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When memory meets distraction: The role of unexpected stimulus-driven attentional capture on contextual cueing

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ABSTRACT
Visuospatial attention plays a critical role in prioritizing behaviourally-relevant information and can be guided by task goals, stimulus salience, and memory. Here, we examined the interaction between memory-guided attention (contextual cueing) and stimulus-driven attention (unexpected colour singletons). In two visual search experiments with different set sizes, colour singletons were introduced unexpectedly in some trials after repeated configurations were used to establish contextual cueing. Reaction times were rapidly impacted by both contextual cueing and colour singletons, without significant interaction. However, introducing color singletons also impeded reaction times for novel configurations without color singletons, while repeated configurations were not impacted. These results suggest that on a trial level, contextual cueing and colour singleton effects are largely two independent factors driving selective attention, but there is evidence for a more general disruption of introducing distraction in cases where memory cannot be relied upon, suggesting a more complex interaction between attentional influences.

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Visual search; contextual cueing; pop-out effect; episodic memory

When we search through an environment, selective attention determines which subset of all possible information gets prioritized for further processing. Accounts of memory-guided attention emphasize that the processes of selective attention can be controlled not only based on perceptual salience of the information (stimulus-driven attention) and task goals of the observer (goal-directed attention) (Carrasco, 2011; Chun et al., 2011; Theeuwes, 2010) but also based on past experience either about the item we are searching for or about the environment that we search in (for related reviews, see Chen & Hutchinson, 2019; Chun & Turk-Browne, 2007; Hutchinson & Turk-Browne, 2012; Võ & Wolfe, 2015; Woodman & Chun, 2006). These influences on attention operate collectively to allocate limited resources to the most important and relevant information determined by factors both internal and external to the observer.

One particular aspect of how memory facilitates attention orientation is based the fact that items are seldom encountered in isolation but rather are situated repeatedly amongst the same set of items. Consequently, these surrounding items form a meaningful spatial context for the target item that we search for. The reoccurrence of the spatial context of the surrounding items has been found to facilitate the search for a target even without explicit awareness, a phenomenon termed *contextual cueing* (Chun & Jiang, 1998). In the original paradigm, when participants were asked to look for a T-shaped target among L-shaped items, the invariant contextual pattern of the items in repeated configurations implicitly guided attention to the target location resulting in faster reaction times (RT). On the other hand, search configurations with non-reoccurring, novel configurations did not receive this benefit. To date, many studies using the same paradigm or related variants, have repeatedly shown the effect wherein memory, through repetitive spatial contextual information, can guide attention towards the target item (e.g., Brockmole et al., 2006; Goldfarb et al., 2016; Goujon et al., 2007; Greene et al., 2007; Tseng & Lleras, 2013) and facilitate response selection process (Kunar et al., 2007, 2008; Schankin et al., 2011; Schankin & Schubö, 2010).

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While memory representations of invariant contextual information can guide attention efficiently, how such guidance is influenced by a change in the search environment is less explored in comparison. Specifically, there is relatively little known about how established memory adaptively guides attention when a salient colour singleton distractor (which was reported as efficient in attracting attentional resources; see Theeuwes, 1992) appears *unexpectedly* in a previously learned context. In such a situation, there are several plausible ways in which the introduction of such a distractor might interact with an established memory. For example, one possibility is that the unexpected appearance of a distractor in a previously learned configuration effectively leads to a largely weakened or complete removal of the contextual cueing effect (e.g., the entire configuration being reinterpreted as novel) (we will refer to this as the *replacement account*; see experimental conditions with previously learned context that were not adaptive to changes in Conci et al., 2011; Conci & Müller, 2012; Song & Jiang, 2005). Another possibility is that memory-guided attention effectively overrides attentional capture. That is, the memory of the previously learned configuration guides attention in such a way that the introduction of a distractor does not slow down search time and the learned configuration is effectively "insulated" from the distracting effect (we will refer to this as the *insulation account*; see Goschy et al., 2014; Peterson & Kramer, 2001a, 2001b). A third possibility, of course, is that the control of attention from memory guidance and the stimulus-driven capture from the colour singleton do not interact in this situation (e.g., they might occur at separate stages in processing). That is, the introduction of a singleton distractor produces slower search times, but the difference in search times between novel and repeated configurations also persists in parallel, suggesting a non-interactive, purely additive dynamic across memory-guided attention and perceptual distraction (we will refer to this as the parallel account; see related study in Conci & von Mühlenen, 2009, Experiment 2).

To investigate how different influences on attention (i.e., memory-guided and stimulus-driven attention) interact, here we employed a modified contextual cueing paradigm. In particular, we introduced an unexpected colour singleton as part of the search context with an attempt to divert attention to a salient singleton after memory's guidance of attention to the target is established. Additionally, as configurations with fewer items have been shown to be easier to learn (see Experiment 4; Chun & Jiang, 1998), we used search configurations with two different set sizes, to ensure differences in learning rate and/or task complexity do not influence our primary results of interest. Participants were asked to identify a T-shaped target among 7 (Experiment 1) or 15 (Experiment 2) L-shaped items. Halfway through the experiment, after the presumed acquisition of the contextual cueing effect, one of the L-shaped items was changed to a colour singleton in half of the trials (equal parts in novel and repeated configurations). This manipulation enabled us to examine the effect of stimulus-driven attention capture (colour singleton distraction) on memory-guided attention (contextual cueing) when both were present (i.e., distractors appearing in configurations which were previously encountered without them).

Methods

Participants

In Experiment 1, 42 participants (20 males; age: mean = 20.05 y, SD = 1.12 y, range = 19-23 y) who were undergraduate students from Northeastern University were recruited and compensated with credit counted towards their class requirements. The study was approved by the Institutional Review Board at Northeastern University. All participants provided written informed consent. Participation criteria required participants to be fluent in English and have normal or corrected-to-normal colour vision. Two participants were excluded from the analysis because of data corruption and low general accuracy (under 60% correct target discrimination on one or more blocks) respectively.

In Experiment 2, 43 participants (14 males; age: mean = 20.07 y, SD = 1.93 y, range = 19-29 y) who were from the same population were sampled with the same participation criteria. The study was approved by the Institutional Review Board at Northeastern University. All participants provided written informed consent. Two participants were excluded from the analysis as they did not complete the entire experiment and two participants were excluded due to low accuracy (less than 60% correct target discrimination on one or more blocks).

