray, dark gray, and green areas indicate the N1pc/Ppc time window (120–180 ms), the N2pc time window (180–350 ms), and the SPCN time window (350–500 ms), respectively.

hemisphere contra- and ipsilateral to the target or, respectively, the distractor in all conditions. Figure 3 shows the contralateral-minus-ipsilateral difference waveforms. As can be seen, the most salient item in the display—that is, the target on target-only (distractor-absent) trials and, respectively, the distractor on distractor-plus-target (distractor-present) trials—elicited an early positivity if it appeared at a rare location and a negativity if it appeared at the frequent location. Similar to the N1pc/Ppc flip reported by Zinchenko et al. (2020) in statistical context learning, this complex polarity pattern is primarily driven by the reference employed in computing the difference waves. It would be simplified when the frequent location is taken as the reference: activation of the N2 was higher contralateral versus ipsilateral to the frequent location, irrespective of the location of the most salient display item. Further, when the target appeared at the frequent location, a late N2pc component appeared to emerge. The difference waveforms then diverge in the subsequent 350–500 ms window among the various conditions. The following sections provide separate analyses of the N1pc/Ppc, N2pc, and SPCN components.

3.2.1 | Early N1pc/Ppc

Target-only (distractor-absent) trials

A two-way repeated-measures ANOVA of the mean amplitude in the early, 120–180 ms time window revealed a significant main effect of Target-Location, $F(1, 19) = 5.13$, $p < .05$, $\eta_p^2 = .21$. As can be seen from Figure 4a, this effect was due to a more negative deflection when the target appeared the frequent versus a rare distractor location (mean difference $\Delta = 1.08\,\mu V$). Further simple t-tests established the mean amplitude to be significantly negative (N1pc) when the target appeared at the frequent location, $t(19) = -2.22$, $p < .05$, but significantly positive (Ppc) when the target appeared at a rare location, $t(19) = 2.21$, $p < .05$. Interestingly, a comparison of the absolute mean amplitudes of the N1pc and Ppc revealed the mean amplitude to be significantly reduced when the target appeared at a rare versus the frequent location, $t(19) = 3.68$, $p < .05$.

Of note, the early L-ERPs were uninfluenced by the Distractor-Target Coincidence (Coincidence main effect, $F(1, 19) = 1.59$, $p = .22$, $\eta_p^2 = .08$; Coincidence × Target-Location interaction, $F(1, 19) = 1.58$, $p = .22$, $\eta_p^2 = .08$).

Target-plus-distractor (distractor-present) trials

Similar to the target-referenced early L-ERPs above, the distractor-referenced difference waves revealed a strong N1pc when the distractor occurred at the frequent location (and the target at a rare location) and a large Ppc when the distractor appeared at a rare location (and the target at the frequent location). While the amplitude difference between the two conditions was significant, due to their opposite signs ($\Delta = 3.99\,\mu V$, $t(19) = 2.78$, $p < .05$); the N1pc and the Ppc were actually of comparable absolute mean amplitude, $t(19) = 1.05$, $p = .31$. This suggests that both lateralized target-distractor configurations elicited a similar N1pc if referenced to the frequent distractor location (rather than to the actual distractor).

Taken together, the results revealed a significant difference in the early lateralized component. When the most salient item in the display—the singleton-shape target (on target-only trials) or the singleton-color distractor (on target-plus-distractor trials)—appeared at a rare location, it engendered a strong Ppc or "Pd." In contrast, a strong N1pc was elicited when it appeared at the frequent location. Note that the frequent location was overall most likely to contain the most salient singleton item in the display: the combined likelihood of the target or the distractor occurring at this location was 47.5%, which is about three times higher compared to any of the rare locations (see Figure 1). In other words, in terms of behavioral decision-making, this location was of the highest "significance:" it needed to be rejected if it contained a distractor or to be selected if it contained a target. Accordingly, as a result of statistical learning, participants may have acquired a strong "overall prior" for processing information from that location (cf. Zinchenko et al., 2020). Thus, when this "prior" was activated by the onset of the search display, whatever item was located at this position (whether the target or a non-target on target-only trials or the target or the distractor on target-plus-distractor trials) elicited an early and large negativity (N1), even when there was a competing singleton item on the opposite side of the display (see Figure 3). In essence, similar to Zinchenko et al. (2020), we take the initial L-ERP to be a negativity referenced to the display location that was learnt to be most significant behaviorally (which is also the location where the distractor is most likely to appear); in other words, it is "agnostic" to the stimulus that generated it.

