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Research Report

# When experience with scenes foils attentional orienting: ERP evidence against flexible target-context mapping in visual search

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ABSTRACT

Visual search is speeded when a target is repeatedly presented in an invariant scene context of nontargets (contextual cueing), demonstrating observers' capability for using statistical long-term memory (LTM) to make predictions about upcoming sensory events, thus improving attentional orienting. In the current study, we investigated whether expectations arising from individual, learned environmental structures can encompass multiple target locations. We recorded event-related potentials (ERPs) while participants performed a contextual cueing search task with repeated and non-repeated spatial item configurations. Notably, a given search display could be associated with either a single target location (standard contextual cueing) or two possible target locations. Our result showed that LTM-guided attention was always limited to only one target position in single- but also in the dual-target displays, as evidenced by expedited reaction times (RTs) and enhanced N1pc and N2pc deflections contralateral to one ("dominant") target of up to two repeating target locations. This contrasts with the processing of non-learned ("minor") target positions (in dual-target displays), which revealed slowed RTs alongside an initial N1pc "misguidance" signal that then vanished in the subsequent N2pc. This RT slowing was accompanied by enhanced N200 and N400 waveforms over fronto-central electrodes, suggesting that control mechanisms regulate the competition between dominant and minor targets. Our study thus reveals a dissociation in processing dominant versus minor targets: While LTM templates guide attention to dominant targets, minor targets necessitate control processes to overcome the automatic bias towards previously learned, dominant target locations.

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## 1. Introduction

Humans possess a remarkable ability for statistical learning, which incorporates long-term memory (LTM) to generate predictions that can improve performance. For instance, a mailbox is recognized faster within a front yard than in a kitchen environment, indicating that previously experienced, typical scene context facilitates the recognition of associated (target) objects (Palmer, 1975; see also Biederman, 1972; Davenport & Potter, 2004; Conci & Müller, 2014; Reber, 1967; Turk-Browne et al., 2005). Such influences of statistical learning upon performance are often investigated with the so-called contextual-cueing paradigm, which allows quantifying the influence of (learnable) spatial regularities without concurrent confounding biases from scene semantics (Chun & Jiang, 1998; for reviews, see, e.g., Sisk et al., 2019; Goujon et al., 2015). In contextual cueing (CC), a searched-for T-shaped target object is consistently encountered within a stable, i.e., repeated, spatial arrangement of L-shaped nontarget, or 'distractor', items. Over time, detecting the target in these repeated search arrays becomes faster than with non-repeated (randomly generated) search arrangements. However, participants are usually unaware of the repeated distractor-target contingencies in the search task. This has been attributed to the incidental, i.e., effortless (long-term) learning of recurring distractor-target spatial 'contexts'. In this view, observers learn the repeating, spatial target-distractor layouts, and when these are subsequently triggered by a given repeated search array on a given trial, the activated (previously learned) contextual associations guide, or 'cue', attention towards the target location.

The CC-effect reveals a behavioral search advantage and modulates electrophysiological, event-related potential (ERP) components that reflect the allocation of spatial attention to the target location. For instance, the N2pc component, which typically manifests 180–350 msec after display onset, is modulated by contextual learning (Johnson et al., 2007; Schankin & Schubö, 2009). Moreover, Zinchenko et al. (2020) showed that such lateralized ERPs reflect effects of contextual memory upon visual search that may occur even earlier, during preattentive, visual processing, some 80–180 msec after display onset in the N1pc component, thus likely reflecting an automatic initial spatial bias from contextual memory, which occurs before the allocation of spatial, i.e., "focal" attention towards the target (as indexed by the N2pc component). Thus, statistical context learning becomes evident at early perceptual/preattentive (N1pc) and attentional (N2pc) stages of visual processing.

Overall, these findings thus suggest that a repeated context can guide search towards a predictable target position. However, relatively few studies have investigated the flexibility of statistical LTM, namely whether CC can bias attention in repeated search arrays towards multiple target locations. For instance, when a given repeated distractor context is paired with two (or more) possible target locations on different trials, successful memory-based guidance of attention would require matching the currently presented search array with a target item at one of two (or, several) possible locations. Such a flexible learning mechanism would help use CC-based guidance in real-world environments where multiple goal-relevant targets might be present in the same scene context. Chun and Jiang (1998, Experiment 6) initially supported this idea by investigating CC in an experiment where a given, repeated distractor context was paired with two possible, frequently repeating target locations. Their results showed a reliable CC-effect with two possible target positions, though there was a 50% reduction compared to the contextual facilitation observed with a single target location.

Zellin et al. (2011) later re-investigated CC with multiple target locations. In general agreement with Chun and Jiang's (1998) initial findings, they also observed that the strength of CC reduced (and developed later) for repeated displays paired with two target locations relative to just a single target location. Moreover, CC even vanished completely with three possible repeating target locations. Additional analyses further showed that the CC-effect observed for dual-target displays resulted from the combined effect of a single "dominant" target location, which revealed a strong and significant CC-effect. In contrast, the second, "minor" target location of a given display did not yield any contextual facilitation, but instead revealed a reliable reaction time (RT) cost (i.e., slower RTs to minor targets in repeated displays than in non-repeated, i.e., baseline, displays). A similar pattern of results was obtained in their subsequent experiment with three target locations, where only a single, dominant target location showed a substantial CC-effect, while no cueing was found for the two other locations of a given, individual repeated distractor array. Together, these findings thus suggest that CC is not very flexible but limited to acquiring just a single distractor-target association for a given repeated distractor arrangement.

Converging evidence for this proposal also comes from studies exploring whether a single repeated context may be paired with multiple target positions by introducing a training-/test-phase design that presents a consistent target location change from one phase to the next. For instance, Manginelli and Pollmann (2009) had participants learn repeated context displays with a single target location in an initial training phase. In the subsequent test phase, the target was relocated to a previously empty display location (that had not contained a distractor item). The results revealed a reliable CC-effect during training. However, after target relocation, CC vanished – presumably because the implicitly learned association still guided attention to the original target location, thus resulting in a slowing of RTs for repeated distractor contexts with relocated targets. Thus, once learned, repeated layouts trigger attentional-priority signals from statistical LTM that, after target relocation, interfere with contextual re-learning (Zinchenko et al., 2020). This interpretation is in line with Makovski and Jiang (2010), who observed the CC-effect to decrease with increasing distance between the original target location and the relocated target. And it is consistent with Zellin et al. (2013), who found that contextual facilitation does not readily re-emerge even after extensive training with relocated targets; in fact, successful adaptation of statistical LTM was seen only after three days of training and after more than 80 encounters of each relocated target in a repeated display context (Zellin et al., 2014).