Participant-level RT data was assessed for outlier data points defined as 3 or greater SD away from the group mean, however 0 outliers were identified using this threshold.

Procedure

Participants were asked to perform a visual search task. The experiments took place in a behavioural testing room. Participants were seated approximately 50 cm from a Dell monitor (1920 × 1080 resolution, 60 Hz refresh rate).

The presentation of stimuli and response collection were programed using MATLAB Psychophysics toolbox (psychtoolbox.org). Participants completed a contextual cueing task with 800 trials (10 blocks) of visual search for a single, rotated T-shaped target among L-shaped items, with shapes subtending approximately 1.9° on a 32.3° × 32.3° grey square background. The shapes were equally distributed in each of the quadrants in the configuration. In Experiment 1, each spatial configuration consisted of 8 shapes (Figure 1(a)), among which one was the T-shaped target and the rest were L-shaped items. Each L-shaped item was equally likely to be 0°, 90°, 270°, and 360° flipped from the original shape in each configuration. The orientation of the T-shaped target faced to the left for half of the trials and right to the other half and was counterbalanced across trial conditions. In Experiment 2, each configuration contained 16 shapes (Figure 1(b)), among which one was the T-shaped target and the rest were L-shaped items. In both experiments, after block 5, one of the L-shaped items turned to a colour singleton for half of the Repeated and half of the Novel trials. Apart from the difference in the number of items in search configurations, all the details in the procedure and design were identical across two experiments. All configurations were uniquely generated for each participant. All colours were subjectively matched in luminance by the experimenter.

During the search task, following a fixation display of 750 ms, participants were asked to search for a rotated T-shaped target and to press the button K using their dominant hand on a keyboard as fast as possible if the target pointed to the left and to press L using another finger of the same hand if the target pointed to the right. Leftward and rightward facing targets were randomly assigned across trials with proportions of each balanced within a block. Each configuration was displayed for 1500 ms with an inter-trial interval (ITI) of 750 ms, and participants were given the stimulus display duration and the following fixation period to respond (total of 2250 ms; Figure 1(d)).

Out of 80 trials in a block, 80% of trials were assigned to have fixed spatial contexts (i.e., the locations of the shapes were fixed across repetitions; Repeated trials) and 20% were assigned to have a novel context on each trial (i.e., the location of the shapes was randomly and uniquely determined for each trial; Novel trials). Each Repeated trial repeated 4 times per block and 40 times across 10 blocks. In total, there were 16 Repeated configurations (8 different pairs) presented for each participant. The total number of novel configurations that a participant viewed was 160. The order of stimuli was pseudo-randomized such that a Repeated pair only reappeared after an entire set of Repeated trials (16 trials) and at least 4 Novel trials had appeared once in a random order.

All Repeated trials consisted of fixed pairs of configurations, as the present study was originally designed to examine the predictability between the pairs. For example, the appearance of configuration A was always followed by configuration B throughout the experiment. To match this structure, the Novel trials also appeared as non-reoccurring pairs (i.e., they were always presented in sets of two trials). However, as pair structure did not produce any differences in either error rate, reaction time, or any interactions with reported results, we excluded any analysis and discussion about this manipulation in the result section.

For the first half of the experiment, all shapes were presented either in green or in red (varied pseudo randomly by participant). Starting at the beginning of the second half of the experiment (block 6), and without notifying the participant, non-target colour singletons of the other colour were introduced (e.g., if all shapes had been shown in red, then a single green shape was introduced and stayed in the same green colour) for half of the trials. Specifically, half of the Repeated configurations had a single,

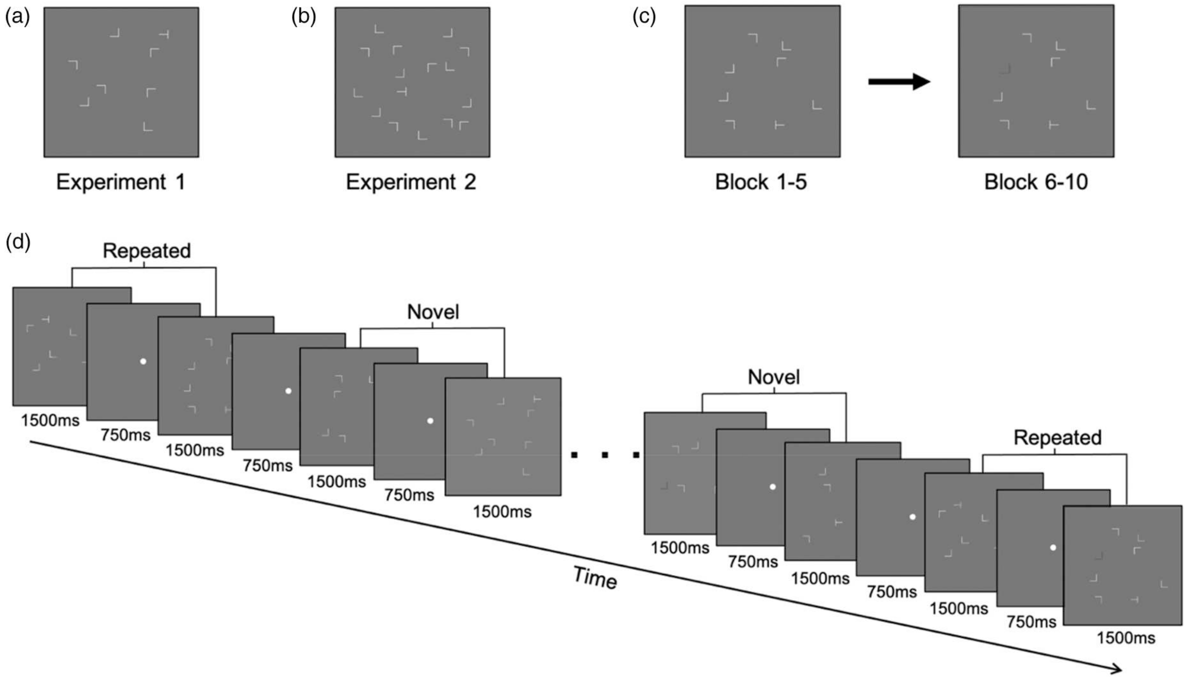

Figure 1. (a) An example of search configuration in Experiment 1. Participants searched for a T-shaped target among 7 L-shaped items. (b) An example of search configuration in Experiment 2. Participants searched for a T-shaped target among 15 L-shaped items. (c) An example of Repeated Singleton configuration in the first and second half of Experiment 1. For half of the Novel and Repeated Singleton trials, one of the items became a colour singleton starting at block 6 in both experiments. Experiment 2 follows the same principle with 1 out of 16 shapes became a colour singleton at the same location. (d) Trial Sequence. All Novel trials only appeared once, but each Repeated trial re-appeared in total 40 times with the same shape arrangement throughout the experiment.

