Distractor rejection in parallel search tasks takes time but does not benefit from context repetition

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Distractor rejection in parallel search tasks takes time but does not benefit from context repetition*

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ABSTRACT

When the spatial configuration of a search display is presented repeatedly, response times to finding the target within that configuration are shorter compared to completely novel configurations, even though observers do not have explicit recognition of the repetition. This phenomenon is known as Contextual Cueing and selective attention is thought to be necessary for the effect. Previous research has suggested that repetition of the context of unattended items does not appear to improve performance; only repetition of attended items does. It has been proposed that this occurs because unattended items are pre-attentively filtered and thus do not contribute to performance. Here we demonstrate that so-called “unattended” items do contribute to performance, just not to contextual cueing. We approach this question from the perspective of the parallel processing of the scene that unfolds at the start of each item and that has been recently modelled by the Target Contrast Signal Theory. We show that the processing time per item during parallel evaluation of the scene is not affected by context repetition, suggesting that the locations of the items rejected in this stage are not integrated into the memory representation underlying contextual cueing. Other alternatives are also discussed.

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KEYWORDS

Contextual cueing; visual search; target contrast signal theory

Contextual cueing is a phenomenon in visual search tasks whereby response times are faster in displays where contextual information is repeated compared to novel displays. As the name suggests, there are two elements in Contextual Cueing. Context refers to information that co-occurs with the target, such as the spatial layout (Chun & Jiang, 1998), identity (Chun & Jiang, 1999; Goujon, Didierjean, & Marmèche, 2007), or motion trajectory (Chun & Jiang, 1999) of the stimuli in the search display. Cueing refers to the guidance of attention. Contextual cueing thus refers to situations in which attention is guided by the contextual information that has been learned. Most often, the context is the spatial layout of the stimuli in the search display (Chun, 2000; Lleras & Von Mühlener, 2004; Rosenbaum & Jiang, 2013). In these experiments, half of the search displays are repeated (i.e., the spatial layout of the search stimuli remains identical throughout the experiment), while the other half are novel (i.e., the spatial layout is randomly generated each time). Response times to repeated displays are faster than to novel displays, suggesting that observers learn the context, which allows their attention to rapidly move to the target location.

Selective attention is thought to be necessary for the development of Contextual Cueing (Jiang & Chun, 2001). In a series of experiments, observers were asked to search for a target with a pre-defined colour among distractors of the same colour (“candidates”) or a very different colour (“lures”).1 All distractors shared the same shape. In Experiment 1, the spatial layout of the candidates was repeated while that of the lures was random. Contextual Cueing was observed even though only half the context was repeated, suggesting that attention to relevant distractors was sufficient for the effect to emerge. In the reverse scenario when the spatial layout of the lures was repeated but the one for the candidates was random, evidence for Contextual Cueing was observed even though only half the context was repeated, suggesting that attention to relevant distractors was sufficient for the effect to emerge. In the reverse scenario when the spatial layout of the lures was repeated but the one for the candidates was random, evidence for Contextual Cueing was observed even though only half the context was repeated, suggesting that attention to relevant distractors was sufficient for the effect to emerge. In the reverse scenario when the spatial layout of the lures was repeated but the one for the candidates was random, evidence for Contextual Cueing was observed even though only half the context was repeated, suggesting that attention to relevant distractors was sufficient for the effect to emerge. In the reverse scenario when the spatial layout of the lures was repeated but the one for the candidates was random, evidence for Contextual Cueing was observed even though only half the context was repeated, suggesting that attention to relevant distractors was sufficient for the effect to emerge.

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*The data that support the findings of this study are openly available on the Open Science Framework at http://doi.org/10.17605/OSF.IO/ZWXBH, reference number ZWXBH.

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such displays. One possible explanation, as the authors pointed out, could be that Experiment 3 included trials in which both candidates and lures were repeated. This could have led to observers paying attention to both lures and candidates because of the potentially useful source of information from the lures when they were repeated along with the candidates. This was confirmed in Experiment 4: when the search was made harder such that observers had to divert more attentional resources to the candidates, repeating the lure context once again failed to produce a Contextual Cueing effect. This was the case presumably because observers did not have enough leftover resources to attend to the lures. Taking all experiments together, Jiang and Chun (2001) argued that Contextual Cueing is dependent on selective attention. Importantly, the authors argued that the attentional process in these tasks with both candidates and lures is markedly different from the standard Contextual Cueing paradigm where all distractors are candidates. They argued that in candidate-only displays, candidates are attended to by selective attention before being rejected (e.g., Duncan & Humphreys, 1989; Jiang & Chun, 2003; Treisman & Sato, 1990). On the other hand, in mixed displays, lures are first filtered by a pre-attentive process (Palmer, 1995) since they differ from the target on at least one salient feature. Selective attention then evaluates and rejects the candidates. This process of selecting, evaluating and rejecting candidates in a more focused fashion was thus proposed to be the locus of the Contextual Cueing effect. That said, other studies found that lure-context repetition can facilitate search (Geyer, Shi, & Müller, 2010; Geyer, Zehetleitner, & Müller, 2010; Harris & Remington, 2017; Kunar, Flusberg, Horowitz, & Wolfe, 2007). Thus, evidence regarding the contribution of lure context to Contextual Cueing is mixed. We will return to this issue in the General Discussion.

The goal of the present study is to re-examine the role of lure-context repetition on Contextual Cueing, given the somewhat mixed results in Jiang and Chun’s (2001) study, as well as the conflicting evidence from other studies (e.g., Geyer, Shi, et al., 2010; Geyer, Zehetleitner, et al., 2010; Harris & Remington, 2017; Kunar et al., 2007). One difficulty in Jiang and Chun’s (2001) design (Experiment 2) arises from the fact that when lure-context was repeated, displays also contained candidates whose locations were not repeated. Thus, the entire display context was varying on each presentation. Further, because candidates attract focused attention (and lures do not), varying the locations of the candidates might overwhelm whatever guiding influence the lure-context might be exerting on attention. This might explain why in their Experiment 3, Jiang and Chun found the largest Contextual Cueing effect when both candidate- and lure-context repeated compared to when only candidate-context was repeated. Perhaps the repetition of candidate-context facilitates the learning of the repeated lure-context.