Together, the evidence indicates that CC is acquired after only few encounters with specific distractor-target arrangements. This learning is incidental, in that participants develop a facilitation from repeated encounters of specific distractor contexts simply by performing the search task and without being instructed that some of the search arrays may be repeated. Once contextual memories are established, they are automatically activated (i.e., reflecting incidental memory) and the contextual memories are therefore resistant against updating after target location changes within otherwise unchanged distractor arrangements (see, e.g., Conci & Zellin, 2022). This pattern of results thus suggests that LTM representations of the distractor-target spatial contexts automatically bias search when encountering a learnt display arrangement. For instance, display repetitions may lead to the build-up of specific – search-guiding 'template' – representations for specific distractor-target arrays, which, on later encounters, are retrieved, and so improve search (e.g., Logan, 1988; Chun & Phelps, 1999). In this view, only a single – dominant – target location in the template will receive a processing advantage, whereas targets appearing at other – minor – locations may be processed only with a cost due to contextual misguidance of attention towards the dominant target position, which must be overcome to find and respond to the 'minor' target. ERP evidence for this form of contextual misguidance, after target relocation (to the opposite hemifield) has previously been revealed in the N1pc, which reverses its polarity after the location change, now exhibiting a, for repeated arrays more pronounced, positive-going deflection towards initially, learned target positions (thereby effectively still indexing the initially learned target location in the ipsilateral hemifield, Zinchenko et al., 2020). Thus, once learned, repeated layouts trigger attentional-priority signals from contextual LTM, interfering with the search after target relocation.

Such an "automatic template-matching" mechanism may explain why CC is typically limited to a single target position per distractor context since the LTM representation of a given, repeated distractor-target array will automatically direct attention toward the memory-matching – dominant – target location in the search array, yielding contextual facilitation if the target indeed appears at this position. However, the same LTM 'bias' towards the dominant target location will "misguide" attention if the target appears at another – minor – location, and this bias will, in turn, need to be overcome by a time-consuming control process to reorient attention to the actual target location.

Based on this account, we predict a specific pattern of attentional (mis-) allocation to arise during the search in repeated arrays with several target locations (see Zinchenko et al., 2020), namely the (i) automatic allocation of attention towards one (of several possible) recurring target items (as indexed by the N1pc), followed (ii) by the subsequent shift of spatial attention to the designated target (N2pc). However, while this sequence of attentional processing ensures efficient, LTM-based orienting towards the learned, dominant target, it nevertheless induces a cost for targets appearing at non-predicted, minor locations. In this case, (iii) time-consuming reorienting processes may become necessary, which could potentially engage additional control mechanisms (Hamm et al., 2002; Kutas & Federmeier, 2011; Zinchenko et al., 2019) that help to overcome the automatic bias of attention from contextual LTM.

To test these predictions, we performed a typical CC visual search experiment that required detecting a T-shaped target among L-shaped distractor items (see Fig. 1 for example displays). Unbeknown to the participants, half of the trials contained repeated arrays, which were paired either with a single target location (as in the standard CC task) or with two possible target locations (with the two repeating target locations alternating across sequential blocks of trials). These repeated context displays were compared to randomly generated, non-repeated contexts paired with a single or two possible targets (alternating across blocks). Besides behavioral RTs, we recorded participants' electroencephalogram (EEG) to isolate the lateralized N1pc and N2pc components at parietal–occipital electrodes, in addition to the N200 and N400 at fronto-central electrodes (and, which could be expected to reflect some top-down control signal when experiencing conflicting information, see Folstein & Van Petten, 2008; Hanslmayr et al., 2008; Bruchmann et al., 2010). Given this setup, we were able to use the ERP signatures to compare (i) CC in displays with one versus two targets and (ii) search in the same two-target displays for the preferred (dominant) and the less preferred (minor) target locations.

## 2. Method

### 2.1. Participants

Twenty-four participants took part in this study (14 females; mean age: 26.25 [age range: 21–31] years; all right-handed; all with normal or corrected-to-normal visual acuity). The data from three participants were not included in the analyses due to a failure to record the EEG data. The final sample thus consisted of 21 participants (12 females; mean age: 26.71 [age range: 21–31] years). On the basis of the main effect of Context on the mean RTs in the learning phase (partial eta2 = .66) as reported in Zinchenko et al. (2020), a power calculation revealed that the current sample size would be appropriate to detect an f(U) effect size of 1.0 with 85% power (partial eta2 = .4, groups = 2, number of measurements = 4), given an alpha level of .05 and a nonsphericity correction of 1 (see also Schankin and Schubö, 2010; Zellin et al., 2011, for comparable sample sizes). Note that our sample size in the current study would also be adequate to resolve the previously reported polarity reversal in the N1pc amplitude in Zinchenko et al. (2020), which is reflected by a Context × Phase interaction (partial eta2 = .45). The Ethics Committee of the Department of Psychology at Ludwig-Maximilian's University Munich approved the study. All volunteers provided written informed consent and received 25 € for participating in the study. No part of the study procedures or analysis was pre-registered before the research was conducted. We report how we determined our sample size, all data exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study.

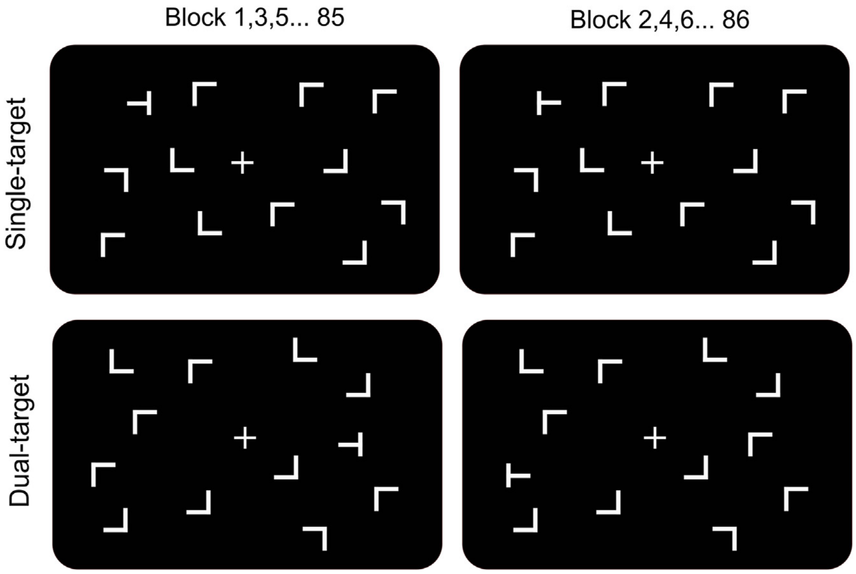

**Fig. 1 – Examples of repeated-context search displays in the single-target (top) and dual-target (bottom) conditions. Each search display presents a single T-shaped target and 11 distractor Ls. In the single-target condition, the repeated distractor arrangement would be paired with a single, fixed target location that would repeat across all blocks in the experiment. In the dual-target condition, two possible target locations would alternate between the left and right hemifields in odd and even blocks (left and right panels, respectively) while maintaining a constant configuration of distractor items. Note that the assignment of target locations to the right and left hemifields was randomized but balanced across both conditions.**