randomly selected L-shaped item become a colour singleton of the other colour (Repeated Singleton; Figure 1(c)). In the same way, half of the Novel configurations also had one of the items become a colour singleton (Novel Singleton). The rest of the Repeated (Repeated No-singleton) and Novel (Novel No-singleton) trials were presented without any singletons. Colour singletons in Singleton trials were counterbalanced to appear in each of the quadrants of the configuration and were counterbalanced to appear in either position of a trial pair (i.e., equal distribution across first position only, second position only, both positions, and neither position) and were therefore controlled for the distance between singleton distractor and target location.

Each participant completed 20 Novel trials as practice before the first block to ensure they understood the instructions. Each block started with 2 "buffer" Novel trials, one of which contained a colour singleton distractor after block 5. Both practice and buffer trials were excluded from the analysis. The blocks were separated by a short break lasting until the participants indicated that they were ready to proceed.

Following the completion of the computer task, to test participants' explicit awareness, there was a short debriefing session during which the participants were asked: 1. "What do you think the experiment was about?"; 2. "Did you use any strategy during the first part of the experiment (the Search phase)?"; 3. "Did you notice any repeating patterns during the first part of the experiment (the Search phase) and if so, what type of patterns did you observe?"; and 4. "Have you done an experiment like this before?".

Results

Accuracy

Mean error rates encompassed trials containing incorrect button presses and no responses before the onset of the next trial (2250 ms). These rates were calculated for each condition and block, separately for each participant. The overall error rate was 3.36% (SD = 1.92%) for Experiment 1. Because Singleton stimuli only appeared in the second half, a two-way Novelty (Repeated vs. Novel) × Block (block 1–5) and a three-way Novelty (Repeated vs. Novel) × Singleton (Singleton vs. No-singleton) × Block (block 6–10) repeated measures analysis of variance (ANOVA) on trial accuracy were conducted separately on the first and second half of the experiment. The two-way repeated measures ANOVA on Novelty × Block (block 1–5) of the first half in Experiment 1 only showed a significant main effect of Block ($F_{(4,156)} = 2.46$, $P < 0.05$, $\eta^2 = 0.03$), due to a decrease in errors with increasing task experience. In the second half, the three-way Novelty × Singleton × Block (block 6–10) repeated measures ANOVA showed no significant main effects or interactions.

Experiment 2 has an overall error rate of 7.03% (SD = 3.38%). In the first half in Experiment 2, there was a significant main effect of Block ($F_{(4,152)} = 32.2$, $P < 0.001$, $\eta^2 = 0.14$), as later blocks produced fewer errors with increasing task experience, and a significant main effect of Novelty ($F_{(1,38)} = 14.93$, $P < 0.001$, $\eta^2 = 0.04$), as Novel trials were more prone to wrong responses. The main effect of Novelty in the same direction remained significant in the second half ($F_{(1,38)} = 23$, $P < 0.001$, $\eta^2 = 0.04$) with the three-way repeated measures Novelty × Singleton × Block ANOVA. There were no other significant differences in accuracy. The significant differences of Novelty shown only in Experiment 2 might be due to the increasing search difficulty for larger set size (i.e., the error rate was further from floor) although the mean error rate difference between Novel and Repeated trials of Experiment 2 was small: 2.21% (Novel: 6.09%; Repeated: 3.88%) in the first half and 2.01% (Novel: 3.24%; Repeated: 1.23%) in the second.

Consistent with previous research (Chun & Jiang, 1998), larger set size increased task complexity, resulting in a higher error rate overall as well as larger error rate differences as a function of Block, Novelty, and their interaction. Comparing the two experiments (set sizes of 8 or 16 respectively), a three-way mixed effects ANOVA on the first half (block 1-5) of both Experiment 1 and 2 with Set Size as between-subject factor as well as Novelty and Block as within-subject factors showed a significant main effect of Set Size ($F_{(1,77)} = 51.89$, $P < 0.001$, $\eta^2 = 0.21$) with a higher error rate on Set Size 16 than Set Size 8. Other significant main effects indicated more errors as a function of Novelty ($F_{(1,77)} = 16.106$, $P < 0.001$, $\eta^2 = 0.02$) and fewer errors across blocks ($F_{(4,308)} = 33.66$, $P < 0.001$, $\eta^2 = 0.09$). Set Size interacted with Novelty ($F_{(1,77)} = 9.992$, $P < 0.01$, $\eta^2 = 0.01$), where Set Size 16 showed a greater difference in error rate between novel and repeated trials than Set Size 8. Set Size also interacted with Block ($F_{(4,308)} = 22.00$, $P < 0.001$, $\eta^2 = 0.05$), whereby Set Size 16 showed a greater decrease in error rate over time than Set Size 8. On the second half (block 6-10) of both experiments, a four-way mixed effects ANOVA with Set Size as between-subject factor and Novelty, Singleton, and Block as within-subject factors showed a significant main effect of Set Size ($F_{(1,77)} = 31.13$, $P < 0.001$, $\eta^2 = 0.05$), a significant main effect of Novelty ($F_{(1,77)} = 24.77$, $P < 0.001$, $\eta^2 = 0.02$), and a significant interaction of Novelty × Set Size ($F_{(1,77)} = 17.65$, $P < 0.01$, $\eta^2 = 0.01$). No other main effects or interactions reached significance.