Another difficulty of the design was the use of lures that were letter-like (Ls). While it is tempting to say that Ls of a non-target colour are unattended, there is strong evidence that letters are compulsory stimuli (Teichner & Krebs, 1974), and as such, focused attention to these stimuli might be stronger than to non-letter lures. Furthermore, no direct evidence was provided that the lures were unattended. In fact, by their shape, the letter lures were very similar to the candidates. This lure rejection process occurs through a parallel process, whereby evidence accumulates
stochastically towards a non-target threshold at all locations across the search display simultaneously. The greater the visual difference between the item and the target template, the faster the evidence accumulation unfolds and, consequently, the faster the rejection of lures. Importantly, this evidence accumulation process is both stochastic and (mostly) independent (see Lleras, Wang, Madison, & Buetti, 2019; Wang, Buetti, & Lleras, 2017). The completion time of each individual lure is thus not dependent on the number of stimuli in the display; that said, identical lures that are in close proximity to each other do tend to speed up each other’s rejection, (Lleras et al., 2019). Because of the stochastic nature of this parallel accumulation process, reaction times increase logarithmically as a function of lure set size (Townsend & Ashby, 1983): the addition of each lure brings with it the possibility that its processing time will exceed the current maximum processing time of the other lures. Thus, even when all elements are processed at the same average rate in parallel, the completion time for a set of those elements will be determined by the total number of elements in the set. Furthermore, Buetti et al. (2016) demonstrated that the slope of the logarithmic function is determined by target-lure similarity, and Lleras et al. (in press) proposed that the rate of evidence accumulation is determined by the magnitude of the contrast signal between the target and the lure. It should be noted that the lure rejection process is quite different from the pre-attentive filtering process that has often been associated with stage one filtering (Palmer, 1995). Indeed, pre-attentive filtering (the concept used by Jiang & Chun, 2003) is supposed to be insensitive to the set size of filtered items (see also e.g., Duncan & Humphreys, 1989; Eckstein, Thomas, Palmer, & Shimozaki, 2000; Verghese, 2001; Wolfe, 2006), whereas our recent work shows that lure set size does impact reaction times.

The output of the first stage of processing is a list of non-rejected locations, that is, the list of locations containing items that are so similar to the target that peripheral vision cannot confidently discard them as non-targets. We refer to those items as candidates. Because candidates are similar to the target, the target-contrast signal that accumulates at those locations is very small and does not reach threshold. During the second stage of processing, focused attention (and/or eye movements) is then directed towards these candidate locations in order to find the target. This stage of attentional scrutiny is characterized by a linear (rather than logarithmic) increase in response times as a function of set size. In this respect, the Target Contrast Signal Theory shares the same interpretation of stage-two linear search slopes with most models and theories of visual search (Treisman & Gelade, 1980; Wolfe, 2007).

In sum, according to the Target Contrast Signal Theory, lures do not get filtered out en masse by a pre-attentive process (see also, Lleras et al., 2019). Rather, all items in a search display, including lures, are processed in parallel, producing significant and systematic processing costs. Recent work also confirmed that the theory is successful at predicting search performance in novel heterogeneous displays (displays containing multiple different types of lures) based on search performance in simple homogeneous displays (containing only one type of lure), across participants (for displays with geometric shapes see Lleras et al., 2019; for displays with real-world objects see Wang et al., 2017). Finally, recent studies have confirmed that the logarithmic nature of the search functions were not due to low-level confounds like crowding (Madison, Lleras, & Buetti, 2018), cortical magnification (Wang, Lleras, & Buetti, 2018) or eye movement artefacts (Ng, Lleras, & Buetti, 2018).

Given this new understanding regarding how lures are rejected, it is important to re-examine the effect of lure-context repetition. Here, we used lure stimuli that are clearly different from candidates (as in Buetti et al., 2016), and we also manipulated lure set size to better characterize the lure rejection process in the presence of context repetitions. As we will review in the General Discussion, using stimuli that are clearly not the target (i.e., lures) is crucial for getting clear evidence from the experiments regarding the contribution of these stimuli to performance (not just Contextual Cueing). Having “unattended” stimuli that are too similar to the target (as has been done before) may lead to a mix of results, depending on the position of those items in the display; items close to fixation might be discarded in parallel, whereas items in the periphery might not, or not consistently so. Thus, stimuli selection is critically important to avoid mixed results. Further, a fine manipulation of lure set size will also help us have a good and stable estimate of the lure-rejection process (Buetti et al., 2016) and evaluate
whether or not this process is impacted by context repetition.

Experiment 1 is an initial investigation to select the candidate set size in the subsequent experiments and provide a baseline estimate of Contextual Cueing in our population, using our methodology. Experiment 2 will examine context-repetition effects in displays where both candidates and lures are repeated, and Experiment 3 will evaluate context-repetition effects in lure-only displays. Finally, in the Contextual Cueing literature, there is ample evidence that participants are at chance at identifying the displays that were repeated throughout the experiment (e.g., Chun & Jiang, 1998; Colagiuri & Livesey, 2016; Jiang & Chun, 2003; but see Annac, Pointner, Khader, Müller, Zang, & Geyer, 2019 for recent evidence showing explicit memory of one or two target locations). That said, we were interested in investigating whether participants would have a better memory for the repeated lure displays; perhaps these relatively easier-to-process displays might be more memorable than candidate-only displays (Khosla, Raju, Torralba, & Oliva, 2015). All code and data can be found on the Open Science Framework (Ng, Buetti, Dolcos, Dolcos, & Lleras, 2019).

**Experiment 1**

The goal of this experiment was to identify what is a small number of candidates that, when repeated, can produce reliable Contextual Cueing effects. This is necessary because when lures are introduced into the displays in subsequent experiments, the set size of lures will be varied across a wide range. The manipulation of lure set size across a wide range of values is necessary to observe the logarithmic increase in RT as a function of set size that indexes parallel evidence accumulation processes (see Buetti et al., 2016 for details).