### *2.2. Apparatus and stimuli*

The experimental routine was programmed in Matlab with Psychophysics toolbox extensions (Kleiner et al., 2007) and was presented on an Intel PC under Windows 7. Participants were seated in a dimly lit room in front of a 23-inch LCD monitor (ASUS, Taiwan; refresh rate: 60 Hz; display resolution: 1920 × 1080 pixels) at a viewing distance of 60 cm (controlled by a chin rest). The search displays consisted of 12 gray items (luminance: 1.0 cd/m$^2$; 1 target and 11 distractors) presented against a black background (.11 cd/m$^2$; see Fig. 1). The target was a “T” shape rotated randomly by 90° to either the left or the right; the 11 remaining items were “L”-shaped distractors rotated randomly at orthogonal (0°, 90°, 180°, or 270°) orientations. All stimuli subtended approximately .4° of visual angle in width and height. The items were arranged on three (invisible) concentric circles around the display center (radii of 1.7°, 3.5°, and 5.2°, respectively). The task required observers to find the target shape and discern the target's left/right orientation. In repeated displays, the locations and orientations of the distractors were held constant across trials; in non-repeated displays, all distractors (i.e., their locations and orientations) were generated anew on each trial. Note that in all (repeated and non-repeated) displays, the location of the target was repeated, while its (left/right) orientation was determined randomly and was thus unpredictable, thereby ensuring that a repeated context could only be associated with a specific (repeated) target location, but not with a specific target identity requiring a specific response. This approach has been used in most CC studies to ensure that contextual learning reflects attentional guidance towards a given (target) location, rather than an association of the context with a given (invariant) manual response (see Chun & Jiang, 1998). Targets were randomly positioned, but with an equal probability to appear on rings 2 and 3. There were 24 possible target locations overall. Four of these (1 per quadrant) were used for single-target repeated displays (i.e., displays with only a single target location and a constant distractor layout throughout all trials as in “standard” CC experiments). Four different target locations were additionally used for single-target, non-repeated displays, in which a fixed target location was always paired with a distractor arrangement that was randomly determined on each trial. Another set of 2 × 4 target locations (2 per quadrant) was selected for the dual-target repeated displays. These 8 target locations in dual-target displays were generated such that for a given repeated display, one possible target location was presented in the left and the other one in the right display half, with the two locations alternating across odd and even trial blocks. Finally, an additional set of 2 × 4 target locations was selected for dual-target, non-repeated displays, which presented randomly generated distractor arrangements on each trial, together with fixed target locations that alternated between the two display halves on odd and even trial blocks (comparable to the procedure for repeated, dual-target displays). Fig. 1 presents example search displays with repeated context layouts in the single- and dual-target conditions. In all displays, the item distribution was balanced between the left and right display halves (6 items on the left and 6 on the right of the central fixation). The target was also equally likely to appear on each display type's left and right sides. The experiment consisted of 86 blocks of 16 trials each (4 single-target repeated, 4 dual-target repeated, 4 single-target non-repeated, and 4 dual-target non-repeated trials, presented in randomized order), yielding 1376 trials. Before commencing the experiment proper, participants performed two practice blocks of 32 trials (data not recorded).

### 2.3. *Trial sequence*

A trial started with the presentation of a central fixation cross (size: .25°; luminance: 1.0 cd/m$^2$) for 500 msec. Observers were instructed to fixate on the cross throughout the trial and use peripheral vision to locate the target and identify its orientation. Each search display was presented for 700 msec and was then removed, leaving only the fixation cross, which stayed on until the observer responded. If the target "T" was tilted to the right (left), they had to press the right (left) arrow button on the computer keyboard with their corresponding index finger. Following an erroneous response, the word "Wrong" appeared on the screen for 1500 msec. A blank inter-trial interval of 1000 msec followed each trial. Note that (except for the infrequent presentation of the additional error message), there was no temporal jitter implemented in the timing of a given trial.

### 2.4. *EEG recording*

The EEG was continuously sampled at 1 kHz using 64 Ag/AgCl active electrodes (acti-CAP system; Brain Products Munich) positioned according to the international 10–10 System. To monitor for blinks and eye movements, the electrooculogram was additionally recorded using electrodes placed at the outer canthi of the eyes and, respectively, the superior and inferior orbits. All electrophysiological signals were amplified using BrainAmp amplifiers (BrainProducts, Munich) with a .1–250 Hz bandpass filter. During data acquisition, all electrodes were referenced to FCz, and re-referenced off-line to averaged mastoids. All electrode impedances were kept below 5 kΩ.

Before segmenting, the raw data were visually inspected to remove non-stereotypical noise manually; subsequently, the data were bandpass-filtered using a .1–70 Hz Butterworth IIR filter (24 dB/Oct). Next, an infomax independent-component analysis was run to identify components representing blinks and horizontal eye movements and to remove these artifacts before the back-projection of the residual components. For the ERP analyses, the continuous EEG was epoched into 1000-msec segments relative to a 200-msec pre-stimulus interval, used for baseline correction. Only trials with correct responses and without artifacts –any signal exceeding ±60 μV, bursts of electromyographic activity (as defined by voltage steps/sampling points larger than 50 μV), and activity lower than .5 μV within intervals of 500 msec (indicating dead channels) – were accepted for further analysis on an individual-channel basis before averaging the ERP waves.

To extract the posterior components of interest (N1pc, N2pc) from overlapping target selection-unspecific components, ERPs from parieto-occipital electrodes (PO7/8) ipsilateral to the target's location were subtracted from contralateral ERPs. The latencies of the components were defined individually as the maximum negatively directed deflection in the time range of 80–180 msec (N1pc) and 180–400 msec (N2pc) post-stimulus. We computed ERP amplitudes by averaging 10 (N1pc) and 20 (N2pc) consecutive sample points before and after the maximum deflection.

Visual inspection of the data revealed that the N200 component was most pronounced between 290 and 330 msec after stimulus onset, while the N400 component was most pronounced between 350 and 500 msec, with both components revealing their maximum activation at electrodes AF3, F3, FC3, AF4, F4, and FC4. The mean amplitude of these six fronto-central electrodes was averaged across these time ranges for the ERP analyses. Note that both N200 and N400 ERP components were not lateralized.

### 2.5. *Recognition test*

At the end of the experiment, observers performed a yes/no recognition test, intended to examine whether any explicit memory about the repeated configurations was established. To this end, the eight repeated displays from the search task and eight newly composed displays were shown, and observers were asked to indicate whether they had seen a given display previously. The eight repeated and eight non-repeated displays were presented in random order. The dual-target displays were presented with the target randomly selected from the two possible target locations for a given display. The recognition responses were non-speeded, and no error feedback was provided.