Reaction time

Next, we considered reaction times, excluding erroneous or missing responses. We calculated the median RT (as the RT distributions are skewed to the right in both Set Size conditions; skewness = 1.28 for Experiment 1 and 0.90 for Experiment 2) for each participant in terms of Novelty (Repeated/Novel), Block (1–10), Singleton (Singleton/No-singleton) and calculated the mean of the medians across participants. Note that Repeated Singleton trials did not actually contain a colour singleton until block 6. That is, there was no distinguishable difference between Repeated Singleton trials and Repeated No-singleton trials in the first half of the experiment (block 1–5).

Novelty, block, and singleton effects

Experiment 1. We first sought to characterize the contextual cueing effect (i.e., impact of novel displays across blocks) and how it was impacted by introduction of a colour singleton. We divided the experiment into pre- and post-singleton periods (blocks 1–5 and 6–10, respectively) to isolate stimulus-driven attention capture from colour singleton in the second half of the experiment. For the first half of the experiment, a two-way Novelty × Block (block 1–5) repeated measures ANOVA was conducted (Figure 2 (a)). Participants performed the task more quickly with time, as there was a main effect of Block such as search time decreased across blocks ($F_{(4,\ 156)} = 81.42$, $P < 0.001$, $\eta^2 = 0.16$, Block 1 > Block 5: 169.2

ms). Consistent with the contextual cueing effect, a main effect of Novelty was also observed ($F_{(1,\ 39)} = 20.40$, $P < 0.001$, $\eta^2 = 0.03$, Novel > Repeated: 67.90 ms). This effect emerged rapidly and remained stable as the Novelty × Block interaction was not significant ($F_{(4,\ 156)} = 0.60$, $P > 0.1$, $\eta^2 < 0.001$).

For the second half of the experiment, a three-way Novelty × Singleton × Block (block 6-10) repeated measures ANOVA was conducted (Figure 2(a)). Similarly, main effects of Block ($F_{(4,\ 156)} = 9.19$, $P < 0.01$, $\eta^2 = 0.02$, Block 6 > Block 10: 72.42 ms) and Novelty ($F_{(1,\ 39)} = 101.80$, $P < 0.001$, $\eta^2 = 0.08$, Novel > Repeated: 107.88 ms) were also observed. In terms of the introduction of distraction, there was a significant main effect in Singleton ($F_{(1,\ 39)} = 17.85$, $P < 0.001$, $\eta^2 = 0.02$, Singleton > No-singleton: 39.80 ms), suggesting the effectiveness of attentional capture by the colour singleton. A significant interaction of Singleton × Block was also found ($F_{(4,\ 156)} = 3.89$, $P < 0.01$, $\eta^2 = 0.002$), showing the impact of the colour singleton decreased as participants possibly habituated to this attention capture in later blocks. No other interactions were found significant in the second half of the experiment.

Experiment 2. This experiment contained twice as many items per display, as so we sought to assess if the same dynamics present in Experiment 1 also were present here (Figure 2(b)). As before, the experiment was divided into pre- and post-singleton periods. Similar to Experiment 1, in the first half of the experiment, a 2-way Novelty × Block repeated measures ANOVA showed significant main effects in both Block ($F_{(4,\ 152)} = 65.79$, $P < 0.001$, $\eta^2 = 0.19$, Block 1 > Block 5: 147.59 ms) and Novelty ($F_{(1,\ 38)} = 39.75$, $P < 0.001$, $\eta^2 = 0.07$, Novel > Repeated: 42.01 ms), but no Novelty × Block interaction ($F_{(4,\ 152)} = 0.89$, $P > 0.1$, $\eta^2 = 0.004$), consistent with a rapidly emerging contextual cueing effect alongside an overall decrease in reaction times as participants performed the task more quickly.

For the second half of the experiment, a Novelty × Singleton × Block repeated measures ANOVA showed significant main effects in Block ($F_{(4,\ 152)} = 18.84$, $P < 0.001$, $\eta^2 = 0.05$, Block 6 > Block 10: 45.37 ms), Novelty ($F_{(1,\ 38)} = 109$, $P < 0.001$, $\eta^2 = 0.15$, Novel > Repeated: 75.17 ms), and Singleton ($F_{(1,\ 38)} = 13.69$, $P < 0.001$, $\eta^2 = 0.03$, Singleton > No- singleton: 33.13 ms). As before, this is suggestive that introducing singletons produced attentional capture and that contextual cueing stayed effective after the introduction of colour singletons. There was a trending Singleton × Block interaction ($F_{(4,\ 152)} = 2.00$, $P < 0.1$, $\eta^2 = 0.004$). No other interactions were found significant in the second half of the Experiment 2.

Comparing Experiment 1 and Experiment 2: Next, we sought to explore if doubling the set size of display had an impact on the above dynamics. As before, we considered pre- and post-singleton periods separately but also introduced an additional factor of Set Size (i.e., Experiment) using mixed within/between subject ANOVA. In the first half of experiments, a three-way mixed effects ANOVA on the first half (blocks 1-5) with Set Size as between-subjects factor and Novelty and Block as within-subject factors showed a significant main effect of Set Size ($F_{(1,\ 77)} = 54.710$, $P < 0.001$, $\eta^2 = 0.34$, Set Size 16 > Set Size 8: 165.50 ms), suggesting that participants take longer to search displays with greater set size. As expected, there was a significant main effect of Block ($F_{(4,\ 308)} = 141.58$, $P < 0.001$, $\eta^2 = 0.17$, Block 1 > Block 5: 158.26 ms) and Novelty ($F_{(1,\ 77)} = 59.28$, $P < 0.001$, $\eta^2 = 0.05$, Novel > Repeated: 54.39 ms) similar to as what was found in each experiment individually. There was a trending Set Size × Novelty interaction ($F_{(1,\ 77)} = 3.15$, $P < 0.1$, $\eta^2 = 0.003$, Set Size 16 showed a greater RT difference between novel and repeated trials than Set Size 8). Set Size also interacted with Block ($F_{(4,\ 308)} = 2.67$, $P < 0.05$, $\eta^2 = 0.006$, Set Size 16 showed a greater RT decrease over time than Set size 8).