**Methods**

**Participants**

All participants were recruited from the subject pool from the University of Illinois at Urbana-Champaign. Participants were given course credit for taking part in the experiment. All participants were tested with the Ishihara colour plates and determined to be non-colorblind. All participants also had normal or corrected-to-normal vision. We aimed to collect 20 participants per experiment. This sample size was chosen after a power analysis based on previously published work which demonstrated that 20 participants are sufficient to be able to reliably measure the separate contributions of candidate and lure stimuli to reaction times with 80% power (Buetti et al., 2016). Although no lures were used in Experiment 1, we chose this number to have identical sample sizes across the three experiments reported in this paper.

**Stimuli and apparatus**

The target was a red letter T that was rotated 90 degrees either clockwise or anti-clockwise. Participants had to respond to the target orientation. The distractor stimuli were red letter ‘L’s rotated either 0, 90, 190, or 270 degrees clockwise. The experiment was programmed and ran in MATLAB using the Psychophysics Toolbox (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007).

In each search display, the stimuli were distributed across a 6-by-6 grid. There were a total of 12 displays (six for set size 4 and six for set size 8) that were repeated throughout the entire experiment. Each of these 12 repeated displays had unique target locations. A separate set of 12 target locations, which did not overlap with those in the repeated displays, was randomly selected and served as the target locations for the novel displays. This was done to equate target location probability between the repeated and novel displays. The novel displays were never repeated and were checked against the repeated displays to ensure that there were also no repeats. All stimuli were presented against a 1024 x 768 pixel black background on a 22-inch (400mm x 300mm) cathode ray tube monitor with a refresh rate of 85Hz. Participants viewed the display, unrestrained, from a distance of approximately 60cm, and were allowed to freely move their eyes during the task.

**Design and procedure**

There were two within-subject independent variables: display type (repeat or novel) and set size (4 or 8). Participants viewed 25 blocks of 24 trials each, for a total of 600 trials. In each block, half the trials were repeated while the other half were novel. Within the repeated and novel trials, half were set size 4 while the other were set size 8. There was thus a total of 4 cells, with 150 trials in each cell. Trial order was randomized.
The participants’ task was to find the oriented T target and report whether it was pointing to the right or to the left. Before the start of the experiment, participants were also presented with the following instructions aimed at improving the likelihood of obtaining Contextual Cueing (Lleras & Von Mühlenen, 2004):

The best strategy for this task, and the one that we want you to use in this study, is to be as receptive as possible and let the unique item “pop” into your mind as you look at the screen. The idea is to let the display and your intuition determine your response. Sometimes people find it difficult or strange to tune into their “gut feelings”, but we would like you to try your best. Try to respond as quickly and accurately as you can while using this strategy. Remember, it is very critical for this experiment that you let the unique item just “pop” into your mind.

The experiment began with a block of six practice trials to familiarize the participant with the experiment and to emphasize the passive instructions. Recording of trials to familiarize the participant with the experiment focused on improving the likelihood of obtaining Contextual Cueing (Lleras & Von Mühlenen, 2004):

1. The experiment began with a block of six practice trials to familiarize the participant with the experiment and to emphasize the passive instructions. Recording of trials to familiarize the participant with the experiment focused on improving the likelihood of obtaining Contextual Cueing (Lleras & Von Mühlenen, 2004):  
2. In sum, Experiment 1 showed that the Contextual Cueing effect was observed both with 4 and 8 candidates. The effect was greater with 8 candidates compared to 4 candidates (61 vs. 15ms on average) and thus we decided to use 8 candidates in Experiment 2, to maximize the chances of obtaining a Contextual Cueing effect driven by the repetition of the candidates, so that we could examine whether the magnitude of this effect is impacted by the repetition of the lures.
Experiment 2 we used 8 candidates on every display, while varying the number of lures. In old displays, both candidate and lure stimuli were repeated. In novel displays, both candidate and lure locations were randomly determined and never repeated. In contrast to Jiang and Chun (2001), the lure stimuli we used were simple geometric shapes (orange diamonds) that were neither letter-like nor similar in shape to the candidates. Buetti et al. (2016) showed that these lures are rejected in parallel when searching for a T target amongst L candidates (in novel displays), producing logarithmic processing costs. If lures are processed in parallel in repeated displays, as proposed by the Target Contrast Signal Theory, response times should increase logarithmically as a function of lure set size (Buetti et al., 2016). In contrast, if lures are filtered out by a pre-attentive process, then there should be no effect of lure set size on response times (Duncan & Humphreys, 1989; Palmer, 1995; Treisman & Sato, 1990).

From the perspective of the Target Contrast Signal Theory, it is unclear what the fate of lures that are rejected in parallel is with regard to Contextual Cueing. One possibility is that since lures undergo an active process of evidence accumulation, their locations might be implicitly learned and form part of the spatial context that determines Contextual Cueing. If this is the case, then the time taken for evidence accumulation in stage one of visual search should be shorter for repeated compared to novel displays. This would be observed in shallower logarithmic slopes, which are an index of the time taken for evidence accumulation in stage one (Buetti et al., 2016; Ng et al., 2018). It should be noted that Kunar and colleagues (Kunar et al., 2007) reported that the Contextual Cueing effect did not manifest in search slopes between repeated and novel displays. However, the search slopes that they examined concerned stage-two processing: the linear cost to process and reject candidate stimuli. Traditionally, search slopes are viewed as a proxy for the efficiency of selective attention in the second stage of visual search. Shallower search slopes indicate shorter processing times per item (or per group of items) or fewer attentional shifts before the target is found, indicating a more efficient search process (Treisman & Gelade, 1980; Treisman & Gormican, 1988; Wolfe & Horowitz, 2004). Thus, these linear search slopes are fundamentally different from the logarithmic search slopes that characterize the evidence accumulation process, which are the focus of Experiment 2.