## 3. Results

### 3.1. *Behavioral data*

Individual RTs and error rates were calculated for each factorial combination. For the RT analysis, error trials and RTs above and below 2.5 standard deviations from the mean were excluded, leading to the removal of ~14.9% of all trials. Mean values for each experimental condition were then submitted to a repeated-measures analysis of variance (ANOVA) with the factors Context (repeated, non-repeated), Target type (Dual-target, Single-target), and Epoch (1–11; where one experimental 'epoch' combines data across 8 consecutive trial blocks, except for epoch 11, which only averaged across 6 blocks). It should be noted that this analysis averaged across both target locations (that alternated across odd and even blocks) in dual-target displays, thus using identical trial numbers for the comparison of the single- and dual-target displays. This ensured that there were comparable "opportunities" to learn the repeating contexts for the two target types. Greenhouse-Geisser corrected values are reported in case Mauchly's test of sphericity was significant ($p < .05$).

Fig. 2A depicts the mean RTs for repeated and non-repeated displays across epochs in the single- and dual-target conditions. The ANOVA revealed a significant main effect of Context, with faster RTs on trials with repeated versus non-repeated displays (833 msec *vs* 860 msec), $F(1, 20) = 12.55$, $p = .002$, $\eta_p^2 = .39$, indicative of an overall CC-effect of 27 msec. The main effect of Target type was also significant, $F(1, 20) = 13.37$, $p = .002$, $\eta_p^2 = .40$: RTs were overall faster in the single-target relative to dual-target condition (832 msec *vs* 861 msec). The main effect of the Epoch was significant, too, $F(10, 200) = 5.38$, $p < .001$, $\eta_p^2 = .21$, showing that the RTs decreased (by 91 msec) from the first to the last epoch of the experiment. Moreover, there was also an interaction of Context by Epoch, $F(10, 200) = 2.62$, $p = .005$, $\eta_p^2 = .12$, which indicated that CC was not reliable, particularly during earlier epochs of the experiment (i.e., in epochs 1, 2, 4 and 7, all

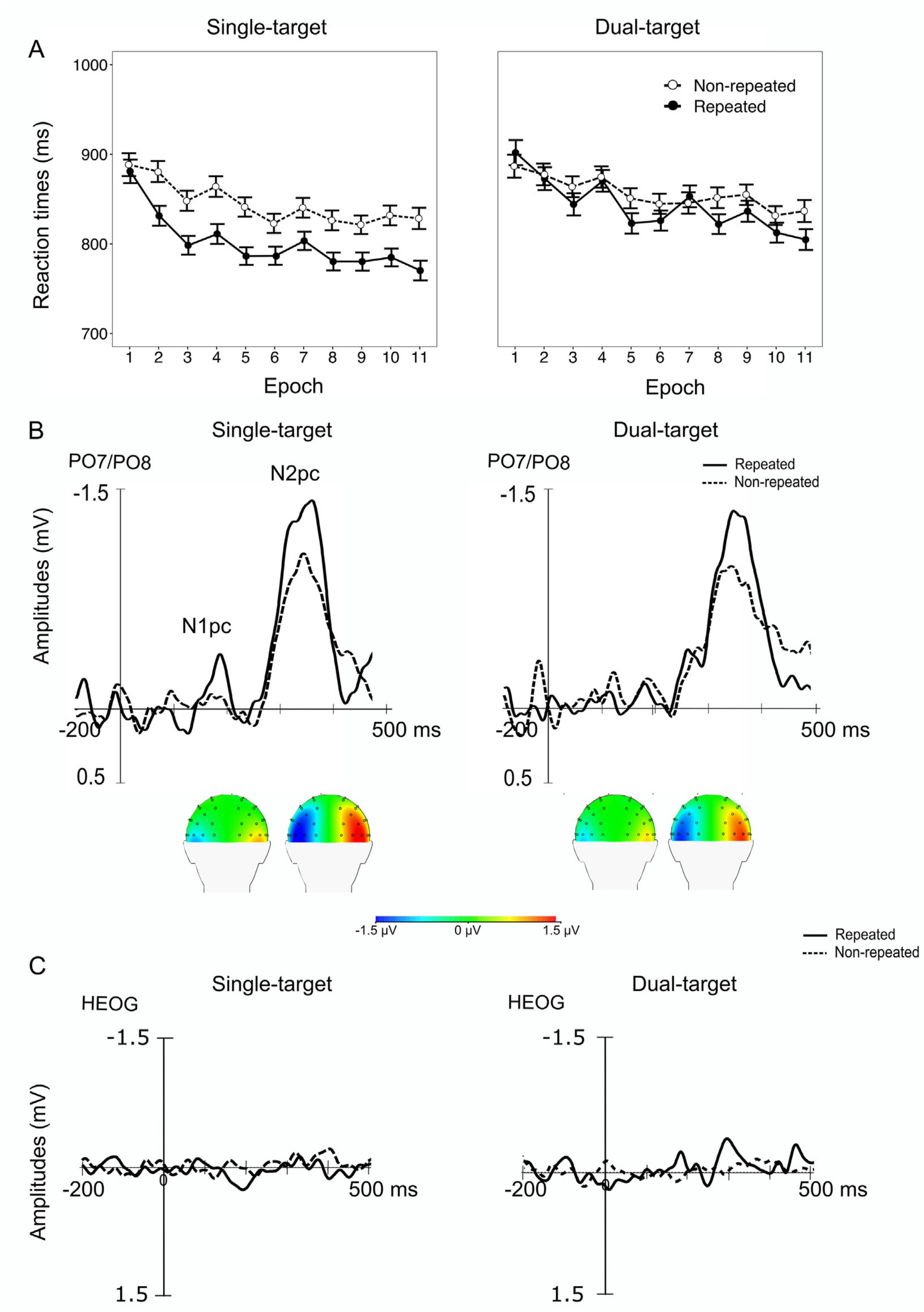

Fig. 2 — A. Mean reaction times (RTs, in milliseconds), with associated standard errors, for repeated and non-repeated contexts (solid and dashed lines, respectively) as a function of epoch in the single-target (left) and dual-target (right) conditions. B. Grand-average, lateralized event-related potentials (ERPs) at electrodes PO7/PO8 contra- [minus] ipsilateral to the target for non-repeated (dashed line) and repeated (solid line) contexts in the single-target (left) and the dual-target (right) conditions. Negative is plotted upward. For illustration purposes, the presented waveforms were low pass filtered at 20 Hz (with zero phase shift Butterworth filters, order 4). Each component (N1pc, N2pc) is depicted with its corresponding scalp distribution. C. Horizontal electrooculogram (HEOG) waveforms show repeated- and non-repeated context trials, averaged across all participants. The graphs show that participants were overall very accurate at maintaining central fixation, irrespective of the experimental conditions.