Interestingly, though, the amplitude of Ppc/N1pc was reduced when the target (on target-only trials) appeared at the rare location, as compared to the frequent location. This suggests there was a biased competition between the initial statistically based prioritization towards the frequent location and the stimulus-based "attend-to-me" signal generated by the target at the rare location (or, conversely, the target may have boosted the prioritization of the frequent location when it occurred at this location). When one singleton was presented at the frequent location and the other at a rare location (on the opposite side), the amplitudes of (distractor-referenced) Ppc and N1pc

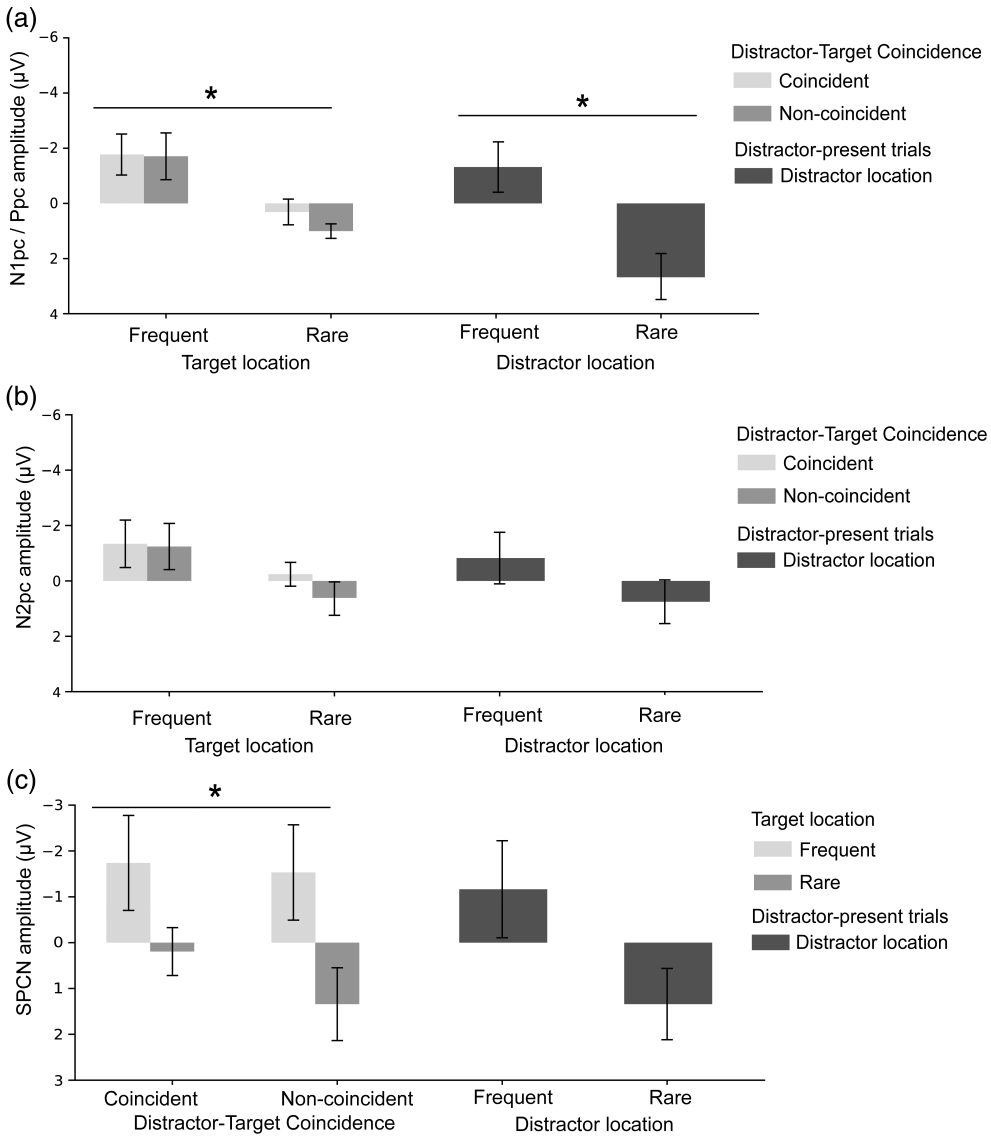

FIGURE 4 Mean *target-related* and *distractor-related* (i.e., left panels and right panels, respectively) N1pc mean amplitude (a), N2pc mean amplitude (b), and SPCN amplitude (d). The *target-related* L-ERPs are plotted as a function of the target location (target at the frequent or a rare distractor location) on (distractor-absent) Trial *n*, dependent on the coincident versus non-coincident positioning of the target on Trial *n* relative to the distractor on Trial *n*–1 (Distractor-Target Coincidence condition). The *distractor-related* L-ERPs are plotted as a function of the distractor location (at the frequent or a rare distractor location), with the target positioned on the opposite side. Error bars depict the one standard SEMs.

were comparable. This is likely attributable to the fact that the "attend-to-me" signals from both sides neutralized the bottom-up competition, leaving the top-down probability-based prioritization of the most significant display location largely intact.

Thus, the fact that presentation of both the lateralized target (on target-only trials) and the distractor (on target-plus-distractor trials) were associated with a pronounced early N1pc/Ppc (depending on whether it occurred at the frequent or a rare location) can be taken to suggest that, as a result of overall statistical learning, a spatially uneven prioritization of attention is triggered at a very early stage of processing, which interacts with the bottom-up registration of "attend-to-me" signals generated by the (target and distractor) singleton items.[6]

[6]Concerning the subsequent components, there were no significant effects (see right-hand panels in Figure 4). In particular, the N2pc mean amplitudes did not differ significantly between distractors occurring at the frequent versus a rare location ($\Delta = 1.58\,\mu V$, $t(19) = .93$, $p = .36$); there were also no differences when the N2pc was assessed in terms of the peak-amplitude metric (amplitude, $\Delta = 1.68\,\mu V$, $t(19) = .95$, $p = .35$; latency: $\Delta = 8.2\,ms$, $t(19) = .46$, $p = .65$). Further, the SPCN, too, did not differ significantly between distractors appearing at the frequent versus a rare location ($\Delta = 2.51\,\mu V$, $t(19) = 1.41$, $p = .17$). Overall, the effect patterns mirror those seen with target-related effects on target-only (i.e., distractor-absent) trials (see Figure 4 right panels), suggesting that distractors at the frequent location were processed similarly to targets at that location.