Figure 1. Response times for novel displays (solid lines) were significantly longer than for repeated displays (dashed lines), for both set size 8 (orange circles) and set size 4 (black triangles) in Experiment 1. The average magnitude of the Contextual Cueing effect was larger in set size 8 (61ms) compared to set size 4 (15ms).
A second possibility is that, since lures are discarded prior to the attentional scrutiny of individual items, it is also possible that they will not contribute to Contextual Cueing. That is to say, what determines the “context” in Contextual Cueing might be the list of candidate locations only (i.e., the list of locations where contrast-evidence accumulators did not reach the non-target threshold). This latter possibility is consistent with Jiang and Chun's (2001) proposal that Contextual Cueing is determined by the set of locations that are “selectively attended”.

Finally, from the perspective of the Target Contrast Signal Theory, it seemed important to evaluate whether or not the parallel lure rejection process would improve when lure context is repeated. For example, imagine a situation where an observer might learn through repetition that the target never appears in the upper left quadrant of the display. Having this information available during the initial parallel accumulation process might allow for faster rejection of stimuli that appear in that quadrant by either reducing the non-target threshold or increasing the evidence accumulation rate in that part of the display. This would be the equivalent of quickly rejecting (or even ignoring) paintings on the wall when looking for a set of keys on nearby tables and shelves. Note that prior evidence that search rates are not systematically improved in contextual cuing experiments (Kunar et al., 2007) does not necessarily imply that logarithmic search rates will also fail to improve in contextual cueing. Indeed, as reviewed above, the logarithmic and linear functions index distinct forms of distractor rejection and are mostly independent of one another (Buetti et al., 2016).

Method

Twenty participants were recruited from the same subject pool as Experiment 1. These participants did not take part in any of the other experiments in this paper. The sample size was determined by a previous power analysis that showed that 20 participants were sufficient to detect separate lure and candidate effects with 80% power (Buetti et al., 2016). All methods are identical to Experiment 1, except for the following changes: in addition to the candidate Ls, there were symmetric orange diamonds (lures). Each display always contained 8 candidates. There were 4 different lure set sizes: 0, 5, 10, 20. As such, there were 3 repeated displays per set size and a total of 12 repeated displays throughout the entire experiment. In the repeated displays, both lures and candidates, as well as the target, were always in the same location. A sample display is shown in Figure 2.

Results

For each participant, response times beyond 2.5 standard deviations of each condition were excluded from analyses. Trials on which participants made an error were also excluded. This led to the removal of 3.4% of trials. No participants had to be replaced in this experiment. All analyses, in this and the following experiments, were conducted in R (R Core Team, 2018).

Figure 2. Example displays for Experiments 1–3 (from left to right). The target in all three experiments was a red letter T rotated 90 degrees clockwise or anti-clockwise. In Experiment 1, the distractors were all candidates (red letter Ls). In Experiment 2, the distractors were either candidates (red letter Ls) or lures (orange diamonds). In Experiment 3, the distractors were all lures (orange diamonds). Stimuli in the figures are enlarged for clarity.
Table 1. Follow-up t-tests for the significant display type by epoch interaction in Experiment 2. Asterisks indicate statistical significance at p < .01 (after Bonferroni correction).

<table>
<thead>
<tr>
<th>Epoch</th>
<th>t(79)</th>
<th>P</th>
<th>M (SD)</th>
<th>Cohen’s d_t</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>−0.16</td>
<td>.877</td>
<td>−3 (191)</td>
<td>−0.018</td>
</tr>
<tr>
<td>2</td>
<td>1.42</td>
<td>.161</td>
<td>23 (142)</td>
<td>.159</td>
</tr>
<tr>
<td>3</td>
<td>2.01</td>
<td>.0482</td>
<td>36 (162)</td>
<td>.225</td>
</tr>
<tr>
<td>4</td>
<td>4.65</td>
<td>&lt;.001*</td>
<td>80 (154)</td>
<td>.52</td>
</tr>
<tr>
<td>5</td>
<td>2.88</td>
<td>.00507*</td>
<td>51 (160)</td>
<td>.322</td>
</tr>
</tbody>
</table>

A 2 (display type) by 4 (lure set size) by 5 (epoch) fully within ANOVA was performed. RTs for novel (M = 990 ms, SD = 174 ms) displays were slower than for repeated (M = 953 ms, SD = 178 ms) displays, F(1, 19) = 4.64, p = .0443, η_p^2 = .148. RTs increased with lure set size (set size 0, 5, 10, 20, respectively: M = 916, 962, 978, 1030 ms, SD = 152, 183, 167, 185 ms), F(3, 57) = 9.68, p < .001, η_p^2 = .299, and decreased as a function of epoch (from epoch 1 to 5: M = 1042, 981, 947, 953, 935 ms, SD = 189, 164, 165, 172, 174 ms), F(4, 76) = 12.17, p_c < .001, ε = .585, η_p^2 = .356. The main effects were qualified by a significant display type by epoch interaction, F(4, 76) = 6.80, p < .001, η_p^2 = .223. Follow-up paired t-tests revealed that RTs for repeated displays were faster than for novel displays only in the last two epochs (Table 1), after adjusting the p-value to .01 (= .05/5, Bonferroni correction). The interactions between set size and display and between set size and epoch were not significant, F(3, 57) = 0.24, p = .868, η_p^2 = .0125; and, F(12, 228) = 1.12, p = .341, η_p^2 = .0557, respectively. Importantly, the three-way interaction between display type, set size and epoch was not significant, F(12, 228) = 1.34, p = .198, η_p^2 = .0659.

To follow up on the absence of a significant effect in the three-way interaction, we used a Bayes factor approach. Bayes factors are preferred over null hypothesis testing when the goal is to provide evidence for null effects (Rouder, Speckman, Sun, Morey, & Iverson, 2009). To better characterize search efficiency, we fitted each subject’s data with a logarithmic function. To determine whether the logarithmic RT by set size slopes were meaningfully different between the novel and repeated displays, the Bayes factor was calculated for a model with display type as a predictor, using the BayesFactor package in R (Morey & Rouder, 2018). The analysis revealed moderate evidence (Kass & Raftery, 1995) for the hypothesis that there was no meaningful difference in slopes between the novel and repeated displays, BF₀₁ = 3.22. Search efficiency did not meaningfully improve with repeated displays. Finally, given that reliable contextual cueing effects emerged only in the last two epochs, it is conceivable that lures could contribute to contextual cueing only after sufficient practice with the task. As such, we conducted the same analysis on data from only the last two epochs. There was again no meaningful difference in slopes between the novel and repeated displays, BF₀₁ = 3.24.