$p$'s > .05) while showing a substantial CC benefit towards the end of the experiment (i.e., in epochs 3, 5, 6 and 8–11, all $p$'s < .01). Most importantly, the Context by Target type interaction was significant, F(1, 20) = 6.03, $p = .023$, $\eta_p^2 = .23$. Follow-up t-tests revealed a significant cueing effect in single-target displays (46 msec), t(20) = 3.99, $p < .001$, Cohen's d = .89, which was not evident in dual-target displays (9 msec), t(20) = .87, $p = .39$, Cohen's d = .19 (see also Fig. 2A, left *vs* right panel). Moreover, planned pairwise comparisons in the dual-target condition additionally revealed some evidence for a residual CC-effect that gradually developed towards the end of the experiment and was evident in Epochs 8 (17 msec), t(20) = 1.88, $p < .05$, Cohen's d = .42 and Epoch 11 (26 msec), t(20) = −1.78, $p < .05$, Cohen's d = .40. There were no other significant effects (all $p$'s > .05).

The overall rate of response errors was 14%, which is high (by the usual standards of search RT experiments), but modest when taking the limited display exposure time and the requirement to fixate the screen center into account (see also Schankin & Schubö, 2009, 2010; Zinchenko et al., 2020 for comparable results). A repeated-measures ANOVA with the factors Context, Target type, and Epoch on the mean error rates revealed a significant main effect of Epoch, F(10, 200) = 4.35, $p < .001$, $\eta_p^2 = .18$, which showed that there were fewer errors towards the end of the experiment in Epoch 11 (12.4%) relative to the beginning, that is, in Epoch 1 (17.9%). Furthermore, the main effect of Target type was significant, F(1, 20) = 8.91, $p = .007$, $\eta_p^2 = .31$: participants made more errors in the dual-target condition (15.1%) relative to the single-target condition (12.8%). Finally, there was an interaction of Target type by Epoch, F(10, 200) = 2.37, $p = .011$, $\eta_p^2 = .11$. Follow-up t-tests showed that the error rates decreased substantially across epochs in the single-target condition (Epoch 1: 18.6%; Epoch 11: 10.9%), t = 2.39, $p < .001$, as opposed to the dual-target condition, which only revealed a trend for a reduction of the errors across epochs (Epoch 1 = 17.1%, Epoch 11 = 13.7%), t = 1.33, $p = .071$, $\eta_p^2 = .08$. No other main effects and/or interactions reached significance (all $p$'s > .1). Overall, the error analysis thus coincides with the RT data in showing that performance was enhanced with fewer possible target locations and with prolonged practice.

In a subsequent analysis, we compared the strength of cueing between individual pairs of target locations for repeated contexts in dual-target displays. For this analysis, we computed, for each observer, the mean RTs for each of the two individual target locations in each repeated, dual-target display, sorting the RTs by size into two bins, one that represents the “dominant” targets (with comparably faster RTs) and a second bin of “minor” targets (with comparably slower RTs, see Zellin et al., 2011, for a comparable analysis procedure). Of note, this sorting procedure, which was based on the mean RTs was done in a post-hoc manner, i.e., the classification into dominant and minor targets on the basis of the RTs could only be achieved after the experiment was completed. Moreover, the statistical comparison of the dominant and minor targets, was once again based on a comparable number of trials, thus equating the opportunities to learn the repeating contexts across both targets.

As can be seen from Fig. 3A, RTs to the dominant targets were indeed faster than RTs in the non-repeated (baseline) condition, while the minor targets elicited comparably slower RTs. Two repeated-measures ANOVAs with Context (Repeated, Non-repeated) and Epoch (1–11) were then performed on the dominant and minor target conditions. These analyses revealed a significant CC-effect with dominant targets, F(1, 20) = 33.46, $p < .001$, $\eta_p^2 = .63$, revealing faster RTs (by 59 msec) for repeated contexts with dominant targets relative to non-repeated contexts. There was also a significant main effect of Epoch, F(10, 200) = 4.14, $p < .001$, $\eta_p^2 = .17$, which again revealed that RTs were faster (by 92 msec) in the last Epoch 11 relative to Epoch 1, t(20) = 2.55, $p = .019$, Cohen's d = .57.

The main effect of Context was also significant for the analysis of the minor targets, F(1, 20) = 10.62, $p = .004$, $\eta_p^2 = .35$, but here, the direction of the effect was reversed, with slower RTs for minor targets with repeated contexts relative to the non-repeated contexts, thus resulting in a negative CC-effect of −45 msec. There was also again a significant main effect of Epoch, F(10, 200) = 5.51, $p < .001$, $\eta_p^2 = .22$, which showed that RTs decreased by 98 msec in Epoch 11 relative to Epoch 1, t(20) = 3.02, $p = .006$, Cohen's d = .68. Both analyses revealed no other significant effects (all $p$'s > .1).

### 3.2. *Electrophysiological data*

We calculated individual participants' mean amplitudes for each factorial (Target type × Context) combination, separately for the N1pc and N2pc components. These values were then submitted to repeated-measures ANOVAs with the factors Context (repeated, non-repeated) and Target type (Dual-target, Single-target). Fig. 2B presents the lateralized ERP waves, where activity at electrodes contralateral to the target was subtracted from activity ipsilateral to the target, separately for the single- (left) and dual-target (right) conditions.

The analysis of the *N1pc*, revealed a significant Context × Target type interaction, F(1, 20) = 9.84, $p = .005$, ηp2 = .33. Pairwise comparisons revealed a significant difference between repeated (−.95 mV) and non-repeated (−.51 mV) contexts in the single-target condition, t(20) = −2.42, $p = .024$, Cohen's d = .54, which was not evident in the dual target-condition, t(20) = .54, $p = .59$, Cohen's d = .12 (repeated = −.57 mV, non-repeated = −.64 mV). Next, the analysis of the *N2pc* revealed a significant main effect of Context, F(1, 20) = 7.03, $p = .015$, ηp2 = .26, which was due to more negative amplitude deflections for repeated (−1.41 mV), as compared to non-repeated (−1.06 mV) contexts. Both analyses revealed no other significant effects (all $p$'s > .05).

