Neural Evidence Suggests Both Interference and Facilitation from Embedding Regularity into Visual Search

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Abstract

■ In this work, we relied on electrophysiological methods to characterize the processing stages that are affected by the presence of regularity in a visual search task. EEG was recorded for 72 participants while they completed a visual search task. Depending on the group, the task contained a consistent-mapping condition, a random-mapping condition, or both consistent and random conditions intermixed (mixed group). Contrary to previous findings, the control groups allowed us to demonstrate that the contextual cueing effect that was observed in the mixed group resulted from interference, not facilitation, to the target selection, response selection, and response execution processes (N2-posterior-contralateral, stimulus-locked lateralized readiness potential [LRP], and response-locked LRP components). When the regularity was highly valid (consistent-only group), the presence of regularity drove performance beyond general practice effects, through facilitation in target selection and response selection (N2-posterior-contralateral and stimulus-locked LRP components). Overall, we identified two distinct effects created by the presence of regularity: a global effect of validity that dictates the degree to which all information is taken into account and a local effect of activating the information on every trial. We conclude that, when considering the influence of regularity on behavior, it is vital to assess how the overall reliability of the incoming information is affected. ■

INTRODUCTION

Identifying relationships between events constitutes the building blocks of understanding (Kareev, Lieberman, & Lev, 1997). Whether it is assessing when an animal is likely to attack, understanding that certain behavior leads to reward, or identifying sequences of sounds in a new language, it is clear that, to cope with the world, we rely on picking up recurring instances of events. Consequently, if regularity exists, it is beneficial to detect it promptly and to assess its degree of precision. It is therefore not surprising that much theoretical and empirical work has dealt with people's ability to pick up and rely on regularities (for a review, see Perruchet & Pacton, 2006). In the present work, we focus on identifying how cognitive processes are affected by visual regularities that are embedded within an ongoing task.

The most famous example of a visual regularity embedded within an ongoing task is the case of contextual cueing in visual search (Chun & Jiang, 1998). In a typical experiment, participants perform a visual search task that unbeknown to them contains two intermixed conditions: consistent mapping and random mapping. In the consistent mapping condition, predefined sets of targets and distractors (i.e., invariant configurations) are repeated across the experiment, whereas in the random mapping condition, the targets appear in novel or unrepeated configurations. Across numerous experiments and a number of different types of regularities, it was shown that participants are faster to find the target in the consistent mapping condition than in the random mapping condition, an effect termed "contextual cueing" (for a review, see Goujon, Didierjean, & Thorpe, 2015).

A widely accepted interpretation of the contextual cueing effect is that the repeating context in the consistent mapping condition is learned implicitly and serves as a cue that guides attention to the target, making the search process more efficient (e.g., Harris & Remington, 2017; Peterson & Kramer, 2001; Chun, 2000). Alternatively, it has been suggested that the difference between consistent and random conditions is a result of speedup in later processes, such as response selection and response execution (Kunar, Flusberg, & Wolfe, 2008; Kunar, Flusberg, Horowitz, & Wolfe, 2007). Presumably, in the consistent mapping condition, the decision criterion is lower than that in the random mapping condition, resulting in shorter decision processes (Kunar et al., 2007).

Importantly, both explanations described above attribute the contextual cueing effect to facilitation in the consistent mapping condition—participants are faster to find the target in the consistent condition, through either attentional guidance, response selection, or both. However, in a recent behavioral study, we have argued that this conclusion is problematic because the experimental design lacks the

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necessary baseline conditions (Vaskevich & Luria, 2018). Specifically, within the classic contextual cueing paradigm, consistent and random conditions are mixed, making it impossible to assess the influence of the conditions on each other. By comparing performance in a contextual cueing paradigm (i.e., consistent and random conditions mixed) with performance in a completely random (random-only group) and a completely structured (consistent-only group) search tasks, we were able to demonstrate that the contextual cueing effect reflects interference to performance, not facilitation: Participants reached faster RTs in a completely random visual search than in a mixed design search, although the latter contained a beneficial regularity on half of the trials.

To account for our results, we introduced the issue of validity, that is, taking into consideration that regularity is information that has a predictive value and that this value may change. When the regularity is valid, applying this knowledge can result in faster performance. Indeed, our results showed that the consistent-only group, which performed a completely structured visual search task, reached the fastest performance. This result indicates that online performance can benefit from regularity. However, for this benefit to occur, the regularity has to be highly reliable. When random and consistent mapping conditions are mixed, as in the contextual cueing paradigm, trying to continuously apply regularity will result in occasional failure when the regularity is applied in the random mixed condition. We argue that these failed attempts to apply regularity result in prediction errors that lead to reduced reliance on all of the accumulating information in the task (Clark, 2013), creating a global interference effect on performance (for a detailed account, see Vaskevich & Luria, 2018).

We have since replicated the pattern of results, which led us to suggest that the contextual cueing effect reflects interference and argue that relative validly is a crucial factor that is responsible for this interference (Vaskevich & Luria, 2019). However, behavioral studies alone cannot tell us where or when this interference occurs: As shown by previous studies, RTs may reflect both search and response processes (Kunar et al., 2007). Moreover, given previous results, it is likely that RTs reflect more than one effect, possibly both facilitating and interfering effects in different stages of the experimental trial. From this perspective, it is possible that the global interference effect we have described is overshadowing some facilitation from regularity.

To separate possible facilitating and interfering effects of regularity on ongoing performance, in this study, we recorded EEG and isolated the relevant ERP components for three groups of participants, while they completed a visual search task. Depending on the group, the task was either completely random, without any regularity, completely structured, in which case the regularity was valid on every trial (i.e., consistent mapping), or a visual search with consistent and random conditions mixed (i.e., classic contextual cueing paradigm). On the basis of previous studies, we focused on the N2-posterior-contralateral (N2pc) and lateralized readiness potential (LRP) components, as they reflect the search efficiency and response processes (Schankin & Schubö, 2009, 2010; Johnson, Woodman, Braun, & Luck, 2007). Below, we outline our predictions for each component and their theoretical implications.

N2pc

Generally, the N2pc is accepted as an indicator of attentional shifts toward the target, or target selection, such that higher amplitude in this component reflects a more efficient target selection process (Woodman & Luck, 1999, 2003; Eimer, 1996; Luck & Hillyard, 1994; for a conflicting view, see Zivony, Allon, Luria, & Lamy, 2018; Kiss, Jolicœur, Dell'Acqua, & Eimer, 2008). With regard to this study, differences between the experimental groups in this component would suggest differences in target selection efficiency during the search process.

For the mixed-design group, we expected to replicate previous studies (Schankin & Schubö, 2010; Johnson et al., 2007), so that a higher N2pc amplitude would be observed for the consistent mixed condition relative to the random mixed condition. Although this result was previously interpreted as evidence supporting a more efficient search process in the consistent mixed condition, we argue that, similarly to the behavioral effects discussed above, this is not necessarily the case: The difference may reflect an attenuated N2pc component for the random mixed condition, which would suggest a less efficient target selection process.