At the end of the experimental session, 30% of the participants responded “yes” when they were asked whether they noticed that some displays were repeated throughout the search experiment. On average, these participants estimated that 32.6% of the displays were repeated (the response from one participant was missing due to a keyboard malfunction). Given that this was a fairly imprecise measure of explicit awareness, we refrain from statistical analyses and discussing this result in detail. Instead, we will examine the question of context awareness in further detail in Experiment 3.

In sum, Experiment 2 showed that when a search display contains both lures and candidates, the magnitude of the Contextual Cueing effect was not affected by the number of lures even though they contributed to response times. Thus, lures are not filtered out preattentively; they are processed and rejected via an evidence accumulation process, as indexed by the logarithmic increase in response time as a function of set size. Yet, the lure rejection process in the first stage of visual search did not benefit from repeating the locations where lures were presented. This also suggests that the locus of contextual cueing is in the second stage of visual search, during which attention is deployed to individual (or a group of) items in a serial fashion. If this conclusion is correct and lures indeed do not contribute to Contextual Cueing despite being actively processed, then we should not observe any Contextual Cueing with lure-only displays. This prediction was tested in the next experiment.

Experiment 3

Here, we tested the extent to which the repetition of the spatial configuration occupied by lures helps the lure rejection process by evaluating the processing cost of lures. In addition, this experiment also included a more precise memory test to assess whether
participants had an explicit recollection of the repeated displays. Multiple previous studies have shown that memory for candidate-repeated contexts is implicit (e.g., Chun & Jiang, 1998; Goujon, Didierjean, & Thorpe, 2015; but see Annac et al., 2019), and we wanted to investigate whether participants had any memory traces of the repeated lure-only displays.

Method

The sample size was chosen to be the same as in Experiments 1 and 2, based on the same power analysis (Buetti et al., 2016). Twenty-two participants were recruited from the same subject pool as previous experiments. One subject did not complete the experiment due to a computer error. One additional participant was replaced because their average RT was more than 2.5 standard deviations higher than the group mean. The included participants did not take part in any of the other experiments in this paper. All methods are identical to Experiment 1, except for the following changes. All distractors were the orange diamond lures used in Experiment 2. In other words, these were lure-only displays (no candidates were ever introduced in this experiment). There were 5 different lure set sizes (0, 3, 9, 19, 31). There were 13 instead of 12 repeated displays: an additional one was included for the target-only condition (lure set size = 0). There were 3 repeated displays for each of the non-zero lure set sizes, and one for the target-only display (set size 0). Finally, there was also a recognition test at the end of the experiment.

The recognition test started by asking participants whether they noticed anything unusual with the display. If they answered “Yes”, they were prompted to describe it by using the keyboard. Regardless of whether they answered “yes” or “no”, they were informed on the next screen that some of the displays were repeated and were asked whether they had noticed this or not. After which, they were asked what percentage of the trials they thought were repeated. Participants were then informed that they would be presented with a recognition test.

The recognition test consisted of 104 trials in total. Each of the 13 repeated displays was presented 4 times, twice with the target rotated 90 degrees clockwise and twice anti-clockwise. Thirteen novel displays, which were never presented in the search task, were created. These novel displays were also presented 4 times, two with the target rotated 90 degrees clockwise and twice anti-clockwise. This was to equate for learning within the recognition task. The target location for these novel displays were the same as the target locations for the novel displays in the search task to equate for target probability. The recognition test was blocked such that each repeated and novel display was presented once before it was presented again.

On each trial, the display was presented until a response was made. Participants pressed the “z” key to indicate whether they had seen the display before during the search task, and the “/” key to indicate that the current display was a novel one. Upon response, a confidence rating screen was presented. Participants had to indicate their level of confidence in their response, ranging from 1 (“completely guessing”) to 5 (“completely confident”). Upon response, a blank screen was presented for a randomly selected duration between 600 and 800 ms before the next trial began.

Results

One participant was excluded from analyses as they had a mean RT that was more than 2.5 standard deviations away from the overall group mean. An additional participant was run to replace this subject. Response times beyond 2.5 standard deviations of the mean of each participant were excluded from analyses. Trials on which participants made an error were also excluded. This led to the removal of 4.5% of trials.

A 2 (display type) by 5 (lure set size) by 5 (epoch) within-subjects ANOVA was performed. RTs increased with lure set size (set size 0, 3, 9, 19, 31, respectively: $M = 507, 528, 548, 561, 570\text{ ms, } SD = 110, 80, 77, 84, 83\text{ ms}$), $F(4, 76) = 31.88, p < .001, \omega_p^2 = .604$. RTs for novel ($M = 545\text{ ms, } SD = 91\text{ ms}$) displays were not significantly different from repeated ($M = 541\text{ ms, } SD = 90\text{ ms}$) displays, $F(1, 19) = 0.74, p = .401, \omega_p^2 = -.0125$. RTs did not differ significantly between epochs (from epoch 1 to 5: $M = 560, 538, 535, 546, 536\text{ ms, } SD = 95, 79, 76, 103, 94\text{ ms}$), $F(4, 76) = 2.17, p_c = .128, \epsilon = .5, \omega_p^2 = .0546$.

There was no significant interaction between set size and display, $F(4, 76) = 0.72, p_c = .505, \epsilon = .554, \eta_p^2 = .0365$; set size and epoch, $F(16, 304) = 0.555$, $p = .71, \epsilon = .279, \eta_p^2 = .0394$; and epoch and display, $F(4, 76) = 1.15, p = .342, \eta_p^2 = .0571$. The three-way
The lack of a significant difference in response times between repeated and novel displays suggests that lure processing did not contribute to Contextual Cueing. The Bayes factor for a model with display type as a factor indicated that there was strong evidence (Kass & Raftery, 1995) that the response times for repeated and novel displays were not meaningfully different, $BF_{01} = 10.961$.

At the end of the experimental session, only one participant responded “yes” when asked whether they noticed anything strange about the experiment but did not elaborate. This participant estimated that 2% of the displays were repeated.