For the second half (block 6-10), we performed a four-way mixed effects ANOVA with Set Size as a between-subjects factor and Novelty, Singleton, and Block as within-subject factors. As before, there were significant main effects of Set Size ($F_{(1,\ 77)} = 41.74$, $P < 0.001$, $\eta^2 = 0.20$, Set Size 16 > Set Size 8: 120.62 ms), Block ($F_{(4,\ 308)} = 27.58$, $P < 0.001$, $\eta^2 = 0.03$, Block 6 > Block 10: 58.72 ms), Novelty ($F_{(1,\ 77)} = 207.14$, $P < 0.001$, $\eta^2 = 0.12$, Novel > Repeated: 91.32 ms). There was also a main effect of Singleton ($F_{(1,\ 77)} = 30.19$, $P < 0.001$, $\eta^2 = 0.02$, Singleton > No- singleton: 36.42 ms). Set Size significantly interacted with both Novelty ($F_{(1,\ 77)} = 6.64$, $P < 0.05$, $\eta^2 = 0.004$) and with Block ($F_{(4,\ 308)} = 2.56$, $P < 0.05$, $\eta^2 = 0.003$). No other main effects or interactions reached significance. Notably, set size did not interact with singleton presence, consistent with past work suggesting the pop-out effect of a singleton does not depend on

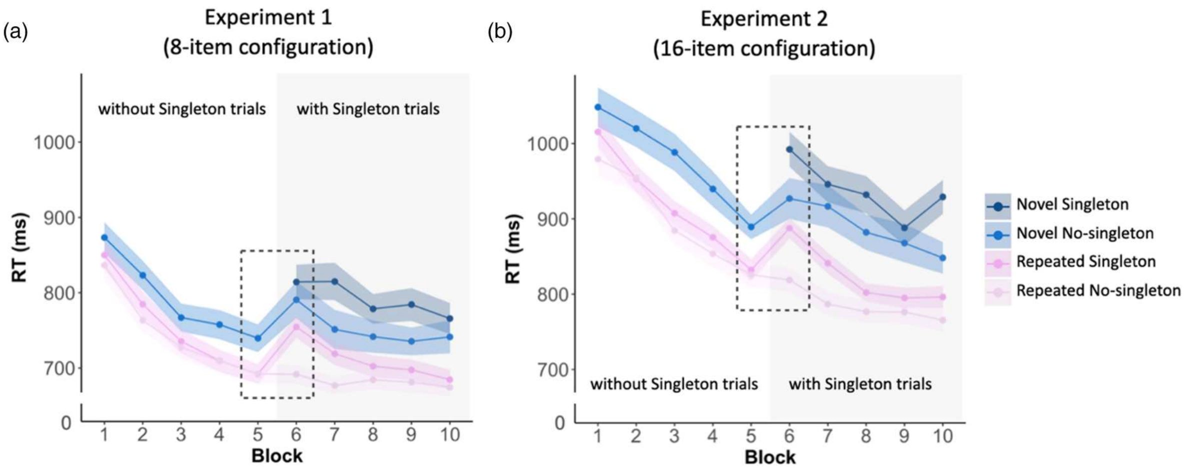

Figure 2. Mean of median RT across participants as a function of Block were shown from Experiment 1 (a) and 2 (b). Only responses from correct trials are shown. The coloured lines denote Novel Singleton (dark blue), Novel No-singleton (light blue), Repeated Singleton (dark pink), and Repeated No-singleton (light pink) trials respectively. Errors bars indicate ±1 standard error of the mean across participants. Note that Repeated Singleton trials are shown in the first half of both experiments for notation purposes only: there was no distinguishable difference between Repeated Singleton trials and Repeated No-singleton trials until block 6. The dotted box highlights when the transition from the last block without colour singleton appearance to the first block with a colour singleton.

set size (Maljkovic & Nakayama, 1994; Treisman & Gelade, 1980).

Overall, the results from both experiments showing reaction time benefits from repeated exposure to configurations replicated the contextual cueing effect (Chun & Jiang, 1998). This effect was learned rapidly and can be seen within the first block (Figure 2). Further, while the implementation of the colour singleton was effective, it did not seem to eliminate the acquired contextual cueing effect or vice versa. Lastly, participants possibly adapted to the distraction of colour singleton as its effect on RT declined over time (Müller et al., 2009; Theeuwes, 1992).

Contextual cueing persists despite distraction

The main effect of Novelty and the lack of interaction between Novelty and Singleton in the second halves of the experiments were suggestive that the appearance of colour singletons did not seem to disrupt previously learned knowledge about Repeated trials and in turn the established memory did not obstruct the capture of attention. These results appeared to be consistent with the parallel account offered above, wherein established memory-guided attention and stimulus-driven capture both remained effective, but in a parallel and simply additive manner. However, the results presented so far cannot completely rule out the replacement account, because it is possible that the contextual cueing effect was eliminated immediately upon singleton appearance but was rapidly re-learned within a block. In other words, there are at least two explanations of this effect: (1) memory about the Repeated configurations was effectively preserved despite the presence of an effective stimulus-driven attentional capture, and therefore trials with a singleton always showed a contextual cueing effect, even early on (parallel account); Or (2) the appearance of singletons did require replacement of previous Repeated configurations, eliminating the contextual cueing effect, which was then quickly re-learned within the first few trials of block 6 (replacement account).