An additional analysis once again employed the RT-based classification procedure described above to categorize the lateralized ERPs for the two target locations in dual-target displays in terms of dominant and minor targets. To this end, the ERP data were sorted into dominant and minor bins depending on the mean RTs for the two (left and right hemifield) targets in each repeated dual-target display. It should be noted that this sorting procedure led, in four participants, to a distribution where all dominant targets were located in one hemifield, while all minor targets were found in the other hemifield. For these participants, it was thus impossible to calculate lateralized ERPs, with the electrophysiological responses being combined across both display halves. The data from these participants were therefore excluded from the

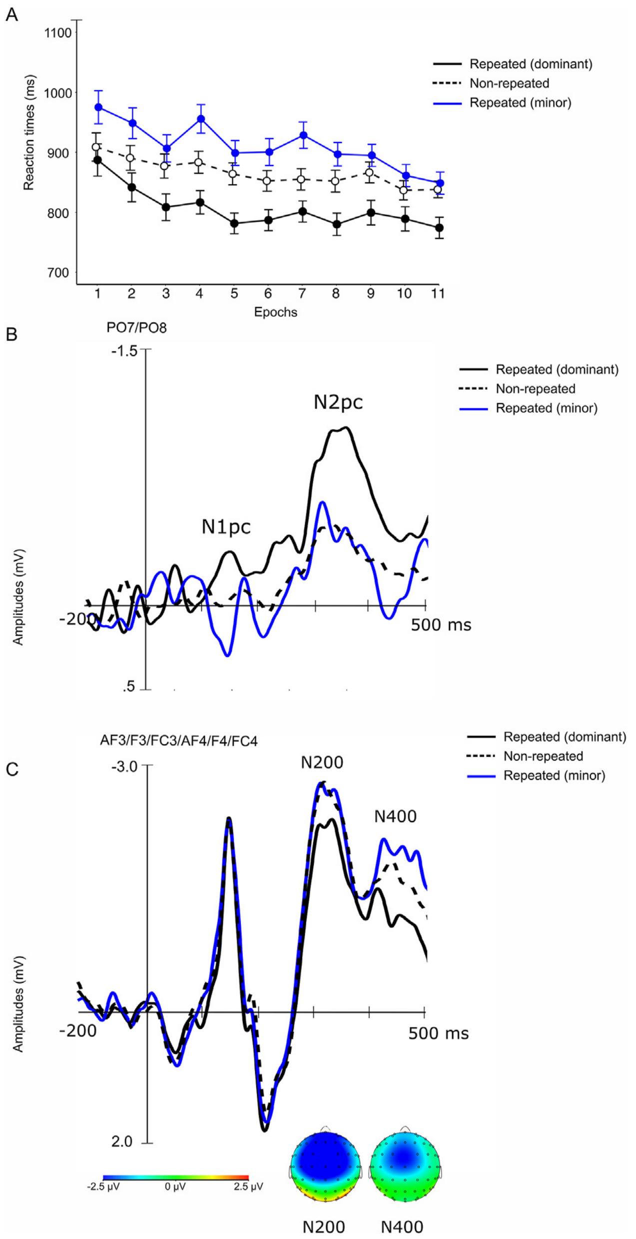

**Fig. 3 – A. Mean reaction times (RTs, in milliseconds), with associated standard errors, for repeated (dominant), non-repeated, and repeated (minor) contexts (black solid, dashed, and blue lines, respectively) as a function of epoch in the dual-target conditions. B. Grand-average lateralized difference waves at electrodes PO7/PO8 for repeated (dominant), non-repeated, and repeated (minor) contexts (solid black, dashed, and blue lines, respectively). C. Grand-average ERPs at electrodes AF3, F3, FC3, AF4, F4, and FC4 plotted for repeated (dominant), non-repeated and repeated (minor) contexts (solid black, dashed, and blue lines, respectively). Negative is plotted upward. The N200 and N400 are depicted with their corresponding scalp distributions.**

current analysis, thus leaving $N = 17$ participants in the data proper. Moreover, for 6 additional participants, three (of overall four) dominant/minor targets were also assigned to the same hemifield, thus again leading to a certain bias when calculating lateralized ERPs because the two hemifields would potentially differ in terms of their signal-to-noise ratio. To consider this imbalance, we employed a weighting functionality of the Brain Vision Analyzer v2.0 (Brain Products, Germany) software, which allows calculating lateralized ERPs proportional to the number of single-trial waveforms available for each hemisphere. In these six participants, we thus specified a weight of 75% for the condition where three dominant/minor targets were assigned to one hemisphere and a weight of 25% for the condition where one target was assigned to the other hemisphere. The resulting 'weighted' difference waves are shown in Fig. 3B.

For the *N1pc*, planned pairwise comparisons revealed a stronger negative-going deflection that was observed for dominant targets (−.25 mV), as compared to a positive-going deflection for minor targets (.26 mV), $t(15) = -1.82$, $p < .043$, Cohen's $d = .47$. Relative to the non-repeated context baseline (−.05 mV), the dominant targets were also (marginally) more negative, $t(15) = -1.49$, $p = .077$, Cohen's $d = .38$, while the minor-repeated targets were (marginally) more positive in amplitude, $t(15) = -1.35$, $p = .09$, Cohen's $d = .35$. In the subsequent *N2pc*, a difference between dominant (−1.25 mV) and minor (−.75 mV) targets was also apparent, $t(15) = -2.05$, $p = .029$, Cohen's $d = .53$. In relation to the non-repeated baseline (−.52 mV), dominant targets were again more negative in amplitude, $t(15) = -3.86$, $p < .001$, Cohen's $d = 1.00$. In contrast, the difference between targets in baseline displays and minor targets was not significant, $t(15) = 1.64$, $p = .12$, Cohen's $d = .42$.

The analysis of the fronto-central *N200* revealed significant differences between dominant (−2.35 mV) and minor (−2.79 mV) targets, $t(15) = 2.79$, $p = .014$, Cohen's $d = .72$, and between dominant targets and targets in non-repeated displays (−2.84 mV), $t(15) = -2.36$, $p = .032$, Cohen's $d = .73$. Finally, minor targets did not differ from targets in non-repeated displays, $t(15) = -.35$, $p > .7$, Cohen's $d = .09$. Identical analyses carried out on the *N400* again yielded a significant difference between minor (−1.88 mV) and dominant (−1.02 mV) targets, $t(15) = 2.84$, $p = .012$, Cohen's $d = .73$. The mean amplitude for targets in non-repeated displays (−1.60 μV) was, in turn, (marginally) more negative than the mean amplitude for dominant targets, $t(15) = -1.93$, $p = .072$, Cohen's $d = .50$, while being comparable to the minor targets, $t(15) = 1.46$, $p < .16$, Cohen's $d = .38$.

### 3.3. *Recognition test*

In the final recognition test, there was no difference between the hit rates (correct recognition of repeated displays as 'repeated': 70%) and the false alarms (erroneous recognition of non-repeated displays as 'repeated': 57%), $t(20) = -.52$, $p > .6$, Cohen's d = .12. Thus, there was little evidence of explicit contextual memory in the current experiment, which mirrors previous findings (e.g., Chun & Jiang, 1998). It should however be noted that this "standard" recognition test in contextual cueing experiments is typically associated with a comparably low sensitivity and these results should therefore be interpreted with caution (Geyer et al., 2020; Vadillo et al., 2016).