3.2.2 | N2pc

The mean amplitudes of N2pc in the time window 180–350 ms were similar across the target-only and the target-plus-distractor conditions (see Figure 4b). For the target-only conditions, a two-way (Target-Location × Distractor-Target Coincidence) ANOVA revealed no significant effects (Target-Location, $F(1, 19) = 1.58$, $p = .23$, $\eta_p^2 = .08$; Coincidence, $F(1, 19) = 1.21$, $p = .29$, $\eta_p^2 = .06$; interaction, $F(1, 19) = 1.20$, $p = .29$, $\eta_p^2 = .06$). Numerically, though, there was a negativity when the target occurred at the frequent distractor location (a-priori one-tailed t-test against zero, $t(19) = -1.57$, $p = .06$), but a positivity (i.e., no negativity) when it occurred at a rare location ($t(19) = .47$, $p = .67$).[7] As an alternative to the mean amplitude approach, we also examined the N2pc using the local-peak detection method (Geib et al., 2020; Gokce et al., 2014). Based on this metric, the N2pc (peak) amplitude turned out to be significantly larger, and the (peak) latency to be slightly delayed (by 25 ms), for targets that appeared at the frequent versus a rare distractor location (see Appendix S2).

Thus, the spatially biased distractor distribution and the distractor-target inter-trial coincidence had little impact on the N2pc. Qualitatively, though, the pattern remained similar to the earlier N1pc/Ppc components (compare Figure 4a,b). If anything, attentional engagement, reflected in the N2pc (peak) amplitude and timing, was somewhat stronger and mildly delayed by targets appearing at the likely location. The timing effect may reflect some (statistically acquired) resistance to deploy attention to the likely distractor location, despite the enhanced "attend-to-me" signal reflected in the N1pc/Ppc.

3.2.3 | SPCN

For the target-only conditions, analysis of the SPCN component revealed a marginally significant main effect of Distractor-Target Coincidence, $F(1, 19) = 3.96$, $p = .06$, $\eta_p^2 = .17$ (see Figures 3e and 4c); neither the main effect of Target Location, $F(1, 19) = 2.35$, $p = .14$, $\eta_p^2 = .11$, nor the Coincidence × Target-Location interaction, $F(1, 19) = 2.03$, $p = .17$, $\eta_p^2 = .10$, was significant. The Coincidence effect was due to the SPCN amplitude being more negative-going (mean difference $\Delta = 0.68\,\mu V$) when the target location was coincident versus non-coincident with the previous distractor location (a-priori one-tailed t-test, $t(19) = 1.99$, $p = .03$). That is, there was an enhanced sustained negativity during the post-stimulus period when the target occurred at the previous distractor location, suggesting that more attentional vWM resources were required to analyze a target at a previous distractor location. As a result, responding to the target at the coincident location was slower compared to a non-coincident location.

In summary, the L-ERP results reveal a difference between the early N1pc/Ppc and SPCN in response to targets at the frequent and rare distractor locations and the spatial coincidence of the target on Trial *n* and the distractor on Trial *n*–1: referenced to the frequent distractor location, an early N1pc was triggered whether the target appeared at the frequent distractor location or a rare distractor location on the opposite side, while an enhanced sustained negativity (SPCN) was evident when the target appeared at the previous distractor location, both for the frequent and rare distractor locations.

3.3 | Time-frequency data

As outlined in the Method section, we further calculated the lateralized alpha-band power during the pre-stimulus period of Trial *n* across all conditions and separately for each of the three distractor conditions on Trial *n*−1 (distractor absent, distractor at frequent location, distractor at rare location). Figure 5a depicts the overall lateralized (contralateral minus ipsilateral, with reference to the frequent distractor location) alpha-band power (8–12 Hz) across all trials. Following (van Moorselaar et al., 2020), we limited the statistical analyses to the anticipatory time window (i.e., −750 ms to 0 ms). A *t*-test on the mean (contralateral minus ipsilateral) lateralization index failed to reveal any significant difference, $t(19) = -.72$, $p = .48$, $d_z = .08$; that is, there was no evidence of increased alpha-band power contra- versus ipsilateral to the frequent distractor location, that would be indicative of proactive suppression, before the onset of the search display. Figure 5b–d show the lateralized pre-stimulus alpha-band power for Trial *n* dependent on the distractor condition on Trial *n*−1 (distractor absent, at the frequent location, at the rare location). Further *t*-tests for each of these conditions also failed to reveal any difference in pre-stimulus alpha power (distractor-absent condition, $t(19) = .50$, $p = .62$, $d_z = .07$; distractor at frequent location condition, $t(19) = .96$, $p = .35$, $d_z = .09$; and distractor at rare location condition, $t(19) = .96$, $p = .35$, $d_z = .12$).