The key to understanding the modulation of target selection under mixed conditions is to compare them to a random visual search. If the contextual cueing effect indeed stems from a benefit to target selection in the consistent mixed condition, the N2pc amplitude observed for the consistent mixed condition should be higher than the N2pc amplitude observed for the random-only group (i.e., random visual search). Alternatively, a higher N2pc component in the random-only group, relative to the random mixed condition, would suggest an interference effect to the search process in the random mixed condition, presumably from failing to observe the expected regularity on the random mixed trials.

With regard to the impact of a reliable regularity, if it enhances target selection processes beyond a random visual search (as was argued by contextual cueing models), we should observe an enhanced N2pc component for the consistent-only group relative to the random-only group. Failing to observe this effect would suggest that the behavioral benefit from a completely valid regularity is not manifested in better target selection during the search process, as indicated by the N2pc.

LRP

The LRP component is regarded as an index of response-related processes (Smulders & Miller, 2012). This component can be measured in two distinct ways: time-locked to the presentation of the stimulus and time-locked to the execution of the response. Stimulus-locked LRP (s-LRP) reflects response selection, that is, the process of determining which response is appropriate for the stimulus. Response-locked LRP (r-LRP) reflects response preparation and execution, after the response has been selected. As both stages of the response process can be affected by confidence and response criterion (Kunar et al., 2007), differences between the present experimental groups and conditions could emerge in either or both LRP components.

Unlike with the N2pc component, the evidence regarding LRP components in contextual cueing is not clear. Schankin and Schubö (2009) did not observe a reliable difference in the size of both s-LRP and r-LRP amplitudes between the consistent mixed and random mixed conditions but found a correlation between the size of the contextual cueing effect and r-LRP onset. A subsequent study by the same authors (Schankin & Schubö, 2010) did not replicate this effect but instead found a nonsignificant trend toward an earlier s-LRP. It is hard to judge these results because, as stated by the authors, the specifics of the tasks in both studies were somewhat different from the classic contextual cueing effect, possibly contributing to the mixed results. In this study, we employ a design that closely resembles the one employed by Johnson et al. (2007) and the standard contextual cueing paradigm.

If there are differences between the consistent mixed and random mixed conditions in response criterion, we should observe a higher LRP amplitude for the consistent mixed condition relative to the random mixed condition in either stimulus-locked, response-locked, or both LRP components. However, as with the N2pc component, observing differences between the two mixed conditions can result from facilitation, interference, or both.

With regard to the impact of a reliable regularity, if it leads to the lowering of the response criterion beyond a random visual search, we should observe enhanced LRP components for the consistent-only group relative to the random-only group. Following the same logic we applied while discussing our expectations for the N2pc component, if the regularity facilitates response processes under mixed conditions, LRP amplitudes should be higher in the consistent mixed condition relative to the random-only group. Alternatively, lower LRP components in the random mixed condition relative to the random-only group would suggest an interference effect in the random mixed condition.

Perhaps, the most interesting prediction of this study is related to the overall interference we expect in the mixed-design group. According to our proposed theory, mixing regularity with randomness creates uncertain conditions, resulting in reduced reliance on all the information in the task (Vaskevich & Luria, 2018). In contrast, the conditions administered alone are both reliable: In the consistent-only group, the expected regularity is always observed, whereas in the random-only group, no regularity is expected or observed. To support the argument that at least some of the slowdown in the mixed group stems from a global effect of validity, at least one of the LRP components should not depend on the type of trial (with or without regularity) but on the overall reliability within the task.

Because uncertainty is a factor known to affect response criterion (Kunar et al., 2007), the overall effect of validity is likely to emerge in one or both of the LRP components. Specifically, we expect to observe similar and high (relative to mixed conditions) amplitudes in s-LRP, r-LRP, or both components. Furthermore, we should observe similarly attenuated amplitudes for the consistent mixed and random mixed conditions, as these are part of the same relatively unreliable environment.

To summarize, comparing the N2pc and LRP components between the three experimental groups (mixed group, consistent-only group, and random-only group) should enable us to identify how search and response processes are modulated by regularity in visual search as a function of its reliability. Previous studies either evaluated ERP components for a mixed-design group only (Schankin & Schubö, 2009; Johnson et al., 2007) or compared between the three experimental groups behaviorally (Vaskevich & Luria, 2018). Combining these two approaches is essential to isolate the origins of the overall behavioral slowdown we have observed in a mixed-design group and characterize which processes, and under what conditions, benefit from regularity in visual search.

METHODS

Participants

To estimate the required sample size, we conducted a power analysis (G*Power software; Faul, Erdfelder, Lang, & Buchner, 2007) using the effect size of a previously observed main effect for Group in a two-way ANOVA (Vaskevich & Luria, 2018). This result suggested a behavioral difference between the three experimental groups, and we expect to replicate it in this study. Applying a conventional alpha of .05 and 80% power, the power analysis indicated that a sample of 57 participants was required to detect a reliable effect. Because this study also contains comparisons between ERP components, we increased this estimation to 72 (24 in each experimental group). This sample size is also in line with previous studies that examined the N2pc and LRP components in visual search and contextual cueing and relied on samples of 16–21 participants (Schankin & Schubö, 2009; Johnson et al., 2007).

Overall, 75 undergraduate students (52 women, mean age = 23.7 years, *SD* = 2.4 years) from Tel Aviv University participated in the study in return for credits or payment. There were no differences in age or sex between the three experimental groups. Three participants exceeded the maximum allowed rejection rate criterion (25% of trials) and were discarded from the study. All analyses are reported for the remaining 72 participants.

Stimuli and Procedure

All participants gave informed consent following the procedures of a protocol approved by the ethics committee at the Tel Aviv University. Participants then received a general explanation regarding EEG experiments and completed three tasks in the following order: visual working memory (VWM) capacity assessment, visual search task, and a surprise familiarity test. EEG was recorded only during the visual search task. The VWM capacity estimation was done with a change detection task (Luria & Vogel, 2011; Luck & Vogel, 1997). All tasks were conducted on a 23-in. light-emitting diode monitor with a 120-Hz refresh rate, using 1920 × 1080 resolution graphics mode.

Stimuli in the change detection task (VWM estimation) were colorful squares that were chosen randomly on each trial from a set of nine colors: blue, brown, cyan, green, orange, pink, red, yellow, and black. Each square subtended approximately 1.2° × 1.2° of visual angle and was randomly positioned within a 20° × 20° region upon a gray background. The minimal distance between each two stimuli was 2.1° of visual angle (center to center).

Stimuli in the visual search task were white Ts and Ls. All stimuli were made up of two lines of equal length (forming either an L or a T). From a viewing distance of approximately 60 cm, each item in the display subtended 1.5° × 1.5° of visual angle. For the L letter, the vertical bar was offset toward the center by 0.1° (Figure 1). All items appeared within an imaginary rectangle (20° × 15°) on a gray background with a white fixation cross in the middle of the screen (0.4° × 0.4°). Because both the N2pc and LRP components are difference waves, targets appeared with equal probability on the right or left side of the screen, never in the middle of the screen (Johnson et al., 2007).