We next turn to the results of the recognition test. First, one-sample t-tests were conducted for each of the lure set sizes (0, 3, 9, 19, 31) to determine whether $d'$ was significantly different from zero, considering recognition performance across the four memory blocks (Table 2). Furthermore, the same analysis was conducted on the first block only. It is indeed possible $d'$ decreased throughout the testing as participants may have become confused as to whether they recognized the displays from the search task or the previous presentations during the recognition test itself (Table 2). Aside from the no lure condition, none of the comparisons were statistically significant, suggesting that participants did not report any conscious awareness of the repeated displays.

Finally, we also examined the possibility that some displays were explicitly recognized. Out of the total two hundred and twenty-eight lure-context displays that were repeated throughout the experiment across all nineteen participants (twelve lure-context displays times 19 participants), forty displays (17.5%) had a perfect accuracy score in the recognition test; fifteen participants indicated that they had seen at least one display during the search task on all four presentations during the recognition test. The mean confidence rating for these displays was 3.59 out of 5 (the average for all other repeated displays was 2.94). This seems to suggest that there is at least some percentage of displays that were explicitly recognized by participants, which is consistent with recent evidence from Annac et al. (2019) showing explicit awareness of a small subset of target locations in Contextual Cueing.

### Between-experiment comparison on the awareness of repeated displays

The percentages of participants who reported awareness of repeated displays in Experiments 1, 2, and 3 were 25%, 30%, and 5% respectively. A chi-square test of independence revealed that noticing rates were not significantly different across the three experiments, $\chi^2(3, N = 59) = 4.09, p = .13$.

### General Discussion

The goal of the present study was to evaluate whether repeating lure contexts over time would produce a similar Contextual Cueing effect to that observed when candidate contexts repeat. Even though the lure stimuli used in the present study were clearly distinguishable from the target, it took participants close to 100 ms to reject them. Experiments 2 and 3 showed converging evidence that lure-context repetition does not in fact contribute to Contextual Cueing. These results are consistent with the findings in Jiang and Chun (2001). That said, what is novel in our study is that in spite of the fact that lure-context repetition does not produce a Contextual Cueing effect, we showed evidence that lures were indeed processed and produced significant costs on reaction time (about 50–100 ms, comparing the zero lure condition to the largest lure set size condition; see Figures 2 and 3). Thus, this finding goes against theories that
assume that since lures are filtered out pre-attentively, or are “unattended”, rejecting them carries no processing cost. In terms of the mechanistic locus of Contextual Cueing, the results imply that Contextual Cueing emerges late, after lures have been discarded from a scene, in what is often referred to as the second stage of visual search (e.g., Treisman & Gelade, 1980; Wolfe, 2006). Importantly, the fact that it took time to process and reject lure stimuli demonstrates that all locations in the display were processed initially (in parallel). Yet, it is not this entire set of locations that constitutes the spatial context of Contextual Cueing. Only the subset of locations that are not rejected during parallel processing will form the memory basis that leads to the facilitation in Contextual Cueing. This conclusion is in broad agreement with Jiang and Chun (2001), who suggested that contextual information is learned only for distractors that undergo processing by selective attention. This conclusion is also somewhat consistent with Geyer, Zehetleitner, et al. (2010), who proposed the target receives a boost in activation when there is a match between the overall-saliency map produced by the current search display and a pattern of activation in the salience map that has been seen before (stored in memory). However, since we did not find any evidence of lures contributing to Contextual Cueing (even though they contributed to overall reaction time), it appears that the map stored in memory in Geyer et al.’s account would not include a representation of the lure locations. This suggests that it is not the overall salience map that is remembered and gives rise to Contextual Cueing, but rather a lower level map, perhaps a feature map that only contains the pattern of activation where candidate features are located (Figure 4).

Coupled with the fact that memory for repeated displays is implicit in typical Contextual Cueing experiments, the current results suggest that Contextual Cueing might be a form of procedural knowledge: given a set of locations to attend to (the list of non-rejected locations), the visual system is faced with a series of decisions regarding the order in which these locations are to be inspected by the eyes/attention. Studies which examined eye movements in Contextual Cueing seem to support this interpretation. Observers make fewer fixations in repeated compared to novel displays (Beesley, Hanafi, Vadillo, Shanks, & Livesey, 2018; Tseng & Li, 2004). These fewer fixations were in fact associated with longer fixation durations, suggesting that context repetition aids in the planning of eye movement decisions rather than the speed at which items are processed (Zang, Jia, & Müller, 2015). Thus, the benefit of repetition might be to lessen the demands on this procedural decision process and to improve performance as the same set of contexts repeat over and over throughout the experiment (Sewell, Colagiuri, & Livesey, 2018). If so, this mechanism might also help explain why there is, at best, a minimal guidance effect of context repetition in Contextual Cueing (Kunar et al., 2007). There have only been a few studies where the set size of the candidate set is manipulated (Chun & Jiang, 1998; Kunar et al., 2007; Kunar, Flusberg, & Wolfe, 2008). If display repetition guided attention towards the target, then one would expect an interaction between display repetition and set size (a smaller set size effect on repeated displays than on novel displays), which has not been consistently observed (or only to a small extent). Thus, perhaps Contextual Cueing is less an attentional effect and

**Figure 3.** (A) Response times for novel displays (solid lines) were significantly longer than for repeated displays (dashed lines) in Epochs 4 and 5. (B) There was no significant difference in logarithmic slopes between novel (solid lines) and repeated (dashed lines) displays, indicating that there was no difference in search efficiency.
more a procedural memory effect: the advantage that comes from repeating the same actions/decisions over time, just like repetition improves playing the same musical piece on the piano.