In order to tease apart these possibilities, we first looked within block 6. For both Experiment 1 and 2, two-way Novelty × Singleton repeated measures ANOVAs did not show a significant interaction between Novelty × Singleton (Experiment 1: $F_{(1,\ 77)} = 0.11$, $P > 0.1$, $\eta^2 < 0.001$; Experiment 2: $F_{(1,\ 77)} = 1.83$, $P > 0.1$, $\eta^2 = 0.006$), indicating that attentional capture effect and the established contextual cueing effect are very likely to be independent. However, given memory can operate over single repetitions, it is possible that averaging over an entire block might obscure a rapid re-learning. Accordingly, we looked at an even smaller timescale (several trials) to assess if and how the factors of Singleton and Novelty relate. Specifically, we grouped each trial condition based on the order of their appearance (i.e., referred here as Occurrence), and each type of trials had 4 occurrences in block 6. Note that the first

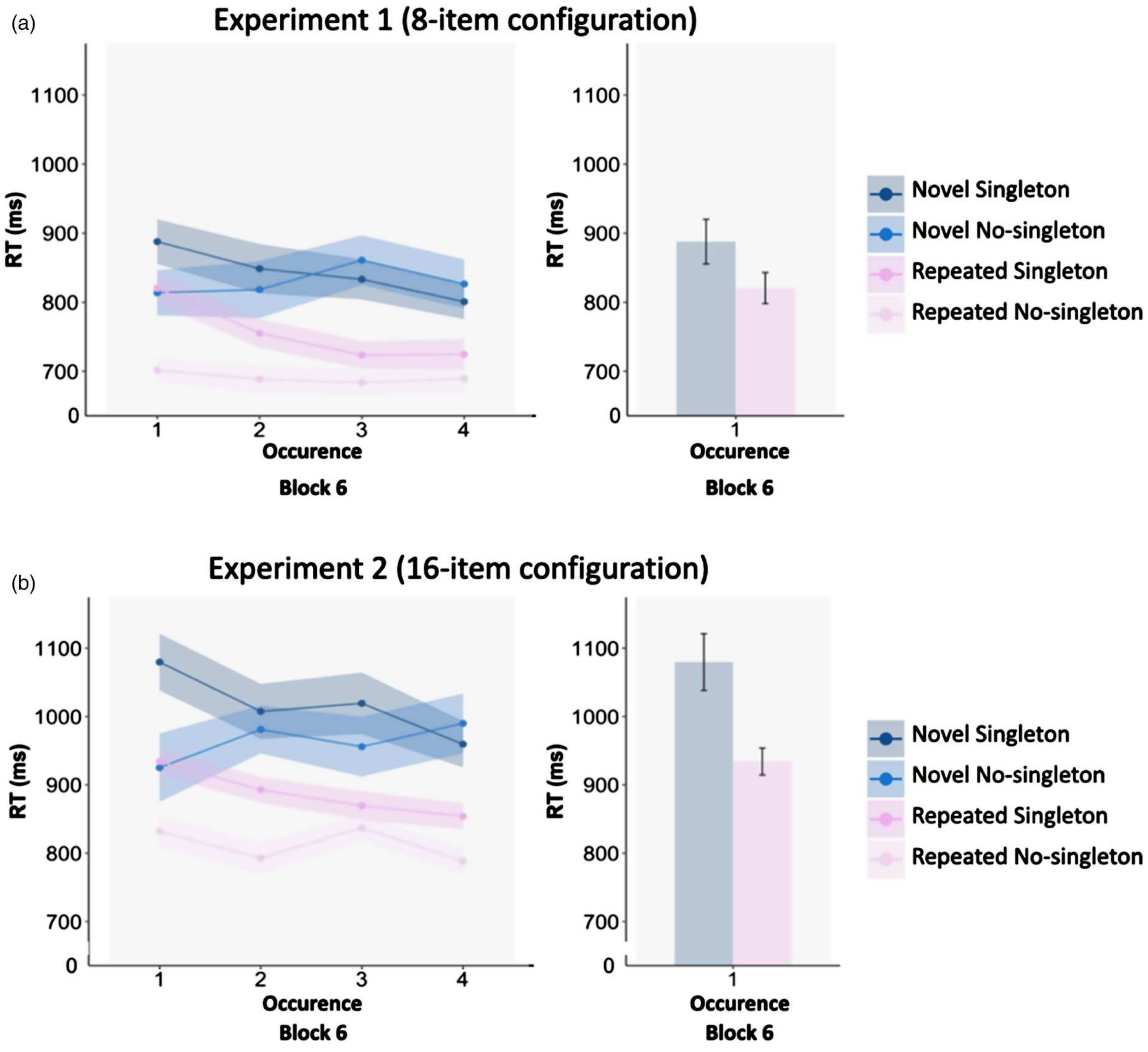

Figure 3. Mean of median RT across participants as a function of trial order of Block 6 were shown from Experiment 1 (a) and 2 (b). Occurrence was grouped by the order of appearance for each type of trials. Only responses for correct trials are shown. Left panels: The different coloured lines denote Novel Singleton (dark blue), Novel No-singleton (light blue), Repeated Singleton (dark pink), and Repeated No-singleton trials (light pink) respectively. Errors bars indicate ±1 standard errors of the mean across participants. Right panels: The bar graphs show the mean RTs for Novel Singleton and Repeated Singleton trials at their first occurrence in block 6.

occurrence of Singleton trials of block 6 was the first time that a participant had seen a colour singleton in a Repeated or Novel trial (after one buffer trial, see Methods). As can be seen in Figure 3, there was no evidence suggesting the contextual cueing effect disappeared on trial-level in block 6.

We assessed the results depicted in Figure 3 statistically by using a three-way Novelty × Singleton × Occurrence repeated measures ANOVA. In Experiment 1, there was a significant main effect of Novelty ($F_{(1,\ 39)} = 23.10$, $P < 0.001$, $\eta^2 = 0.11$, Novel > Repeated: 112.87 ms), a significant Singleton × Occurrence interaction ($F_{(3,\ 117)} = 6.70$, $P < 0.01$, $\eta^2 = 0.017$), and a trending Novelty × Singleton interaction ($F_{(1,\ 39)} = 3.10$, $P < 0.1$, $\eta^2 = 0.009$). Critically, a paired t-test showed that, at the very first appearance of each trial type in block 6, there was a significant difference between Repeated Singleton and Novel Singleton trials ($_{t(39)} = 2.46$, $P < 0.05$, $d = 0.40$, Novel Singleton > Repeated Singleton: 67.27 ms). This suggests that there was no temporary un- and re-learning of the configuration, as repetition had an effect on the first occurrence after singleton introduction. Similarly in Experiment 2 (Figure 3(b)), a three-way repeated measures ANOVA showed significant main effect of Novelty ($F_{(1,\ 38)} = 31.84$, $P < 0.001$, $\eta^2 =$ 0.12, Novel > Repeated: 141.57 ms), Occurrence ($F_{(3,\ 114)} = 4.97$, $P < 0.05$, $\eta^2 = 0.01$, Occurrence 1 >

Occurrence 4: 53.15 ms), a trending main effect of Singleton ($F_{(1,\ 38)} = 2.94$, $P < 0.1$, $\eta^2 = 0.02$, Singleton > No-singleton: 61.72 ms), and a significant interaction of Singleton × Occurrence ($F_{(3,\ 114)} = 6.58$, $P < 0.05$, $\eta^2 = 0.005$). Importantly, just as in Experiment 1, RTs of Repeated Singleton and Novel Singleton trials were significantly different at the first appearance of each trial type in block 6, ($t_{(38)} = 3.76$, $P < 0.001$, $d = 0.60$, Novel Singleton > Repeated Singleton: 154.33 ms), as shown in Figure 3(b).