Visual Working Memory Task

VWM capacity estimation was done with a change detection task: Arrays of either four or eight colored squares (memory array) appeared for 150 msec. After a 900-msec retention interval, one colored square (test probe) appeared at the location of one of the items from the memory array. Participants indicated with an unspeeded keyboard press whether the color of the test probe was the same or different from the color of the item presented previously in that location (with equal probability for same and different test probes). The task consisted of 60 trials for each array size in one intermixed block (120 trials overall). On change trials, the original item was replaced with a color not presented in the memory array. VWM capacity was computed with a standard formula: $K = S(H - F)$. K is the memory capacity, S is the size of the array, H is the observed hit rate, and F is the false alarm rate (Pashler, 1988).

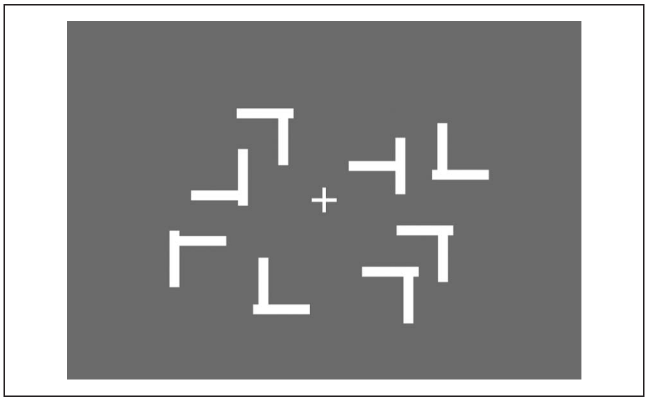

Figure 1. Visual search task. The target was a letter T rotated either left or right that appeared among rotated Ls (distractors). Participants pressed a response key corresponding to the appropriate target as fast as possible.

Visual Search Task

Participants searched for a rotated T (target) among heterogeneously rotated Ls (distractors) while keeping their eyes on the fixation cross. Each trial began with the presentation of a fixation cross for 2100, 2200, or 2300 msec (randomly jittered) followed by an array of one of two possible targets (left or right rotated T) among seven distractors. The search display was present on the screen until response. Participants were instructed to press a response key corresponding to the appropriate target as fast as possible. The fixation period in the beginning of each trial was chosen after a pretest that determined the amount of time needed for participants to blink comfortably after they have finished responding.

Depending on the group, the visual search contained the consistent mapping condition, the random mapping conditions, or both. For the consistent mapping condition, spatial configurations of targets and distractors were randomly generated for each participant (eight layouts for the mixed-design group and 16 layouts for the consistent-only group). The order of layouts was randomized between blocks. In the random mapping condition, targets and distractors appeared in random locations throughout the task (within an imaginary rectangle of 20° × 15°), with the exception that for the mixed-design group, targets in the random condition could not appear in the same locations as targets in the consistent condition. In all conditions, the identity of the target (left or right rotation) was chosen randomly on each trial and did not correlate with the spatial regularity (Figure 1). Participants completed 16 epochs of trials (each epoch was composed of two blocks), so overall there were 512 trials in the experiment. Every block contained 16 trials. Depending on the group, these were all consistent mapping (i.e., repeating spatial layouts), all random mapping, or eight consistent and eight random mapping trials that were presented in a random order. The order of trials in the consistent mapping conditions was randomized between blocks so that the spatial layout was the only regularity in the task.

Familiarity Test

Upon completing the search task, participants in the consistent and mixed groups were asked whether they have noticed any regularity throughout the experiment. To test for explicit knowledge, participants were then presented with the spatial layouts that appeared in the visual search task intermixed with randomly generated new spatial layouts. For each layout, participants indicated whether they have seen the layout during the visual search task or not.

Note that, although the familiarity test is widely accepted within the contextual cueing literature (Conci & Müller, 2012; Zellin, Conci, von Mühlenen, & Müller, 2011; Schankin & Schubö, 2009; Chun & Jiang, 1998), it is different from the memory test used in our previous studies in which participants were required to actively indicate where they think targets have appeared (Vaskevich & Luria, 2018, 2019). Although assessing explicit memory with active matching tasks is highly sensitive, it was not appropriate for this study. Because of the EEG recording, it was vital that participants stay on fixation while they search for the target. To ensure that participants are able to do so, the area in which all stimuli could appear was relatively small (compared to previous studies). A pretest showed that this adjustment made it impossible to separate random guessing from traces of explicit knowledge: Similar "memory" was exhibited by participants who were given the memory task after completing a visual task that contained regularity and participants who were given only the memory test and asked to randomly add an item to the display.

EEG Recording and Analysis

EEG was recorded inside a shielded Faraday cage, with a Biosemi ActiveTwo system (Biosemi B.V.), from 32 scalp electrodes at a subset of locations from the extended 10–20 system, including mostly occipital and parietal sites (in which the N2pc is most pronounced), namely, Fp1, Fp2, AF3, AF4, F3, F4, F7, F8, Fz, FCz, C3, C4, Cz, T7, T8, P1, P2, P3, P4, P5, P6, P7, P8, Pz, PO3, PO4, PO7, PO8, POz, O1, O2, and Oz), as well as from two electrodes placed on the mastoids. EOG was recorded from two electrodes placed 1 cm laterally to the external canthi, to detect horizontal eye movements, and one electrode beneath the left eye to detect blinks and vertical eye movements. The single-ended voltage was recorded between each electrode site and a common mode sense electrode (CMS/DRL). Data were digitized at 256 Hz. Offline signal processing was performed using the EEGLAB Toolbox (Delorme & Makeig, 2004), ERPLAB Toolbox (Lopez-Calderon & Luck, 2014), and custom MATLAB (The Mathworks, Inc.) scripts. All electrodes were referenced offline to the average of the left and right mastoids.

Artifact detection was performed using a sliding window peak-to-peak analysis, with a threshold of 80 μV for the EOG electrodes and 100 μV for the analyzed electrodes (P7, P8, PO3, PO4, PO7, and PO8 for the N2pc component; C3 and C4 for the LRP component). These procedures resulted in the following mean rejection rates: mixed group: 2.2% N2pc, 3% s-LRP, and 7.7% r-LRP; consistent-only group: 3.3% N2pc, 3.2% s-LRP, and 8% r-LRP; random-only group: 3.1% N2pc, 2.7% s-LRP, and 5.7% r-LRP. Of the 72 participants, five exhibited high rejection rates in the r-LRP component (<35%). However, these were because of the number of blinks made with the response. As all stimulus-locked rejection rates were low (<11%), these participants were not removed from the analyses. The epoched data were then averaged and low-pass filtered using a noncausal Butterworth filter (12 dB/oct) with a half-amplitude cutoff at 30 Hz. Only trials with a correct response were included in the analysis.

For analysis of the N2pc component, the continuous data were segmented into epochs from −200 to + 600 msec relative to the onset of the stimulus and were normalized relative to the 200-msec window before stimulus onset. The component was then isolated from the overall ERP waveform by computing difference waves in which the waveform for ipsilateral targets was subtracted from the waveform for contralateral targets and then averaged over the left and right hemispheres (Johnson et al., 2007). Given previous results, the measurement of interest was N2pc amplitude that was quantified from the difference waves at the P7/8, PO3/4, and PO7/8 electrode sites.