[7] Following an approach used by van Moorselaar et al. (2021), we further categorized participants into two groups, "learners" and "non-learners," according to whether they showed a behavioral target-location effect (i.e., slowed responding to targets appearing at the frequent versus a rare distractor location). However, this analysis failed to reveal any differential N2pc effects between the two groups (see Appendix S3 for details).

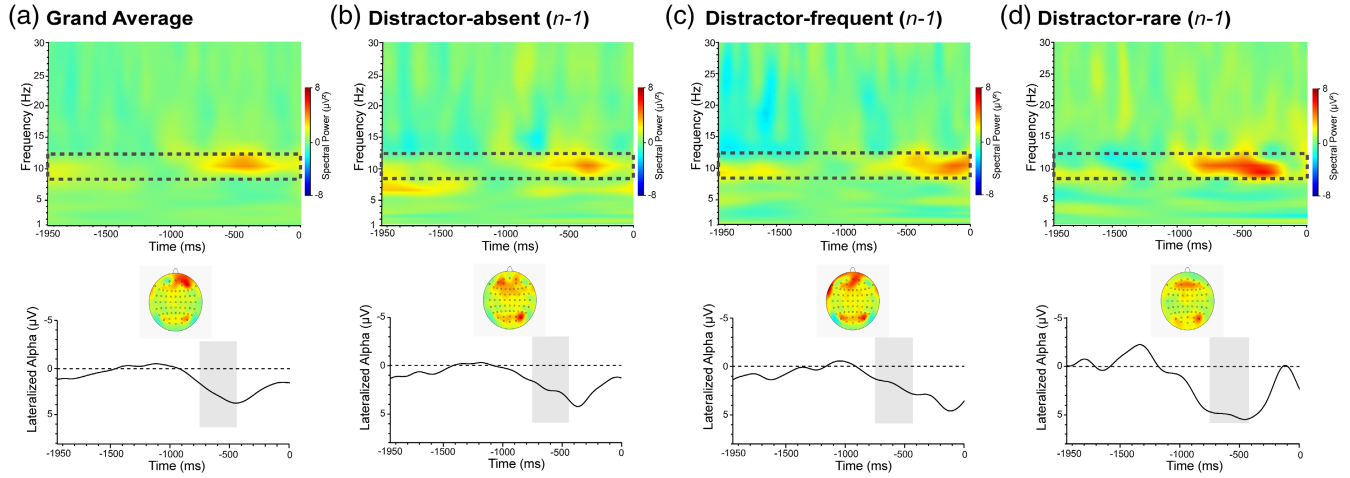

FIGURE 5 Grand-average results for the EEG time-frequency anticipatory alpha power. (a) The upper panel presents the lateralization index (contralateral minus ipsilateral) with reference to the frequent distractor location, for all trials. The bottom panel depicts the time series of the lateralization index waveform plotting the averaged alpha power (10 Hz) averaged across electrodes O1/2, PO3/4, and PO7/8, along with the grand-average scalp distribution of alpha power, prior to search-display onset (−1950 to 0 ms). (b–d) Lateralization index (contralateral minus ipsilateral) with reference to the distractor condition on the previous Trial $n-1$: distractor absent, distractor at the frequent location, distractor at the rare location. For each condition, the upper panel shows the grand-average time-frequency oscillation (time series: −1950 to 0 ms prior to the search-display onset; frequency band: 1 to 30 Hz) at contralateral-minus-ipsilateral electrode clusters (O1/2, PO3/4, and PO7/8). The bottom panel presents the two-dimensional waveform plot of the central alpha power and its grand-average scalp distribution. Note that the power spectrum bars indicate the lateralization index from −8 to 8 μV^2; the black dashed boxes in the upper panels represent the alpha-band range used for statistical analysis.

To rule out smearing effects, it is advisable to avoid time points around 0 ms, which may contain information from data points well after 0 ms. Accordingly, we conducted a second time-frequency analysis for the pre-stimulus window of −750 to −450 ms. Because the safety margin is half of the wavelet length of the lowest frequency of interest, a sufficient temporal distance to zero would be equal to or greater than 423.87 ms (lowest frequency of interest = 8.26 Hz, time resolution = 269.85 ms, frequency resolution = 2.40 Hz, wavelet length = 847.74 ms). However, again, there was no reliable increase in alpha power contralateral versus ipsilateral to the likely distractor location in any condition ($ts(19) > .52$, $ps > .61$, Bonferroni-corrected), corroborating the above results.

To search for potential anticipatory suppression that we might have missed with the above method. We adopted the cluster-based permutation tests across the 1–30 Hz frequency band between the contralateral and ipsilateral region over the whole pre-stimulus interval from −1950 to 0 ms ($p < .05$, cluster-corrected, 1000 iterations). Again, the analysis failed to find any reliable clusters exhibiting enhanced pre-stimulus oscillations among three distractor conditions (i.e., the distractor absent, at the frequent, and at the rare location). Further permutation tests among three distractor conditions also failed to reveal any reliable difference in the lateralization power among them.

Taken together, the time-frequency analyses failed to provide any evidence that the distractor-location suppression observed in the behavioral data derives from anticipatory suppression prior to the search display. This non-finding is at variance with some reports in the literature (Wang et al., 2019), but consistent with others (van Moorselaar et al., 2021).