Taken together, these results suggest that even when a singleton appeared unexpectedly and effectively captured attention, the influence of memory on Repeated configurations was still effective – as they were not replaced or re-interpreted as novel configurations. This is consistent with the parallel account described above wherein the influence of the contextual cueing effect did not eliminate stimulus-driven attentional capture and likewise, the unexpected introduction of a colour singleton did not change the influence of memory on search.

Influence of singleton on novel no-singleton trials

In order to further understand the impact of the introduction of distractors, we assessed RTs covering the critical transition point across blocks 5–6. During the transition from block 5 to 6 (before and after colour singleton appearance; as seen in dotted box of Figure 2) as expected, both Repeated and Novel Singleton trials had increased RT compared with No-singleton trials, as seen in the dotted box of Figure 2. Interestingly, Novel No-singleton trials without colour singleton presence also had apparently increased RTs in block 6 compared with block 5, while Repeated No-singleton trials did not.

In order to better understand the nature of these transition-related effects, we conducted a two-way Novelty × Block (only using blocks 5 and 6) repeated measures ANOVA on No-singleton trials alone (light blue and light pink lines in the dotted box in Figure 2) for both experiments. In Experiment 1, there was a trending effect of Block ($F_{(1,\ 39)} = 3.16$, $P < 0.1$, $\eta^2 = 0.01$, Block 6 > Block 5: 16.55 ms), a significant main effect of Novelty ($F_{(1,\ 39)} = 28.33$, $P < 0.001$, $\eta^2 = 0.09$, Novel > Repeated: 73.11 ms), and importantly a significant Novelty × Block interaction ($F_{(1,\ 39)} = 6.08$, $P < 0.05$, $\eta^2 = 0.01$), implying that Novel No-singleton trials were affected *simply by the presence of a colour singleton in other trials* while Repeated No-singleton trials were not. In Experiment 2, there was a similar pattern of results with a significant Novelty effect ($F_{(1,38)} = 20.76$, $P < 0.001$, $\eta^2 = 0.11$, Novel > Repeated: 84.15 ms) and a trending interaction between Novelty × Block ($F_{(1,38)} = 4.00$, $P < 0.1$, $\eta^2 = 0.02$). Taking the experiments together, a three-way mixed effects ANOVA (including Set Size) showed a significant main effect of Set Size ($F_{(1,\ 77)} = 45.74$, $P < 0.001$, $\eta^2 = 0.26$, Set Size 16 > Set Size 8: 137.86 ms), a trending main effect of Block ($F_{(1,\ 77)} = 3.24$, $P < 0.1$, $\eta^2 = 0.01$, Block 6 > Block 5: 14.68 ms), a significant main effect of Novelty ($F_{(1,\ 77)} = 46.93$, $P < 0.001$, $\eta^2 = 0.10$, Novel > Repeated: 78.56 ms), and also a significant Novelty × Block interaction ($F_{(1,\ 77)} = 9.39$, $P < 0.005$, $\eta^2 = 0.01$). This interaction between Novelty × Block on No-singleton trials in block 5 and 6 suggest that Novel No-singleton trials, despite staying without the presence of colour singleton, were associated with a slowing of RT, presumably due to the presence of colour singleton on other trials. Conversely, Repeated No-singleton trials did not show any slowing and were effectively insulated from this effect. Therefore, although the results above suggest that the effects of memory and colour singletons functioned largely in parallel during the present task, this result highlights how memory might relate to indirect consequences of frequent attentional capture.

In order to better characterize the nature of this indirect impact of the introduction of distractors, we performed a follow-up analysis to assess the approximate timescale of such an influence. Specifically, we sought to explore the possibility that the impeded performance for Novel trials without colour singleton in block 6 was due to processing of the preceding trial, as previous research has shown that the status of the previous trial of being, for example, erroneous can disrupt the processing of the current trial (i.e., post-error slowing; Laming, 1968; Notebaert et al., 2009; Rabbitt & Rodgers, 1977). To test this possibility, we compared the RT of Novel No-singleton trials based on whether their preceding trials contained a singleton or not. A paired t-test showed no influence of immediately preceding singleton on current trials (Experiment 1: $t_{(39)} = 1.501$, $P > 0.1$, $d = 0.481$; Experiment 2: $t_{(38)} = 0.780$, $P > 0.1$, $d = 0.253$), suggesting that there was no strong evidence in favour of trial-to-trial influence leading to RT slowing for novel configurations (such that increasing cognitive load could slow RT in the following trial), and instead this influence could be operated on a larger timescale.

Debriefing

All participants were naïve to the purpose of the study. In addition, 31 out of 40 participants from Experiment 1 reported no awareness of repeating nor sequential patterns of the configuration during learning even after being told about how the trials were constructed. Five participants claimed to have noticed some repeating or same configurations, and 3 claimed to have noticed similar or same target locations. No participant claimed to have noticed pairs. In Experiment 2, 32 out of 39 participants reported no awareness of repeating nor sequential patterns of the configuration, with 4 claimed to have noticed repeating configuration and 3 claimed to have noticed similar target locations. Thus, most participants operated without explicit awareness of the underlying structures between configurations during searching, as suggested by previous research (Chun & Jiang, 1998). All the results discussed above did not differ by participants' subjective awareness in both experiments.