The LRP was calculated both relative to the onset of the search display (stimulus-locked, s-LRP) and relative to the onset of the response (response-locked, r-LRP). For analysis of the s-LRP component, the continuous data were segmented into epochs from −200 to +700 msec relative to the onset of the stimulus and were normalized relative to the 200-msec window before stimulus onset. For analysis of the r-LRP component, the continuous data were segmented into epochs from −600 to +200 msec relative to the response and were normalized relative to a 200-msec window from −600 to −400 msec before response. The procedure was similar to the computation of the N2pc component. However, the LRP was calculated relative to the response hand, not target location, at electrodes placed over the motor cortex (C3/C4).

It is important to note that, during the visual search task, targets appeared to the left and right of the participant's midline. As such, the direction of attentional shifts and the response hand could covary, making it impossible to rule out the contribution of attentional factors to the LRP component (Praamstra, 2007; Eimer, 1998). This limitation will be taken into consideration when we interpret the LRP results and addressed again in the Discussion section.

For both N2pc and LRP components, the measurement time windows (Table 1) were chosen by visual examination of the data collapsed across conditions, participants, and groups (Luck, 2014). This procedure was done to avoid any bias based on the timing of the experimental effects of interest.

Table 1. Measurement Time Windows for Each Component

Component	*Time Window (msec)*
N2pc	200–350 (stimulus locked)
s-LRP	400–600 (stimulus locked)
r-LRP	−150 to 0 (response locked)

RESULTS

The data were aggregated and organized before the statistical analyses using *prepdat* (Allon & Luria, 2016). For all null effects, we complement the p values of our main analyses with a Bayes factor BF_{01} (indicating the degree of support for the null hypothesis), calculated using the JASP software (Cauchy prior width = 0.707).

Behavioral Results

Visual Search

For the behavioral results, data were grouped into 16 epochs, each consisting of two blocks. As in our previous work, RTs below 100 msec and above 4000 msec, error trials, and trials immediately after errors were excluded from analysis (Vaskevich & Luria, 2018). Accuracy was high in all experimental groups and conditions (>94%). However, small but significant differences emerged. We first report analyses for RTs and then for accuracy.

Reaction times. To assess the contextual cueing effect in the mixed group, we conducted repeated-measures ANOVA with the factors Condition (consistent mapping/random mapping) and Epoch (1–16). There was a significant main effect for Condition, $F(1, 23) = 41.5, p < .001, \eta_p^2 = .64$, with significantly faster RTs for the consistent mixed condition ($M = 961, SD = 251$) than for random mixed condition ($M = 1160, SD = 260$), reflecting a contextual cueing effect. There was also a significant main effect for Epoch, $F(15, 23) = 68.72, p < .001, \eta_p^2 = .75$, indicating a practice effect. The interaction between Condition and Epoch was not significant, $F < 1$.

To isolate the effect created by mixing regularity with random trials, the two mixed conditions were compared to the completely random visual search (random-only group). The difference between RTs in the random mixed condition ($M = 1160, SD = 226$) and the random-only group ($M = 935, SD = 159$) was significant, $t(1, 46) = 4, p < .001, d = 1.15$ (false discovery rate [FDR]-corrected p value was .025; Benjamini & Hochberg, 1995), indicating that the random-only group was 225 msec faster than the random mixed condition. The difference between the consistent mixed condition and the random-only group was not significant, $t(1, 46) = 0.5, p = .6, B_{01} = 3.1$. These results replicate our previous findings, demonstrating that the contextual cueing effect stems from an interference effect in the random mixed condition and not from facilitation in the consistent mixed condition (Figure 2).

For completeness, we performed a repeated-measures ANOVA with the within factor Epoch (1–16) and between-factor Group (mixed/consistent only/random only). There was a significant main effect for Epoch, $F(15, 69) = 203.57, p < .001, \eta_p^2 = .75$, and a significant main effect for Group, $F(2, 69) = 9.1, p < .001, \eta_p^2 = .2$. Further analysis revealed that the main effect for Group resulted from the mixed group performing significantly slower than both the consistent-only ($p < .001$) and random-only ($p < .001$) groups. The interaction between Group and Epoch was not significant, $F < 1$. Note that, for this analysis, the data in the mixed group were collapsed across random mixed and consistent mixed conditions. However, to provide an accurate illustration for all of the behavioral results, the consistent mixed and random mixed conditions are plotted separately in Figure 2.

Accuracy. Analyses for accuracy were similar to the analyses conducted for RT data.

In the mixed group, we conducted repeated-measures ANOVA with the factors Condition (consistent mapping/random mapping) and Epoch (1–16). There was a significant

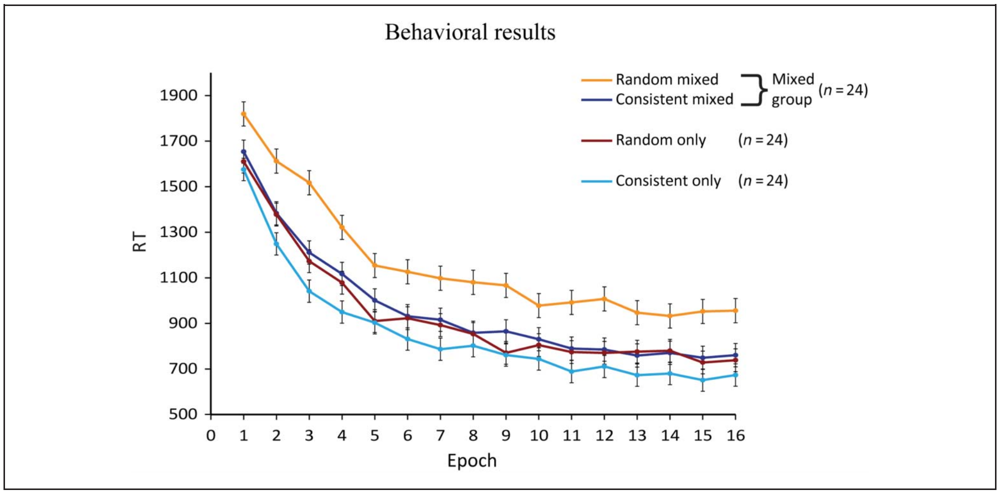

Figure 2. Visual search task. RTs are plotted as functions of epochs (two blocks per epoch). In the consistent mapping condition, targets appeared in the same spatial configuration throughout the task. In the random mapping condition, targets and distractors were presented in random locations. A contextual cueing effect was observed in the mixed-design group. However, performance in the mixed group was slower than performance in both the random-only and consistent-only groups ($n = 24$ in all groups).

main effect for Condition, $F(1, 23) = 15.7, p < .001, \eta_p^2 = .4$, with significantly higher accuracy for the consistent mixed condition ($M = 96.7, SD = 0.03$) than for the random mixed condition ($M = 94.3, SD = 0.04$). This result is in line with the contextual cueing effect observed for the RT data. There was also a significant main effect for Epoch, $F(15, 23) = 2.96, p < .001, \eta_p^2 = .11$, indicating that participants made more mistakes as the task progressed. The interaction between Condition and Epoch was also significant, $F(15, 345) = 1.99, p = .015, \eta_p^2 = .08$. Further analyses revealed that, in the second half of the experiment, more mistakes were made in the random mixed than in the consistent mixed condition in three of eight epochs (Epochs 9, 14, and 16; all p values smaller than .023; FDR-corrected p value was .025; Benjamini & Hochberg, 1995).