4 | DISCUSSION

The aim of the present study was to investigate the neural mechanisms involved in long-term probability-based (proactive) and short-term inter-trial-based (reactive) distractor handling and related distractor suppression effects. Behaviorally, we replicated the distractor-location probability-cueing effect: distractor interference (i.e., the RT slowing on distractor-present vs. -absent trials) was reduced when the distractor appeared at the frequent location, compared to one of the rare locations. Further, on target-only trials, responding to a given target was slowed when it appeared at a location occupied by a distractor on the preceding trial, compared to a non-distractor location, and this spatial target-distractor coincidence effect was little affected whether the critical location was the frequent or a rare location. Electrophysiologically, we observed a dissociation between the early N1pc/Ppc and the late SPCN.

The polarity of the early lateralized component was dependent on the target, on target-only trials, appearing at either the frequent location—in which case a target-referenced N1pc was triggered—or a rare location—in which case a target-referenced Ppc was triggered. An analogous, distractor-referenced N1pc/Ppc pattern was observed on target-plus-distractor trials. Further, the amplitude of the late SPCN was more negative-going when the target location coincided with the preceding distractor location than when it did not. Finally, time-frequency analysis failed to reveal any evidence of anticipatory suppression induced by the uneven spatial distractor distribution in terms of differential alpha-band activity contra- versus ipsilateral to the likely distractor location.

The most robust effect observed in distractor-location probability-cueing paradigms is the generally reduced RT interference caused by distractors appearing at the frequent location compared to a rare location (Allenmark et al., 2019; Allenmark, Shi, et al., 2021; Goschy et al., 2014; Sauter et al., 2018; Wang & Theeuwes, 2018; Zhang et al., 2019). It is believed that this effect results from statistical learning across trials of where distractors are likely to occur in the display, which leads to "proactive" suppression of the respective locations—evidenced, for instance, by distractors at frequent locations attracting fewer eye movements (e.g., Allenmark, Shi, et al., 2021; Sauter et al., 2021). In addition, when a distractor does capture attention, whether overtly or covertly, its location needs to be suppressed "reactively" for attention to disengage and move towards the target location (e.g., Geng, 2014). This reactive inhibition carries over to the next trial, evidenced by slowed RTs to a target presented at the same location as a distractor on the previous trial (e.g., Allenmark, Shi, et al., 2021; Geyer et al., 2006; Kumada & Humphreys, 2002; Sauter et al., 2018). While this may reflect an "inhibition-of-return" tag carried over across trials, it might also reflect an adjustment of decision criteria in post-selective "target" decisions, that is, in deciding whether an attentionally selected item is actually the searched-for target or an irrelevant distractor (or non-target) item.[8]

[8]In fact, the globally measured behavioral distractor-location probability-cueing effect may also, to some extent, reflect such post-selective processes, evidenced by findings from studies of oculomotor capture that it takes less time to disengage the eye from a frequent versus a rare distractor location (Sauter et al., 2021). While this may have to do with the overcoming of oculomotor "hold" processes, it may also reflect a shift in post-selective decision criteria: if decisions are biased towards "distractor" and away from "target" at frequent locations, the (perceptual) signal to disengage the eye would be issued faster, expediting oculomotor disengagement from distractors at frequent locations.

4.1 | Statistical long-term learning of frequent distractor locations

Our findings indicate that whether an early lateralized negativity (N1pc) or positivity (Ppc) was observed was contingent on whether the most salient display item (the target on target-only trials or the distractor on target-plus-distractor trials) appeared at the frequent distractor location (early negativity) or a rare location on the opposite side (early positivity). This polarity pattern may be best understood by inspecting the original ERP waveforms (Figure 3a–d). Irrespective of the side on which the most salient display item appeared, the N1 peaked earlier and more prominently contralateral versus ipsilateral to the side of the frequent distractor location. This suggests that, as a result of statistical learning, participants acquired a strong memory "prior" where the most salient, and in terms of behavioral decision-making, most significant item (the target on target-only trials or the distractor on target-plus-distractor trials) is likely to appear in the display, and this prior then top-down biased attentional selectivity towards this location. Previous work has linked the early N1pc and Ppc/Pd to the registration of an "attend-to-me" signal and attentional orienting to salient display items (Dodwell et al., 2021; Donohue et al., 2018; Itthipuripat et al., 2014; Johannes et al., 1995; Sawaki & Luck, 2010; Schettino et al., 2016), or to (proactive) suppression of task-irrelevant distractors (Kerzel & Burra, 2020; Sawaki & Luck, 2010). In the present study, however, the initial lateralized activity is likely to reflect an (as a result of statistical) acquired bias in spatial attention. The fact that such a bias can be purely driven by statistical learning is consistent with the N1pc/Ppc polarity flip in contextual cueing reported by Zinchenko et al. (2020): participants persisted in prioritizing the initially learnt target locations within repeated display arrangements even after consistent re-location of the targets to the opposite side of the displays. We suggest that, under the conditions of the present study, the search-guidance system has learned that salient stimuli at the frequent location may engender a decision "conflict" (see, e.g., Schneider et al., 2012): "pay special attention" to the stimulus at this location because, although it is highly likely to be a distractor, it may actually be a target.