It should be noted, though, that a few studies have found evidence of Contextual Cueing in displays containing lures. However, it is unclear whether these studies truly reflect the influence of lure-context repetition. Geyer, Zehetleitner, et al. (2010) reported contextual cueing in lure-only displays. In their displays, distractors were always green bars rotated 45 degrees to the right, while the target could be either a red bar rotated 45 degrees to the right or a green bar rotated 45 degrees to the left. The target was randomly defined on each trial, preventing participants from having a specific target template in mind to help them parse the display. From the perspective of the Target-Contrast Signal Theory, having a target template in mind allows observers to compute and accumulate a “target-contrast signal” at each location in the display (i.e., evidence of visual dissimilarity between the target template and the stimuli at each location in the display). When observers do not know ahead of time what the target will be (i.e., in so-called oddball tasks), there is a large processing cost associated with not knowing what contrast to compute at first. This cost is particularly high at low set sizes (when it is unclear what elements in the display are the distractors), and results in reaction times that decrease with set size (Bravo & Nakayama, 1992; Buetti et al., 2016). Indeed, the type of unknown-target search in Geyer, Zehetleitner, et al. (2010) might be closer to oddball search tasks (where RTs decrease with set size) than to fixed-target search tasks (as used here, where RTs increase logarithmically with set size). In addition, the search display was preceded by placeholders which previewed the spatial locations before the distractors appeared; participants presumably attended to the placeholders ahead of the presentation of the lures. Thus, it is therefore difficult to conclude which context repetition was improving performance: that of the lures or that of the placeholders.

Other studies reported very small Contextual Cueing effects in lure-only displays (12–33ms; Harris & Remington, 2017; Kunar et al., 2007). In Experiment 2b in Kunar et al. (2007), lures (either 8 or 12) were always accompanied by placeholders. The target was a letter T and was red in colour, as was the placeholder it appeared in. Lures were green letter Ls placed in green placeholders. Although they reported a statistically significant Contextual Cueing effect with 12 lures, the main effect of display repetition was not statistically significant, and the Contextual Cueing effect for set size 8 was only marginally significant ($p = .09$) after collapsing across the last 3 epochs. Thus, the difference across studies could arise either from a false positive result in Kunar et al. (2007) or from a lack of power to detect a small effect in the present study. However, we believe the latter possibility is less likely than the former. First, we had almost twice as many participants than in Kunar et al. (20 vs. 12). Second, Bayes factors analyses in our experiments revealed strong evidence for the lack of any effect of lures on Contextual Cueing. Therefore, we believe it is more likely that the Contextual Cueing effect detected in Kunar et al. (2007) was a false positive. Nevertheless, future experiments should look at the impact of placeholder displays on contextual cueing (with and without lures). A final possibility could be that some of the lures may have acted as candidates instead. The categorization of a stimulus as a lure or...
candidate is determined by whether the visual system can differentiate it from a target in peripheral vision. It is possible that some of the lures in Kunar et al. may have functioned as candidates because the stimuli were letters that may be hard to resolve, particularly when they are presented far in the periphery. If so, it may have been the context provided by these lures-acting-as-candidates that contributed to the small Contextual Cueing effect reported in that study.

**Considerations for future studies**

The Attentional Engagement Theory (Duncan & Humphreys, 1989) proposes that search efficiency is influenced by both target-distractor similarity and distractor-distractor similarity. When target-distractor similarity is low, as we have investigated here, search is more efficient. When distractor-distractor similarity is low, search is less efficient. Feldmann-Wüstefeld and Schubó (2014) examined the latter in a series of Contextual Cueing tasks and reported that distractor homogeneity (high distractor-distractor similarity) increased the magnitude of the Contextual Cueing effect (or conversely, that distractor heterogeneity decreased Contextual Cueing). Their displays were candidate-only displays, while our study involved lure-only and mixed candidate + lure displays. It is unlikely that lure rejection played any role in that study, whereas in our study, lure rejection played a critical role in segmenting the display by discarding lures and retaining candidate locations. That said, it is interesting to note that in Feldmann-Wüstefeld and Schubó’s study, more Contextual Cueing was observed when distractors were more similar to one another. Perhaps when distractor-distractor similarity of candidates is high it creates a more coherent spatial context than when distractor-distractor similarity is low. As a follow-up to that study, it would be interesting to see whether increasing lure heterogeneity would provide a more robust spatial context, and therefore, might allow Contextual Cueing to emerge. Indeed, recent findings by Wang et al. (2017) and Lleras et al. (2019) have shown that when lure heterogeneity is high, RTs are slowed down in a multiplicative manner (in logarithmic space), while lures continued to be rejected in parallel. Thus, future experiments could use lure-heterogeneous displays to slow down RTs and examine whether Contextual Cueing would emerge in these lure-only displays. Incidentally, the findings of Wang et al. (2017) and Lleras et al. (2019) challenge the basic premise from the Attentional Engagement Theory that lures are grouped and rejected en masse because they demonstrate that lure rejection takes place on a per-item basis (in parallel) and can be facilitated when identical lures appear in nearby locations.

There has been considerable debate on whether the Contextual Cueing effect arises from an explicit memory trace of the repeated displays (Colagiuri & Livesey, 2016; Goujon et al., 2015; Schlagbauer, Muller, Zehetleitner, & Geyer, 2012; Vadillo, Konstani-nidis, & Shanks, 2016). The results in the recognition task in Experiment 3 indicated no overall memory for the repeated-lure contexts, but at the same time, display-level analysis suggested perfect memory for a small subset of lure contexts. This finding suggests that future studies should consider more precise tests of the memory for repeated displays and a more careful analysis of whether or not explicit memory for a subset of displays can drive the overall Contextual Cueing effect. For example, Annac et al. (2019) just recently reported evidence that participants may in fact have a small degree of explicit memory about the repeated target locations. The authors showed that observers were more accurate in explicitly generating the layout (in the target quadrant) of the repeated compared to the novel displays. In addition, explicit recognition of the target quadrant in repeated displays was enhanced when observers fixated on that quadrant compared to other quadrants. Furthermore, this effect was more pronounced when the analysis was limited to the subset of displays that produced the contextual cueing effect. Together with our findings, these recent findings by Annac et al. (2019) do suggest that in Contextual Cueing participants may have an explicit memory trace for at least some of the displays and repeated locations used during the experiment. In fact, Smyth and Shanks (2008) reported that Contextual Cueing may arise from just one or two instances of repeated displays in the average experimental session. That is to say that although twelve contexts are repeated in a typical Contextual Cueing experiment, the repetition of just one or two of those displays drive the entire effect in a given experimental session. Thus, Contextual Cueing might in fact arise not from procedural implicit memory but rather from the explicit
recognition of one or two displays in any given experiment.