Next, the mixed conditions were compared to the completely random visual search (random-only group). Accuracy rates did not differ between the random mixed condition ($M = 94.3, SD = 0.04$) and the random-only group ($M = 94.3, SD = 0.03$), $t(1, 46) = 0.04, p = 1, B_{01} = 3.5$. The difference between accuracy rates in the consistent mixed condition ($M = 96.7, SD = 0.03$) and the random-only group was significant, $t(1, 46) = 2.7, p = .009, d = 0.8$ (FDR-corrected p value was .025). These results suggest that, contrary to RTs, there was an advantage for accuracy (2%) for consistent trials in a mixed setting over a random visual search.

Finally, we performed a repeated-measures ANOVA with the within-factor Epoch (1–16) and between-factor Group (mixed/consistent only/random only). There was a significant main effect for Epoch, $F(15, 69) = 10, p < .001, \eta_p^2 = .13$, and a significant main effect for Group, $F(2, 69) = 5.2, p = .008, \eta_p^2 = .13$. Further analyses revealed that the main effect for Group resulted from the random-only group performing less accurately than the consistent-only group ($p < .001$). The interaction between Group and Epoch was marginally significant, $F(30, 1035) = 1.4, p = .07$.

To summarize, the behavioral results for RTs replicate our previous findings and further support the argument that, although a reliable regularity is beneficial to performance, mixing regularity with random trials results in interference (Vaskevich & Luria, 2018). Overall, the pattern of results observed for RTs suggests that the main force that drives the contextual cueing effect is interference to performance in the random mixed condition. Unlike our previous studies, a small advantage in accuracy (2%) was observed when regularity was present, regardless of validity. To identify what processes are affected by the presence of regularity, and how, we now turn to the EEG results.

EEG Results

N2pc

As with the behavioral results, we first assessed the differences in N2pc amplitude between conditions within the mixed group. Next, the two mixed conditions were compared with the random visual search. Finally, to test whether a valid regularity benefits target selection beyond regular visual search, we compared the consistent-only and random-only groups.

For the mixed group, a repeated-measures ANOVA with the factor Condition (consistent mixed/random mixed) showed a higher N2pc amplitude for the consistent mixed condition ($M = -0.8, SD = 0.7$) relative to the random mixed condition ($M = -0.37, SD = 0.3$), $F(1, 23) = 10.83, p = .003, \eta_p^2 = .32$. This result is a replication of previous findings (Schankin & Schubö, 2010; Johnson et al., 2007). In line with the behavioral results, a higher N2pc amplitude was observed for the random-only group ($M = -0.67, SD = 0.4$) relative to the random mixed condition ($M = -0.37, SD = 0.3$), $t(1, 46) = 2.8, p = .007, d = 0.8$ (FDR-corrected p value was .017). In addition, there was no difference between the random-only group and the consistent mixed condition, $t(1, 46) = 0.8, p = .4, B_{01} = 2.7$. This pattern of results suggests that the difference between N2pc amplitudes between the mixed conditions stems from attenuation in the random mixed condition, not enhancement in the consistent mixed condition (Figure 3).

Interestingly, there was no difference in N2pc amplitude between the consistent-only ($M = -0.86, SD = 0.5$) and random-only ($M = -0.67, SD = 0.4$) groups, $t(1, 46) = 1.4, p = .17, B_{01} = 1.6$. If a reliable regularity facilitates the target selection process, such an effect should have been observed.

As in previous EEG studies, the ERP comparisons relied on the analyses of the entire data set (Schankin & Schubö, 2010; Johnson et al., 2007). To provide additional insight into any possible differences between the ERP components when participants have reached optimal performance, after analyzing the entire data set, all ERP analyses were repeated using data only from the second half of the experiment. This measurement is meant to reflect, as closely as possible, the end-of-session measurement that is often used in behavioral studies (last three epochs collapsed; Vaskevich & Luria, 2018; Kunar et al., 2008; Kunar, Flusberg, & Wolfe, 2006; Chun & Jiang, 1998). Because comparing ERP components requires a large number of trials, we relied on the entire second half of the experiment, not the last three epochs. When analyzing the second half of the experiment, all results remained the same, except for a marginally significant benefit for the consistent-only group over the random-only group, $t(1, 46) = 1.8, p = .072$. This result suggests that a valid regularity may have a benefit to target selection. However, this benefit is small and takes time to develop.

Overall, the N2pc results showed interference in the random mixed condition, when the overall validity in the task is low. This interference seems to drive, at least partially, the contextual cueing effect. We found no evidence for enhanced target selection in the consistent mixed condition. A trend for a facilitation effect in target selection was observed only under valid conditions (i.e., consistent-only group) and only late in the experiment (second half).

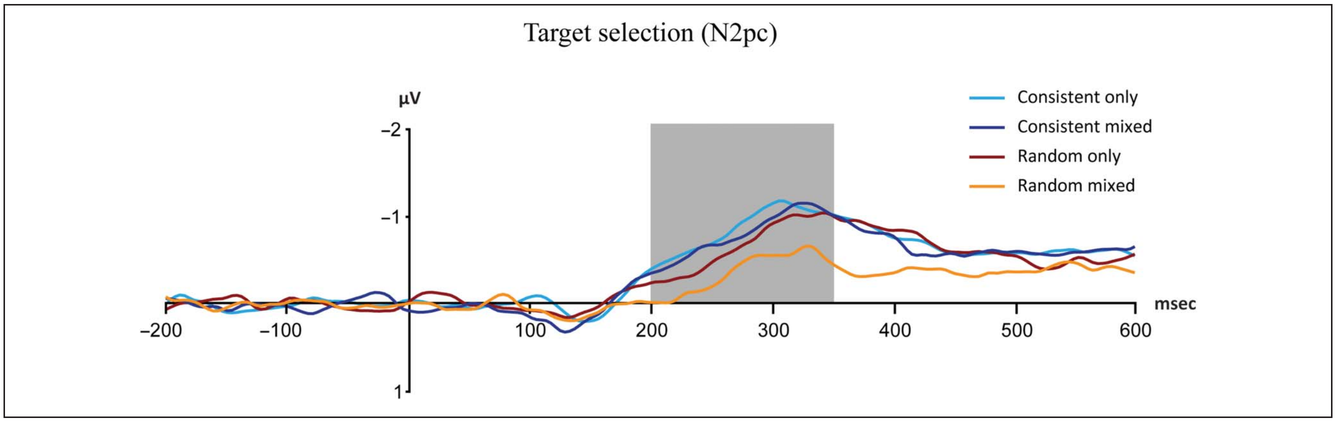

Figure 3. N2pc results for the visual search task. The gray rectangle marks the analyzed time window (av(P8,PO8,PO4)/av(P7,PO7,PO3). Within the mixed-design group, N2pc amplitude was attenuated for the random mixed condition relative to the consistent mixed condition. In addition, N2pc amplitude was attenuated for the random mixed condition relative to the random-only group.

s-LRP

Analyses for the s-LRP component were the same as for the N2pc component. The mixed-design group contained an outlier subject (both s-LRP and r-LRP amplitudes > 3 *SD*s than the mean amplitudes observed). We report here the results for all participants and results calculated excluding the outlier participant when these differ from the main analyses.