## 4. Discussion

The current study investigated whether a given, repeated context can be associated with multiple target locations. While it is, in general, well accepted that repeated contexts facilitate search by guiding visual attention to the target location (Chun & Jiang, 1998; Spaak & de Lange, 2020), it is less clear whether one repeated context may be associated with two (or more) target locations and facilitate search for both (or several) recurring targets. In addition to the inspection of the behavioral data, complementary EEG analyses were performed on lateralized posterior ERPs (reflecting memory-based attentional guidance) and non-lateralized frontocentral ERPs (reflecting processes of top-down attentional control), while focusing not only on the comparison of single- versus dual-target displays, but also on the differentiation of "dominant" and "minor" target locations within the repeated dual-target displays. These behavioral and neurophysiological measures should thus allow us to test whether contextual LTM templates can guide search towards only a single target or to multiple predictable targets.

Our results showed that the CC-effect with dual-target displays was significantly reduced relative to single-target displays, which revealed the typical pattern of contextual facilitation in RT measures. CC for single-target displays was also reflected in amplitude variations in the lateralized N1pc and N2pc components. However, the N1pc modulation was lacking with dual-target displays. This indicates that statistical learning of regularities was compromised at the early stages of information processing when two possible target locations alternated across blocks and required a rather flexible association with the repeated contexts. A subsequent, target-specific analysis of the dual-target displays, which differentiated between the more "dominant" and the comparably "minor" target location, revealed that one (dominant) target showed a strong CC- effect, while the other minor target conversely revealed a cost. In the ERPs, these CC benefits and -costs were directly reflected by the N1pc amplitude modulation, which revealed a reliable negative-going deflection towards the dominant target and, conversely, a reliable positive-going deflection towards the minor target. Of note, the two possible target locations in each dual-target repeated display would always be presented in opposite hemifields, such that the positive deflection with the minor target effectively reflects a negative-going bias in the N1pc amplitude towards the other, dominant target in the other display half. This shows that even with dual-target displays, participants were able to learn one specific distractor-target spatial relation, which, however, comes at the cost of (mistakenly) prioritizing this – 'dominant' – target location when the target appeared at the 'minor' location (thus showing some evidence of misguidance in this case). Subsequently, in the N2pc, a reliable negativity was again found, which was particularly pronounced for dominant targets, while the amplitude deflection for minor targets was now comparable to the (non-repeated) baseline. That is, the initial misguidance signal (in the N1pc) was effectively attenuated in the subsequent N2pc. Moreover, the frontal N200 and N400 components were found to be more negative for the minor (as compared to the dominant) targets, suggesting that top-down control processes attempt to overcome the spatial-attentional, though erroneous, bias towards the dominant target location – as indexed by the N1pc.

### 4.1. *Contextual learning is limited to single target positions*

Taken together, our behavioral findings replicate and extend the work by Zellin et al. (2011), who also investigated the flexibility of CC given multiple targets. They reported a substantially reduced CC-effect when a repeated context was paired with two possible target locations, while no cueing effect was observed at all with three possible target locations. Our behavioral results also mirror their target-specific analyses in multiple-target displays, which showed that repeated contexts paired with two (or three) possible targets may be differentiated regarding one dominant location engendering a reliable contextual benefit. In contrast, the other minor locations would eventually reveal no CC and/or a contextual cost. Consistent with this, our findings also indicated that the mechanisms underlying CC can bias attention effectively towards only one spatially confined region in each repeated display. However, it might be argued that sorting the target locations into dominant and minor categories inevitably results in larger versus smaller cueing effects for these target categories, that is, the RT sorting procedure would, at least in part, also determine the result of this comparison.

To overcome this problem, and to further test the single-location learning account, the current study also assessed the underlying neuronal representations associated with dominant/minor target processing. The initial categorization was still based on the mean RTs for individual targets in dual-target displays (which replicated previous findings as described above). However, we additionally analyzed the ERPs that were elicited by the minor and dominant targets, thus effectively assessing a measure that is independent from the sorting procedure. Interestingly, the overall conclusion of Zellin et al. (2011) and from the current RT analysis that contextual guidance is limited to only a single target location was also reflected in the N1pc: in the single-target condition, the acquisition of effective search-guiding contextual cues (as evidenced by a CC RT facilitation) was associated with an increased negativity in the N1pc (see also Chaumon et al., 2008; Zinchenko et al., 2020), but there was no comparable N1pc modulation in the amplitude of the dual-target condition when averaging across both targets. However, a reliable negative deflection was evident with the dominant target, while it reversed its polarity and revealed a positive-going deflection when the display contained a minor target (thus effectively providing an "erroneous" bias towards the currently irrelevant, dominant target in the opposite hemifield). This may be interpreted in terms of an early and automatic bias that occurred towards one of two overall possible targets, thus showing that the difference in RTs between dominant and minor targets may also be revealed during early-stage neuronal processing. It thus appears that the N1pc reflects both attentional guidance towards the dominant targets and the concurrent misguidance towards the minor targets, thus mirroring, yet crucially extending the previous behavioral work by Zellin et al. (2011).

In general agreement with these findings, previous studies also showed that the N1pc reflects early automatic 'priority signaling', that is, a reflexive attention bias triggered by the repeated context (Zinchenko et al., 2020; 2023; note that an N1pc is also visible between 100 and 200 msec poststimulus onset in Fig. 3 in Schankin & Schubö, 2009, but the authors did not formally analyze this component). However, in these studies, guidance and misguidance in the N1pc was related to separate experimental phases. During an initial learning phase, observers learned to associate a given repeated context with a given target, and this resulted in an enhanced N1pc. In a subsequent test phase, the target was relocated unexpectedly to a new position in the opposite hemifield (while then remaining at this position), and as a result cueing vanished and the N1pc was reversed in polarity. This is comparable to our current findings, but related to sequential phases in the experiment, whereas in the current study, the polarity switch is associated specifically (and in a post-hoc sorting procedure) with a learned target-context association versus a non-learned association that is evident on a trial-by-trial basis, thus proving further evidence that the polarity reversal in previous studies indeed reflected a bias that arises from contextual learning as observed in individual display configurations.

### 4.2. *Control of interference from within contextual LTM*

Following the N1pc, we also found a significant N2pc that was more pronounced for repeated relative to non-repeated displays, irrespective of the number of targets associated with a given, repeated context. However, additional target-specific analyses in the dual-target condition revealed an enhanced N2pc *only* for displays with a target at the dominant location. In contrast, targets at a minor location did not give rise to a significant difference relative to non-repeated displays. In contrast to the N1pc, the N2pc to minor targets did not reveal a "misguidance" signal (to the dominant targets) but did not reveal *any* bias. This may indicate that the N1pc-related misguidance signal was subsequently downregulated or attenuated in the N2pc. Together this pattern of results thus again supports the idea that the automatic (early) bias from statistical context learning can guide attention only to one restricted spatial region.