It should be noted, however, that both the statistically acquired top-down prior and the bottom-up "attend-to-me" signal generated by the stimulus influence the early prioritization of spatial attention: when both are spatially congruent—that is, when the target appears at the frequent location—the N1pc is enhanced. Conversely, when the two are incongruent—that is, when the target appears at a rare location on the opposite side and so competes with the top-down prioritized location—the

Ppc amplitude is reduced. In contrast to the target-only (distractor-absent) trials, this competitive interaction is lessened on distractor-present trials, where the target signal on one side and the distractor signal on the other side already compete with each other, curtailing the influence of the top-down prior. As a result, the N1pc and Ppc are of comparable (absolute) amplitudes in the target-plus-distractor conditions (Figure 3).

How does our finding compare to previous ERP studies of distractor-location probability cueing? Overall, the results from these studies were inconsistent. In our study, we observed statistical learning to impact the early lateralized component (N1pc/Ppc), while having little influence on the N2pc amplitude; if anything, the N2pc appeared only slightly delayed to targets at the frequent versus a rare distractor location. In contrast, Wang et al. (2019) reported a reduced N2pc amplitude for frequent location targets, which they attributed to a suppression-related Pd component simultaneously acting on the frequent location, rendering the target-elicited N2pc less robust (consistent with their finding of a Pd for the frequent location when the target appeared on a vertical midline position). It is worth noting that the lack of an N2pc modulation by the distractor likelihood is not an uncommon finding. For instance, van Moorselaar et al. (2021) also failed to find a difference in N2pc amplitudes between targets at frequent versus rare locations. Similarly, Sauter et al. (2017) did not find a latency/amplitude difference in the N2pc between targets occurring in a frequent versus a rare distractor region on distractor-absent trials: lateral targets elicited a pronounced N2pc whether they appeared in the frequent or the rare distractor region, suggesting that attention was consistently allocated to the target.

One crucial aspect that has been overlooked in the debate is the interplay between statistical learning and the bottom-up saliency in the N2pc. The majority of studies examining the N2pc have employed designs with equal (i.e., spatially unbiased) distributions of the lateralized target or distractor singletons, that is: they were not devised to study *spatial* statistical learning. Recent studies focusing on distractor-location probability cueing implemented heterogeneous display configurations: some studies presented displays with eight stimulus locations, but used only four of these as locations where the distractor or target could occur (e.g., van Moorselaar et al., 2021; Wang et al., 2019, and the present study), while others employed displays with only four stimulus locations in total (e.g., Kerzel & Burra, 2020). These differences in the display design may have contributed to the inconsistent findings in the literature. Here, we found that the early lateralized component (N1pc/Ppc) influenced by statistical-learnt attentional prioritization has implications for the subsequent N2pc component. For instance, when the target appeared at a rare distractor location (on the side opposite to the frequent location), we did not observe any posterior-contralateral negativity in the window of the N2. This may appear surprising initially, as one would have expected the rare side to be least suppressed by statistical *distractor*-location learning. However, the reason becomes clearer when taking the preceding N1pc/Ppc component into account, that is, the consistent negativity referenced to the top-down prioritized, frequent distractor location—which had the highest occurrence (47.5%) of the most salient display item (the target on target-only trials and the distractor on target-plus-distractor trials) across all trials. As a result of statistical learning, this location was prioritized for processing—either for a "reject" decision or a "select" decision—at the onset of the display, irrespective of any bottom-up "attend-to-me" signals. As a result, when the target appeared at the rare location, it had to compete with the probability-based prioritization of the frequent location. Although the biased competition greatly reduced the early Ppc amplitude (as compared to the absolute N1pc amplitude), it remained positive, preventing the subsequent negative-going wave ("N2pc") from reaching the negative region.

Of note, while our results are reasonably clear as to how targets at the frequent location are processed on target-only (distractor-absent) trials, we cannot tell what the reduced RT interference caused by distractors at the frequent versus one of the rare locations (which we observed, in line with a plethora of other studies) is due to on target-plus-distractor (distractor-present) trials. What we find is that, electrophysiologically, the distractor at the frequent location is handled similarly to a target at this location. In particular, it elicits an early N1pc that is as large as that generated by a target. Thus, if not due to early signaling, the cueing effect would have to originate in later processes involving attentional selection and engagement and/or post-selective processing of the selected item. Recall that the present study was designed to examine the origin of the slowed processing of targets (on target-only trials) occurring at a preceding distractor location, and so it did not incorporate conditions with lateral distractors only or, respectively, lateral distractors and targets on the vertical midline (on distractor-plus-target trials). Accordingly, it is hard to isolate distractor-related L-ERPs indexing of these later processes. In particular, we cannot examine for differential Pd effects, and how these may impact the N2pc and SPCN components, between distractors at the frequent and rare locations, limiting our conclusions as to the origin of the cueing effect.

4.2 | Short-term (cross-trial) after-effects of distractor rejection

To examine the effects of short-term, inter-trial "inhibition" of distractor locations, we selected sequential trial

pairs with Trial *n*−1 always containing a distractor that appeared at either the frequent or a rare location, followed by Trial *n* with the target only. Further, we categorized Trials *n* into coincident and non-coincident trials based on the target appearing at either the same or a different location to the distractor on Trial *n*–1. The behavioral results showed the cross-trial coincidence effect: it took longer to respond to a target at a previous distractor versus a non-distractor location. This coincidence effect was mirrored in the SPCN component. The SPCN turned out more negative for coincident, versus non-coincident, positioning of the target on Trial *n* with respect to the distractor on Trial *n*–1 (i.e., when the target appeared at the same, versus a different, location to the preceding distractor).