For the mixed group, a higher s-LRP amplitude was observed for the consistent mixed condition ($M = -0.57$, $SD = 0.56$) relative to the random mixed condition ($M = -0.22$, $SD = 0.67$), $t(1, 23) = 2.1$, $p = .049$, $d = 0.4$. This result mirrors the pattern observed for the N2pc component. To provide further interpretation of this difference, the mixed conditions were compared to a random visual search. An independent *t* test showed that the difference between the random-only group ($M = -0.55$, $SD = 0.7$) and the random mixed condition ($M = -0.22$, $SD = 0.67$) did not reach significance, $t(1, 46) = 1.6$, $p = .11$. However, when the outlier in the mixed group was removed (s-LRP amplitudes > 3 *SD*s), the difference became significant, $t(1, 45) = 2.5$, $p = .015$, $d = 0.7$ (FDR-corrected *p* value was .033). This result points to an interference effect in response selection in the random mixed group. Though, note that, because the targets in the visual search were lateralized, it is possible that interference in the search process (N2pc) also contributed to the observed s-LRP suppression (Praamstra, 2007; Eimer, 1998). As with the N2pc component, there was no difference between the random-only group and the consistent mixed condition, $t(1, 45) = 0.1$, $p = .9$, $B_{01} = 3.46$. This result suggests that there was no benefit in response selection in the consistent mixed condition (Figure 4A).

A higher s-LRP amplitude was observed for the consistent-only group ($M = -1$, $SD = 0.75$) relative to the random-only group ($M = -0.55$, $SD = 0.7$), $t(1, 46) = 2.2$, $p = .029$, $d = 0.6$ (FDR-corrected *p* value was .033). This result suggests that the faster RTs observed for the consistent-only group stem primarily from an advantage to the response selection process. As with the suppressed s-LRP observed for the random mixed condition, it is possible that search efficiency (i.e., target selection) also contributed to the effect. We return to this issue in the Discussion.

r-LRP

In our predictions, we stated that we expect to see an effect either s-LRP or r-LRP that would reflect the role of validity: similar LRPs for high-validity conditions versus low-validity conditions. We did not have a prediction whether this effect would emerge in response preparation or response execution (i.e., s-LRP, r-LRP). Upon examining the data, it seems that the effect is in response execution: Similar r-LRP amplitudes were observed for the low-validity conditions (consistent mixed [$M = -1.5$, $SD = 1.2$] and random mixed [$M = -1.47$, $SD = 1.2$]) and for the high-validity conditions (consistent-only [$M = -2.1$, $SD = 0.98$] and random-only [$M = -2$, $SD = 1.45$] groups).

To test whether high-validity conditions differed in response execution from low-validity conditions, we collapsed the two high-validity groups into one group (consistent only and random only) and compared it with the low-validity group (consistent mixed and random mixed conditions averaged). The difference between r-LRP amplitude for the high-validity ($M = -2$, $SD = 1.2$) and low-validity ($M = -1.5$, $SD = 1.16$) groups was marginally significant, $t(1, 70) = 1.8$, $p = .07$. However, when the outlier in the low-validity group (r-LRP amplitudes > 3 *SD*s) was removed, the difference between the high- and low-validity groups became significant, $t(1, 69) = 2.4$, $p = .016$, $d = 0.6$ (Figure 4B). As with the N2pc component, for both s-LRP and r-LRP components, we conducted an analysis of the second half of the experiment. All results remained the same.

In general, the EEG results point to both facilitating and interfering effects from regularity embedded within visual search. Under conditions of high validity (consistent-only group), facilitation was observed for the response selection (s-LRP) and possibly target selection (N2pc) processes.