A second implication of our findings is that the manner in which stimuli are rejected determines whether or not they contribute to the spatial context driving Contextual Cueing. When items can be rejected via peripheral vision through parallel processing, the locations of these items do not form part of that context. Those items that cannot be rejected in parallel in the periphery probably do contribute to that context. In other words, it is not the stimulus per se that matters, but the interaction between a stimulus and its location on the visual field: a stimulus that is somewhat similar to the target might act as a lure in the near periphery (where resolution is somewhat high), but it might act as a candidate farther in the periphery. As a result, experiments with such “lures” might be difficult to interpret because these peripheral “lures” wouldn’t be rejected in parallel, and thus their locations would be part of the list of to-be-scrutinized locations. If so, these locations would create the sort of spatial context that does facilitate repeated search. This scenario might be aggravated by other peripheral processing constraints like crowding. This might explain the inconsistent findings between studies that investigated the effects of lures on contextual cueing and should be examined further in future experiments.

Future experiments should also explore the possibility that lure locations are in fact stored in memory but are too slow to emerge or too weak to have an impact on efficient search. Suppose it takes 500 ms to recognize a repeated context (irrespective of whether it is composed of lures or candidates). When the repeated display only contains lures, by the time the context has been implicitly recognized by the visual system, the target has already been found. When the repeated display contains candidates, it takes longer to find the target; the recollection of the context thus has time to impact the deployment of attention and therefore facilitate search, producing a Contextual Cueing effect. That said, there are reasons to doubt this hypothesis as it appears to be inconsistent with the data of Jiang and Chun (2001). In Experiment 2 of Jiang and Chun (2001), a small contextual cueing effect was observed when lures were repeated (in the presence of non-repeating candidates). When the authors made search more difficult (and thus increased overall response times), the small contextual cueing effect that was observed in Experiment 2 was eliminated rather than enhanced. These results suggest that slower reaction times are not necessarily what is required to observe lure-driven contextual cueing.

Another possibility that is worth considering relates to the difference between the learning and the expression of learning in Contextual Cueing. Similar to the findings reported in Jiang and Chun (2001), Jiang and Leung (2005) reported that Contextual Cueing was observed in candidate-repeat and both-repeat displays (i.e., lure and candidates repeat), but not in the lure-repeat displays. In a subsequent “transfer” phase in the second half of the experiment, the locations of the candidates and lures in the repeated displays were swapped. Now, there was a Contextual Cueing effect in the candidate-repeat displays (which were previously lure-repeat displays). Thus, the authors concluded that lure locations must have been learned, but that the learning was not expressed until attentional scrutiny was required. In our experiments, it is possible that the spatial arrangements of the repeated lures may have been learnt, but that this learning was not expressed in the experiment. Not expressing the learning may have occurred because the lure rejection process unfolded too quickly or because of a floor effect: it may be that, in lure-only displays, the time taken to move attention to the target (after lure rejection is completed) cannot be made any faster by the knowledge of the repeated context. The learning may have also failed to express itself in displays containing both lures and candidates because the context provided by the candidates may have a stronger impact on performance than the context provided by the lure-and-candidate contexts. Indeed, it is probably the case that displays with fewer items in them (with only candidates in Experiment 2) have more memorable/unique configurations than displays with candidates and, say, 31 lures.

It is possible that any amount of context repetition will be beneficial provided that the search task is sufficiently difficult. Even if a repeated context takes a relatively long time to be recognized, this could be useful in difficult search displays consisting of both lures and candidates. A future experiment could involve novel displays that consist of random arrangements of both lures and candidates, and repeated displays that consist of repeated arrangements of lures.
only and random arrangements of candidates. This might provide a chance for lure context to influence search behaviour.

It should be noted that typically Contextual Cueing has been observed from the start of the first or second epoch, as was the case in our Experiment 1. However, Contextual Cueing emerged only in the last two epochs in our Experiment 2, when both candidates and lures were repeated. This opens up the possibility that the presence of lures may have in fact interfered with the learning of the spatial context that gives rise to Contextual Cueing. Thus, we cannot rule out the possibility that the presence of lures delays the learning of the association between the spatial context of the lure stimuli and the target location. In order to test that possibility, one might only need to run Experiment 2 or 3 but with more trials (perhaps twice as many) to give more time for this association to be learned. Another possibility might be that the lure manipulation is not strong enough to survive the somewhat noisy conditions that give rise to Contextual Cueing. If, as suggested by Smyth and Shanks (2008) and Annac et al. (2019), Contextual Cueing arises from just a small subset of contexts, then subdividing the number of repeated contexts into separate lure set size conditions might be ill-advised. This follows because some participants benefit from a repeated lure context in one or two displays at a given set size, while other participants would benefit from a different lure set size condition. Averaging across would show little, if any, benefit of lure-context repetition at each set size condition. A solution would be to re-run Experiment 2, but manipulate lure set size across subjects.

Summary

In conclusion, the results show that lure processing does not benefit from context repetition, even though lure processing incurs a significant time cost. This suggests that lure locations are not stored in the memory trace that drives Contextual Cueing, consistent with the proposal by Jiang and Chun (2001). The results are also consistent with the Target Contrast Signal Theory, which proposes that locations containing lures are rejected early on, during parallel processing, and are not considered as targets for the attention and eye movement system. Only those locations that are likely to be fixated contribute to Contextual Cueing.

Notes

1. Jiang and Chun (2001) referred to these as the “attended” and “unattended” color respectively. However, we prefer to use the term “candidate” to describe a distractor that is very similar to the target such that selective attention is required to distinguish it from the target, and the term “lure” to describe a distractor that is sufficiently different from the target such that the visual system can distinguish it from the target in peripheral vision without the need for focused selective attention (Buetti et al., 2016; Lleras, Buetti, & Mordkoff, 2013; Neider & Zelinsky, 2008).

Disclosure statement

No potential conflict of interest was reported by the authors.

References