Previous work has shown the SPCN component, in the time interval between 350 to 500 ms post-stimulus, to be reliably observed under conditions requiring realized target stimuli to be selected and maintained in visual working memory (vWM) for "in-depth" processing in order to select the appropriate response (Hilimire & Corballis, 2014; Jolicoeur et al., 2008; Kiss et al., 2008). For instance, Kiss et al. (2008) found the SPCN to be increased on target-present (vs. target-absent) trials, on which participants had to discriminate the cut-off side of a singleton target diamond in order to decide on the appropriate response. By comparison, the SPCN was attenuated on target-absent trials, on which the search arrays were perceptually homogeneous—allowing participants to rapidly reject a display as not containing an odd-one-out item, without the need for any further, in-depth processing of any response-relevant features (participants had simply to refrain from making a response on such trials). Also, the SPCN amplitude is increased when multiple odd-one-out items within a given display are to be individuated and precisely enumerated, or when a decision is to be made whether the individuated items are arranged in a particular spatial configuration (Maheux & Jolicœur, 2017; Mazza & Caramazza, 2011)—that is, in tasks posing increased demands on vWM. Similarly, in a flanker task, the SPCN is more negative when the target-flanker distance is short rather than long (Bacigalupo & Luck, 2015)—likely due to the target needing to be individuated from the flankers in vWM when attention fails to focally select it under conditions of "crowding."

In the present study, the *distractor-target inter-trial effect* is defined by whether the processing of a given target (on Trial *n*) is in some way "inhibited" when it occurs at the same location as the distractor on the preceding Trial *n*–1. As considered in the Introduction, there are two possible explanations of such a short-term distractor-target inter-trial effect: (i) an additional inhibitory tag may be (reactively) placed on the distractor on Trial *n*–1—which, on the next trial (Trial *n*), would make the allocation of attention to a target item at this location harder; or, (ii), attentional selection of the item at this location is itself unaffected, but the distractor on Trial *n*–1 shifts the starting point of the post-selective (vWM-demanding) decision process determining what the item is at this location—a task-irrelevant distractor or the response-critical target—towards a "distractor" decision, so that a diffusion-type decision process would take longer to reach the target boundary, prolonging the RT. Given that the most robust coincidence effect we observed was on the vWM-related SPCN component, without an effect on the attentional selection-related N1pc and N2pc components, would argue in favor of the coincidence inter-trial effect reflecting mainly post-selective processes, in line with alternative (ii). This is in line with our previous eye-movement study (Allenmark, Shi, et al., 2021), in which we found that even though, on some critical trials, participants made an overt eye movement to the target, they mis-identified this item and rejected it as a distractor and kept on searching other items before eventually returning to the target and making the correct decision. Erroneous rejection of the fixated target as a distractor would be in line with alternative account (ii), because, when a previous distractor shifts the starting point of the decision process towards "distractor" (and away from "target"), one would expect a diffusion-type process of evidence accumulation to randomly drift towards the nearer, "distractor" boundary, resulting in the wrong decision on "target" trials. Of note, in Allenmark, Gokce, et al. (2021) study, this oculomotor pattern was more marked when a target followed a distractor at a rare (distractor) location, compared to the frequent location (and it was more marked in individuals with ASD compared to healthy controls). Allenmark, Gokce, et al. (2021) explained this by assuming that the shift towards the "distractor" boundary caused by a distractor appearing at a given location is more marked when distractors are unexpected, rather than highly expected, at that location. In the present study, the SPCN pattern (depicted in Figures 3g and 4d) looks generally similar (in that the coincidence effect appears driven more by targets at rare locations), though only the Coincidence main effect was reasonably robust, that is, the Coincidence × Target-Location interaction was not significant. Further work with a larger participant sample is required to examine the existence of the analogous interaction in the SPCN.

4.3 | Anticipatory suppression of distractor-location probability cueing

To date, it remains controversial whether the statistically learned (long-term) "inhibition" of the frequent distractor location reflects a process of proactive location suppression in anticipation of search-display onset, where this process would be purely spatial (i.e., feature-blind),

suppressing the allocation of attention to the learnt location whether a distractor or target appears in the search display. One recent study, by Wang et al. (2019), has reported alpha power to be enhanced contralateral to the frequent location prior to display onset. Oscillatory alpha activity (~10 Hz) has been shown to be inversely related to cortical excitability (Benwell et al., 2019; Lange et al., 2013), and lateralized alpha-band activity has been related to anticipatory suppression (Bengson et al., 2012; Jensen & Mazaheri, 2010; Kelly et al., 2006); in particular, an increase in lateral alpha-band power has been linked to the functional suppression of task-irrelevant information (Mazaheri et al., 2014). Accordingly, the finding of Wang et al. (2019) would argue in favor of proactive suppression of the frequent distractor location. However, in the present study, we failed to find any increase in pre-stimulus alpha-band power over the hemifield contralateral to the frequent distractor location within the pre-stimulus time window of [−750 to −450 ms] and [−750 to 0 ms].