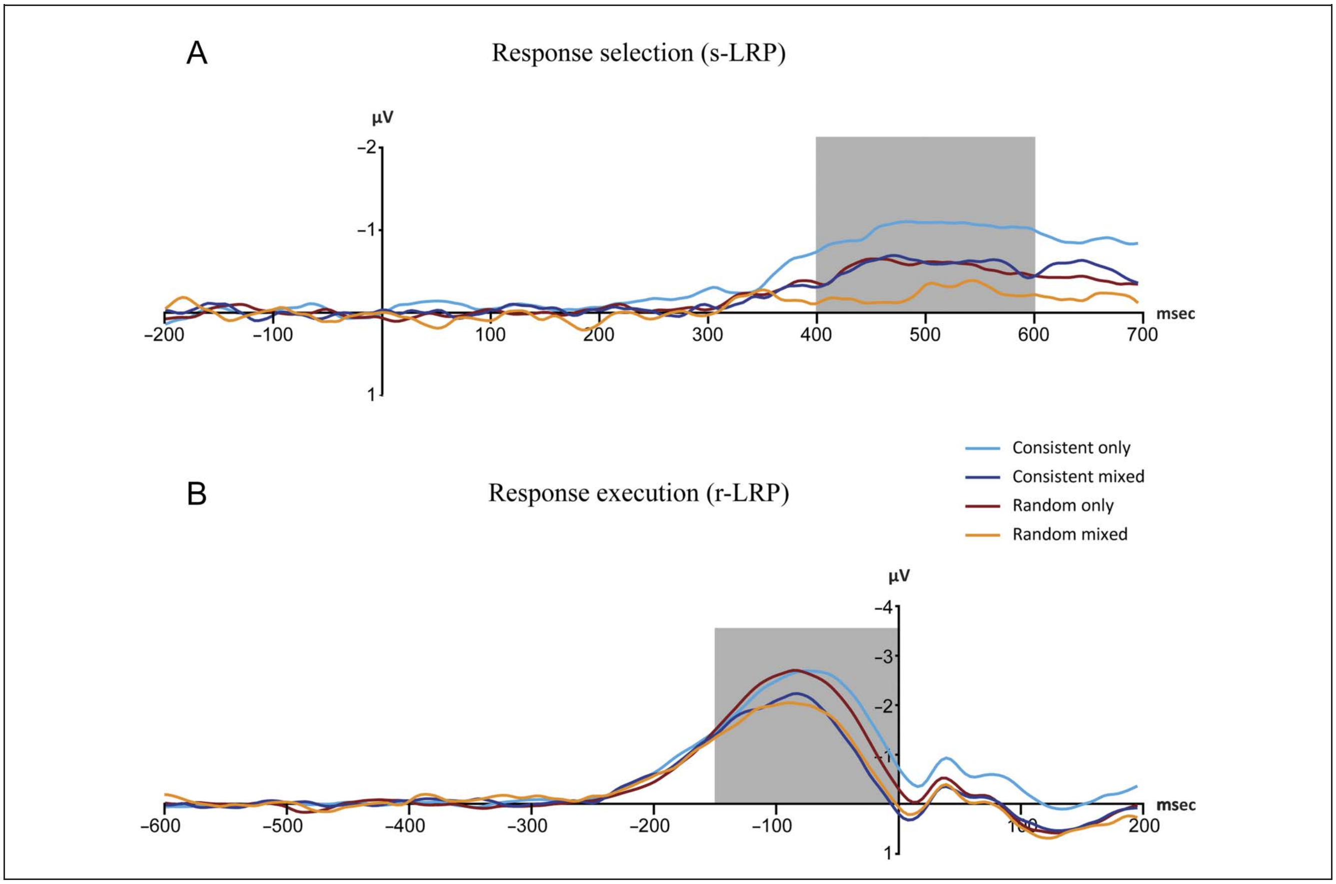

Figure 4. LRP results for the visual search task. The gray rectangle marks the analyzed time window (C3–C4). s-LRP: Within the mixed-design group, s-LRP amplitude was attenuated for the random mixed condition relative to the consistent mixed condition. In addition, s-LRP amplitude was enhanced for the consistent-only group relative to the random-only group (Figure 3A). r-LRP: The consistent-only and random-only groups were collapsed into a high-validity group and compared to the mixed-design group (low validity). r-LRP amplitude for the low-validity group was attenuated relative to the high-validity group (Figure 3B).

Under conditions of low validity (mixed group), the presence of regularity in the task led to a specific interference effect for the random mixed condition in both target selection (N2pc) and response selection (s-LRP) and an overall general interference effect for both consistent mixed and random mixed conditions in response execution (r-LRP).

Familiarity Test

Mean accuracy in the familiarity test was 53% in both the mixed and consistent-only groups. In the mixed group, participants correctly classified previously seen layouts as familiar on 57% of the trials (hit rate) and incorrectly classified new layouts as familiar on 50% of the trials (false alarm rate). In the consistent-only group, participants correctly classified previously seen layouts as familiar on 55% of the trials (hit rate) and incorrectly classified new layouts as familiar on 48% of the trials (false alarm rate). In both groups, the differences between hit rate and false alarm were not significant, $F < 1$.

We then calculated the ratio between hit rate and false alarm for each participant. Anything above twice the hit rate relative to the false alarm rate was considered as possible evidence for explicit memory. Five participants (two in the mixed group and three in the consistent-only group) met this criterion. All of the results were recalculated while excluding these participants. The only difference in the results was observed for the s-LRP component: The difference between s-LRP amplitude in the consistent mixed condition and s-LRP amplitude in the random mixed condition was now marginally significant, $F(1, 23) = 3.3, p = .08$.

VWM Capacity

Mean VWM capacity estimate was as follows: 2.5 ($SD = 0.63$) in the mixed group, 2.7 ($SD = 0.8$) in the random-only group, and 2.5 ($SD = 0.9$) in the consistent-only group. VWM did not correlate with either RTs or ERP amplitudes in any of the groups.

DISCUSSION

The focus of this work was to separate the facilitating and interfering effects of an embedded regularity on performance in visual search. EEG was recorded from three groups of participants while they completed a visual search task. Depending on the group, the task was either random (random-only group); structured, in which case the regularity was valid on every trial (consistent-only group); or a visual search with consistent and random conditions intermixed (mixed group, contextual cueing). On the basis of previous studies, we focused on the N2pc and LRP components that reflect search efficiency (i.e., target selection) and response processes, respectively (Schankin & Schubö, 2009, 2010; Johnson et al., 2007).

As predicted, the results showed that the impact of regularity on ongoing performance depends on the overall validity of the task. When regularity was valid (consistent-only group), its presence drove performance beyond general practice effects, resulting in faster RTs through facilitation in both search efficiency (N2pc component, marginally significant in the second half of the experiment) and response selection (s-LRP components). Under low-validity conditions (mixed group), embedding regularity within the task resulted in interference to the target selection, response selection, and response execution processes (N2pc, s-LRP, and r-LRP components, respectively).

In general, we argue that the observed pattern of results can be accounted for by two distinct effects. First, we identify a global effect of validity that dictates the degree to which all information is taken into account (Vaskevich & Luria, 2018). The influence of this effect does not depend on the specific trial type (random or consistent), only on the frequency of the regularity. In addition, our results suggest the presence of a local effect of activating the accumulating information on every trial. Unlike the global effect of validity, the local influence of regularity depends on the specific type of trial and can result in either facilitation (on consistent trials) or interference (random mixed trials), with each instance of repeating patterns contributing to the impact of the local effect. In the following section, we discuss how each cognitive process (target selection, response selection, and response execution) is affected, while considering the implications of our results on the interpretation of the contextual cueing effect.

In line with previous results, the present contextual cueing effect was accompanied by higher N2pc and s-LRP amplitudes for the consistent mixed condition relative to the random mixed condition (Schankin & Schubö, 2010; Johnson et al., 2007). However, when compared with a random visual search, the ERP results confirmed that the difference between the conditions is driven by interference effects, not facilitation: Both N2pc and s-LRP amplitudes were attenuated in the random mixed condition, not enhanced in the consistent mixed condition relative to a random visual search (random-only group). In addition, r-LRP amplitude for both mixed conditions was attenuated relative to the conditions administered alone, reflecting the presence of a general interference effect in response execution.

The pattern of results described above suggests a specific interference effect in the random mixed condition in both target selection and response selection. We argue that these effects are a result of failing to apply the expected regularity on random trials and that each such failing results in a prediction error within the system (Vaskevich & Luria, 2018; Clark, 2013). The common view is that the N2pc component reflects the efficiency of shifting attention to the target location (Eimer, 1996; Luck & Hillyard, 1994). From this perspective, the observed attenuation in the random mixed condition reflects misguidance of the attentional shifts toward targets that do not appear where they are expected. With regard to response processes, it is generally accepted that these are modulated through the adjustment of response criterion (Kunar et al., 2007). That is, the amount of evidence required within the system before a response is chosen, prepared, and executed varies. Presumably, the specific attenuation of response selection suggests that the initiation of response processes demands additional caution, reevaluation, and "double checking" before it is set in motion on trials that produce prediction errors (i.e., random trials within a mixed design). Finally, in addition to the local interference effects observed for the random mixed condition, a general attenuation was observed in response execution. This result suggests that, in the case of a mixed design, under conditions of uncertainty (i.e., low validity), more evidence is needed before a response is executed, regardless of the specific condition.

Surprisingly, we did not observe any evidence to suggest facilitation in the target selection or response processes in the consistent mixed condition. Clearly, participants did rely on previous knowledge in the mixed design group: Interference was observed in the random mixed condition, when the regularity was not valid. Given that on the consistent mixed trials the embedded regularity was valid, one may have expected to observe local facilitation on these trials. Moreover, our results suggest that such facilitation is possible, as the consistent-only group showed a benefit in response selection (marked by a higher s-LRP amplitude than in a random visual search) and a benefit in target selection in the second half of the experiment (marked by N2pc amplitude relative to a random visual search). The key difference between the consistent-only and mixed groups is the overall validity in the task. In the case of the mixed group, it is possible that there is some local facilitation on consistent mixed trials but that this facilitation is overshadowed by the global interference effect created by unreliable conditions. Importantly, this interpretation of the results suggests that global validity affects both search and response processes. Presumably, the unique contribution of the global detrimental effect of validity was observed in response execution because, by this stage, the influence of the search process is negligible.