Previous studies investigating the N1pc predominantly reported that this component reflects an attentional bias that arises in response to salient items such as singleton targets or distractors (Wascher & Beste, 2010). While salient items often appear to elicit an N1pc independently of the top-down task set, Donohue et al. (2018) reported that an initial N1pc can be followed by the voluntary allocation of attention towards that element (indexed by N2pc) or away from it, thus revealing attentional suppression (indexed by the $P_D$; Hickey et al., 2009) if the salient item was categorized as a distractor item. Thus, the N1pc appears to reflect an early (pre-) attentive bias that marks important scene elements for further processing, including their selection as potential targets or their suppression in case of a distractor. Applied to the present investigation, we propose that the N1pc can also be elicited in a relatively difficult letter search task with little or minimal bottom-up guidance (Moran et al., 2013), but following experience with repeated search arrays. Thus, in contrast to the above-mentioned studies (i.e., Wascher & Beste, 2010; Donohue et al., 2018) that used pop-out targets versus (task-irrelevant) pop-out distractors for eliciting an N1pc from feature-contrast signals, the N1pc in the current experiment appears to reflect activity from a visual priority map, which is sensitive to one's previous experience, i.e., information derived from LTM-based statistical learning. – In support of this, several other previous ERP studies that also employed the CC paradigm reported an N1pc component (e.g., Zinchenko et al., 2020; 2023; see also Fig. 3 in Schankin & Schubö, 2009). Moreover, a comparable (occipital) activation with similar timing has also been reported in a CC MEG study (Chaumon et al., 2008).

As in the study by Donohue et al. (2018), the initial attentional bias from LTM (as reflected in the N1pc) was followed by a subsequent shift of spatial attention towards the target hemifield (as indexed by the N2pc). In most previous studies, the N2pc is measured in a time window between 180 msec and 350 msec (Eimer, 1996; Hickey et al., 2009; Hilimire et al., 2009; 2010; 2012; Luck & Hillyard, 1990; 1994; Luck et al., 1993; Papaioannou & Luck, 2020, which is comparable to the current study. Moreover, the N2pc would usually peak earlier in search tasks that are rather efficient, e.g., because the target is a salient stimulus that is rather easy to detect and/or where only few nontargets are presented (e.g., Eimer, 1996; Luck & Hillyard, 1994). As search difficulty increases, the N2pc then tends to peak substantially later (e.g., Conci et al., 2011; Luck et al., 1993; Töllner et al., 2011, 2015), and it has also been reported to last longer (Conci et al., 2011; Luck & Hillyard, 1990). The N2pc thus appears to vary in timing as a function of search difficulty. Several previous EEG studies also investigated CC, presenting a very similar, rather difficult search task, and also reported a comparable N2pc latency and topology to the one reported in our current study, which was also modulated by the repeated contexts (see Johnson et al., 2007; Schankin & Schubö, 2009; 2010; Zinchenko et al., 2020; 2023). Together, these latter findings thus provide coherent evidence that the allocation of spatial attention towards the target is facilitated by repeated search contexts in the N2pc.

Finally, the N200 and N400 components have been linked to attentional control processes (e.g., Bruchmann et al., 2010; Coderre et al., 2011; Heidlmayr et al., 2014; Naylor et al., 2012). For instance, they typically manifest with incongruent stimuli in a Stroop task, with the N200 possibly reflecting enhanced cognitive control relating to the inhibition of a given response and error monitoring (Boenke et al., 2009), while the N400 is usually associated with higher cognitive engagement when experiencing incongruent, conflicting stimuli. In this view, the enhanced frontal N200 and N400 with targets at minor locations reflects the effort necessary to downregulate the bias provided by the distractor configuration towards the dominant location. Consistent with this idea, Pollmann and Manginelli (2009; see also Pollmann, 2016) showed that after a consistent target location change in a CC search task, updating previously acquired target-context associations elicited enhanced activity over the frontopolar cortex. Moreover, using repetitive transcranial magnetic stimulation, Zinchenko et al. (2019) found that stimulation of the anterior prefrontal cortex "blocked" contextual updating after an unexpected target location change. These previous studies thus already reported some evidence for a contribution of frontal, executive control functions in suppressing task-irrelevant yet learned context–target associations. The current study provides novel evidence showing that such control mechanisms may also be measured at frontal electrodes sites with ERP measures. In this view, the frontal N200 and N400 might reflect enhanced attentional processing when presented with the minor targets to overcome the automatic bias towards dominant targets (even though this effortful attempt to compensate for an erroneous bias is – in terms of the behavioral measures – only partially effective).

Moreover, the enhanced N400 for minor (i.e., non-matching) target locations in repeated spatial contexts might not solely reflect top-down compensatory processes. Instead, they could additionally index the registration of a prediction error signal, as postulated by predictive coding models (e.g., Clark, 2013). For instance, previous studies observed a comparable enhanced N400 negativity when sentences were presented with words that violate predictions (e.g., when reading the sentence "I had a cup of coffee with sugar and dog"; Hunt et al., 2013, Kutas & Hillyard, 1980) or when images of natural scenes contained mismatching objects (e.g., a hammer in a kitchen scene; Võ & Wolfe, 2013). Violated predictions thus seem to be captured in the N400. In this view, the observed N400 modulation in the current study may likewise signal a prediction error, namely when the learned context is paired with a minor, that is, with an unpredicted target location.

## 5. Conclusion

Our results emphasize the view of context-guided visual search as an automatic attentional orienting process, where repeated configurations of items can bias attentional priorities and reflexively guide attention. In some cases, this may also lead to attentional misguidance when a learned configuration of distractors is paired with an unexpected (not learned) target location, thus leading to both behavioral costs and neurophysiological signatures of misguidance. CC thus appears to be limited to learning a single distractor-target association, thereby only biasing attention towards a single region of space during visual search. Moreover, overcoming the misguidance from the learned target-context associations may, in turn, engage frontal regions that detect the prediction error and exert top-down attentional control.

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## Data availability

The data that are reported in this study are available at: https://osf.io/gfkt6/

## Open practices

The study in this article has earned Open Data and Open Material Badges for transparent practices. The data and materials used in this study are available at: https://osf.io/gfkt6/.

## CRediT authorship contribution statement

**Artyom Zinchenko:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Thomas Geyer:** Writing – review & editing, Validation, Project administration, Funding acquisition, Conceptualization. **Xuelian Zang:** Software, Methodology, Conceptualization. **Zhuanghua Shi:** Software, Methodology, Conceptualization. **Hermann J. Müller:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Markus Conci:** Writing – review & editing, Validation, Supervision, Resources, Funding acquisition, Conceptualization.

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