It should be noted that our null-finding is not unique. Noonan et al. (2016) also failed to find any distractor-location-related anticipatory alpha lateralization in a study of distractor suppression. More recently, examining expectation-dependent distractor suppression, van Moorselaar et al. (2020) also found no differential contralateral versus ipsilateral alpha-band activity prior to search-display onset. In the present study, we further controlled the target- and distractor-defining shape and color features by swapping them unpredictably across trials to maximize location-based and minimize feature-based statistical learning. But, again, we found no evidence of an active suppression process initiated in anticipation of the search display. Consistent with van Moorselaar et al. (2020) and Noonan et al. (2016), this points to anticipatory alpha-band modulations *not* playing a significant role in the statistical long-term learning and "suppression" of likely distractor locations.

This leaves two possibilities. Either distractors at likely locations are "reactively" suppressed (preventing them from summoning attention) in the sense that suppression is invoked only once the presence of a distractor (or saliency signal) is registered at some level in the system; that is, the distractor rapidly activates some acquired suppression "routine," and this works more efficiently for frequent as compared to rare distractor locations. Such fast-acting, phasic suppression may be evidenced by an early distractor-related Pd component (preventing the elicitation of an N2pc), as reported in some studies (Gaspelin & Luck, 2018a, 2018b, 2018c). This notion would appear to be consistent with Gaspelin et al.'s (2015); Gaspelin and Luck (2018a) "signal suppression hypothesis." [Correction added on June 14, 2023, after first online publication: Few modification has been changed in the previous sentence.] Alternatively, the acquired suppression mechanism may work more tonically in that distractor-location learning down-modulates the responsivity of local neuron populations at some (higher and/or lower) level in the functional architecture of priority computation. Accordingly, any signal at such locations would be attenuated "passively," without the need for the intervention of some "(re-)active" suppression process. This would be consistent with habituation-type accounts of statistical distractor-location learning (Allenmark et al., 2022; Turatto et al., 2018; Turatto & Pascucci, 2016; Zhang et al., 2022).

5 | CONCLUSIONS

In summary, the present study investigated the mechanisms involved in distractor-location suppression through long-term statistical learning and short-term (inter-trial) adjustments. Behaviorally, we replicated the classical distractor-location probability-cueing effect, showing that participants can statistically learn to reduce the interference caused by salient distractors at frequent (vs. rare) distractor locations (Allenmark et al., 2019; Goschy et al., 2014; Müller et al., 2009; Sauter et al., 2018; Wang & Theeuwes, 2018), as well as the inter-trial coincidence effect, that is, the slowing of RTs when the target appears at the same (vs. a different) location as a distractor on the preceding trial. Electrophysiologically, statistical learning of the likely distractor location manifested in an early N1pc/Ppc post-display onset, but not in lateralized alpha power during the pre-stimulus period. The polarity of the early lateralized component N1pc/Ppc was due to the reference used to calculate the difference wave: the Ppc turns into an N1pc when referenced to the side of the frequent distractor location, indicative of acquired top-down attentional bias towards the frequent distractor location (which contained the most salient stimulus on nearly 50% of the trials overall in our display design). This top-down attentional prioritization (activated only upon the appearance of the search display) competes with the "attend-to-me" signals generated by the singleton target and distractor items, potentially rendering the classic N2pc unobservable in some circumstances. On the other hand, the inter-trial distractor-target coincidence effect was primarily associated with an enhanced SPCN, indicative of increased (vWM) resource demands to decide upon a response to the (selected) target at a previous distractor location. Accordingly, we attribute the coincidence cost on the RTs to a late, post-selective process, plausibly as a result of a short-term bias (induced by the distractor on Trial n–1) against identifying the item at the frequent distractor location (on Trial n) as a target, rather than a distractor. We acknowledge that these interpretations, especially of the early ERP effects, are post hoc and need to be

corroborated in future research. Our study design did not allow us to isolate distractor- and target-related activity on distractor-present trials (since distractors and targets were always placed on opposite sides), so we cannot tell at which stage(s) in later processing the interference reduction originates. Future work, implementing lateralized distractors and midline targets, is necessary to answer this question.

AUTHOR CONTRIBUTIONS

Nan Qiu: Conceptualization; data curation; formal analysis; methodology; project administration; visualization; writing – original draft; writing – review and editing. **Bei Zhang:** Conceptualization; data curation; methodology; validation; writing – review and editing. **Fredrik Allenmark:** Conceptualization; methodology; resources; validation; writing – review and editing. **Jan Nasemann:** Conceptualization; methodology; validation; writing – review and editing. **Shao-Yang Tsai:** Conceptualization; methodology; validation; writing – review and editing. **Hermann J. Mueller:** Conceptualization; funding acquisition; investigation; methodology; resources; supervision; validation; writing – review and editing. **Zhuanghua Shi:** Conceptualization; funding acquisition; investigation; methodology; project administration; resources; supervision; validation; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

We have no known conflict of interest to disclose.

DATA AVAILABILITY STATEMENT

Raw data used for analyses presented within this article will be made available upon request. If you would like to access the raw data and analysis, please email Nan Qiu at the following e-mail address: shirleyqiunan@gmail.com.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Appendix S1

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