Before discussing further the implications of the present work, it is important to note two limitations in our interpretation of the ERP results. First, we have regarded the N2pc component as a reflection of the target selection process, that is, the spatial shifting of attention to the target (Eimer, 1996; Luck & Hillyard, 1994). However, recent studies have challenged this assumption, suggesting instead that the

N2pc reflects attentional engagement at the location of the target (Zivony et al., 2018; Kiss et al., 2008). Attentional engagement refers to processes that occur after the attentional shift and include identification, binding, and consolidation of the attended stimulus into working memory (Zivony et al., 2018). These stages require the recurrent activation of neural networks (Töllner, Rangelov, & Müller, 2012). With regard to this study, this recurring activation may account for the above-discussed local interference, as it includes the activation of expectations created by the regularity in the task. At this point, we cannot separate between these two explanations. However, whether through shifting of attention or attentional engagement, the effect of regularity on the random trials in a mixed design task is misguidance.

An additional limitation that has to be addressed concerns our interpretation of the differences observed in the s-LRP component. When the experimental design relies on stimuli that appear to the left and right of the participant's midline (as in this study), the direction of attentional shifts can covary with the response hand, making it impossible to rule out the influence of attentional contribution to the s-LRP component (for reviews, see Praamstra, 2007; Eimer, 1998). As such, it is possible that some of the interference that was observed in the random mixed condition and the facilitation observed in the consistent-only group stem from search-related processes, not response selection. This criticism is particularly important in the case of the facilitation effect. We have argued that, when the regularity is reliable, it benefits both search and response processes. However, the evidence for a benefit for the search process in the consistent-only group appeared only in the second half of the experiment. Keeping in mind that the s-LRP may, in part, reflect search-related activity provides additional support for arguing that a reliable regularity facilitates both search and response processes.

From a broad perspective, the interference effects that were observed in the present work can be characterized as a type of "mixing cost" (Los, 1996). This cost is typically observed in paradigms that involve either task switching (Los, 1996; Meiran, 1996) or stimuli switching (Lupker, Kinoshita, Coltheart, & Taylor, 2003; Los, 1999), so two intermixed tasks or types of stimuli are responded to more slowly than when they are presented separately (Monsell, 2003; Meiran, 2000). Importantly, these costs are often asymmetric, affecting one task or type of stimuli more than the other (Schneider & Anderson, 2010; Koch, Prinz, & Allport, 2005; Los, 1996). With regard to the present work, one can argue that the slowdown in the mixed group is a type of mixing cost, with the random mixed condition affected to a greater extent than the consistent mixed condition. However, unlike mixed designs in other domains, in the case of contextual cueing, there is no difference in task, response, or type of stimuli between the two mixed conditions. Moreover, the additional information in the consistent mixed condition is considered beneficial to the task at hand. As such, the currently proposed models of the contextual cueing effect share the assumption that the difference between the mixed conditions stems entirely from facilitation in the consistent mixed condition, overlooking any possible slowdown effects (i.e., mixing costs).

In line with the assumption discussed above, current models of contextual cueing do not include any elements that restrict performance under mixed conditions, making it impossible for them to predict the overall slowdown in performance that was observed in the mixed group of this study. As an example, let us consider the influential model proposed by Brady and Chun (2007). Within this model, the difference between consistent mixed and random mixed conditions is accounted by modulations in the search process alone. All possible locations are assigned weights, which are then adjusted as the system learns to predict where targets are likely to appear. Consequently, attention is biased toward locations with higher weights. The main contribution of this model is that the weights are adjusted as a function of spatial proximity from the target, resulting in the restriction of configural learning almost entirely to the local area around the target.

Introducing spatial constrains on learning enabled the model proposed by Brady and Chun (2007) to elegantly account for several findings within the contextual cueing literature, such as stronger cueing from local configurations (Olson & Chun, 2002) and the fact that contextual cueing tolerates combined, rescaled, or displaced displays (Jiang & Wagner, 2004), but not displays in which local context moves around within a global configuration (Brady & Chun, 2007, Experiment 4). However, the model cannot account for the present findings as it predicts faster RTs in the consistent mixed condition than in the random-only group: The weights are adjusted to reflect positive learning only (i.e., facilitation), so that attention should be biased toward locations that previously contained a target more than toward random target locations regardless of whether the consistent trials appeared within a mixed design or not.

Note that we are not the first to suggest that the model proposed by Brady and Chun cannot fully account for the contextual cueing effect. A number of studies have shown that response processes, which are beyond the scope of this model, play a vital role in creating the difference between the mixed conditions (Schankin & Schubö, 2010; Kunar et al., 2007). We add to these results, by showing that an accurate account of the processes underlying the contextual cueing effect has to also take into consideration the overall implications of mixing consistent and random conditions, therefore introducing some element that is adjusted by validity.

This study may also provide a new interpretation of previous results that show a contextual cueing effect in what is considered to be optimal or nearly optimal visual search tasks, such as cued and "pop-out" search tasks (Harris & Remington, 2017; Kunar et al., 2007). Theoretically, if contextual cueing relies on guidance of attention, no effect should be observed when guidance of attention is already optimal. However, such effects have been consistently demonstrated (Harris & Remington, 2017; Schankin &

Schubö, 2010; Kunar et al., 2007). Harris and Remington (2017) argued that the conditions created in a pop-out visual search are only nearly optimal, so some guidance is still possible. We propose an alternative to this interpretation and argue that the interference effects observed in this study can easily account for the presence of contextual cueing in pop-out and cued search tasks. As with a regular visual search, the conditions in a mixed-design pop-out visual search are not optimal because regularity is mixed with randomness, thus resulting in interference to performance and allowing for the contextual cueing effect to emerge in what otherwise would be optimal attentional guidance conditions.

To summarize, relying on EEG recordings, we were able to separate between two types of effects created by embedding regularity in a visual search task: a global validity effect and a local effect of applying the regularity on a given trial. Contrary to previous findings, our results show interference effects in both target selection and response processes when the regularity is mixed with random trial, thus supporting the argument that the relative validity of the embedded regularity modulates its impact (Vaskevich & Luria, 2018). We argue that, when considering the influence of regularity on behavior, it is vital to assess how the overall reliability of the accumulating information is changed by its presence, beyond the potential benefit it may seem to provide on a given trial.

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Diversity in Citation Practices

A retrospective analysis of the citations in every article published in this journal from 2010 to 2020 has revealed a persistent pattern of gender imbalance: Although the proportions of authorship teams (categorized by estimated gender identification of first author/last author) publishing in the *Journal of Cognitive Neuroscience (JoCN)* during this time period were M(an)/M = .408, W(oman)/M = .335, M/W = .108, and W/W = .149, the comparable proportions for the articles that these authorship teams cited were M/M = .579, W/M = .243, M/W = .102, and W/W = .076 (Fulvio et al., *JoCN*, 33:1, pp. 3–7). Consequently, *JoCN* encourages all authors to consider gender balance explicitly when selecting which articles to cite and gives them the opportunity to report their article's gender citation balance.

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