Discussion

Previous studies have shown that prior experience can effectively guide attention (e.g., Chen & Hutchinson, 2019; Chun & Turk-Browne, 2007; Hutchinson & Turk-Browne, 2012; Võ & Wolfe, 2015; Woodman & Chun, 2006). When salient changes occur within a familiar environment, both established memory representations and stimulus-driven capture might either jointly or separately influence how we direct our attention. In this study, we demonstrated whether and how attention can be influenced by both established memory (contextual cueing) and unexpected stimulus-driven distraction (colour singleton) during visual search. We investigated this question using a modified contextual cueing paradigm wherein an unexpected colour singleton was introduced as a distractor after participants had learned repeated contextual information as cues to find the target. Across two experiments, we found that both memory and distraction effects were effective at block level and even at trial level during the first unexpected colour singleton appearance. Notably, although memory and distraction effects were both present, there was no evidence that they were interactive. However, we also found that having unexpected colour singleton on some trials imposed deficits in performance (longer RT) on other trials that did interact with memory. That is, novel, but not repeated, trials that did *not* contain a colour singleton also showed longer search time, after the appearance of colour singleton distraction on other trials. These findings suggest that, although established memory and the change of contextual information did not interact within single trials, the unexpected change might be able to generalize uncertainty on a greater scale that disrupted the processing of novel information.

Our findings are consistent with results suggesting that contextual information speeded search time or response selection for the target, mirroring the initial finding of the contextual cueing effect (Chun & Jiang, 1998) and many other following studies (for review, see Chun, 2000; Jiang & Sisk, 2020; Sisk et al., 2019). This facilitation was shown at a very early stage for both experiments with set size of 8 and 16 within the first block (4 repetitions of the Repeated configurations). Interestingly, past work has suggested that the ratio of repeated to novel displays influences the onset, but not the magnitude, of the contextual cueing effect (Zang et al., 2018; Zinchenko et al., 2018), with a higher proportion of repeated displays leading to a faster emergence of the effect. Here, we used a high ratio of repeated to novel displays (4:1), so it is possible that this rapidly emerging cueing effect might differ in terms of its sensitivity to distraction relative to an effect established more slowly in a paradigm using a balanced ratio. We believe another interesting direction for future research will be to assess how the rate of acquisition of contextually-cued attention might correspond to its subsequent robustness to distraction.

Using different set sizes, we found that all the key results concerning memory and perceptual distraction were replicated across two independent samples. That is, both set sizes showed similarly robust colour singleton effect, in line with previous literature suggesting the influence from salient distractor on search time is independent of set sizes (e.g., Horstmann, 2002, 2005; Horstmann & Becker, 2011; Treisman & Gormican, 1988; Treisman & Gelade, 1980; Treisman & Souther, 1985). The main difference between set sizes was a generally slower reaction time for set size 16 versus 8, presumably due to the increased difficulty of searching for a target among more items. Increasing search time as a function of set size or distractor complexity has been observed in other studies (Chun & Jiang, 1998; Kunar et al., 2007; Neider & Zelinsky, 2008). We also found that the two experiments differed in terms of RT difference between novel and repeated trials as well as in terms of the change in RT across blocks. That is, a larger set size produced a larger contextual cueing effect and was associated with a greater decrease of RT across time. Both effects might be explained by a relative compression of reaction times in Experiment 1 with smaller set size compared to Experiment 2.

The key innovation of the current design beyond traditional contextual cueing paradigms was that one of 7 (Experiment 1) or 15 (Experiment 2) L-shaped items became a colour singleton unexpectedly halfway through the experiment (after 5 blocks and 20 repetitions of the Repeated configurations). This manipulation was implemented to test how unexpected stimulus-driven attentional capture that is independent of current behavioural goals can influence previously learned contextual memories and vice versa. As mentioned above, we offered three possible accounts of how this interaction could unfold: (1) The replacement account suggests that the appearance of unexpected colour singleton resets previously learned memory representation for repeated configurations, making them equivalent to novel configurations; (2) The insulation account suggests that memory for repeated configurations can adaptively override the distraction, such that that the contextual cueing effect stays intact through the addition of colour singleton distractor; (3) The parallel account suggests that both processes of attention control work largely in parallel, in a way that both memory and colour singleton effect remain effective without much interference to one another.

In terms of the replacement account, we found that contextual cueing stayed effective before and after the introduction of the colour singleton, suggestive that there was no representational replacement. Our block-level analysis showed that the effect of contextual cueing was not altered by the addition of the colour singleton. Further analyses suggested that this effect was reliable at the trial-level, for which even during the first few trials of singleton appearance, the memory effect stayed effective. Although these analyses were supported by few trials, the result was confirmed across two independent samples, consistent with previous study where a colour singleton non-target item was introduced since the beginning of the task (and therefore, there was no unexpected change after memory was established) and both colour singleton and contextual cueing effects were simultaneously effective in parallel, although small contextual cueing effect was observed for trials with colour singleton (Conci & von Mühlenen, 2009, Experiment 2). This result, at the same time, is inconsistent with the replacement account which implies a rapid disruption and relearning of the learned context, in contrast with previous research which has found support for replacement in certain situations after contextual cueing effect was established. The difference between our findings and those of previous research suggests that replacement might only occur in situations where there are changes in target-related features or changes in a large proportion of contextual features. For example, several past studies reported an increase in reaction times following target relocation, suggestive that unpredictably altering the target necessitates a relearning of configural information (Conci et al., 2011; Conci & Müller, 2012; Higuchi et al., 2019; Makovski & Jiang, 2010; Manginelli & Pollmann, 2009). Here, the relatively local changes (introduction of a singleton distractor) did not alter the overall contextual representation, perhaps making relearning less likely.

In terms of the insulation account, we found that attentional capture by the colour singleton was effective in both repeated and novel configurations, suggesting that contextual cueing effect did not offset stimulus-driven influences. In contrast, some previous studies have found that memory can cancel the influence of an introduced distraction. For example, Goschy et al. (2014) and Wang and Theeuwes (2018) found that interference from colour or shape singleton in visual search could be suppressed when it appeared in a predictable location. In a contextual cueing paradigm that encouraged serial searching, Peterson and Kramer (2001a) found some evidence for insulation using a pre-masking paradigm wherein all items of the configuration were masked by their location except for one L-shaped item, resulting in a distraction from the un-masked item at the onset of configuration presentation. Specifically, they observed that distraction using pre-masking was evident only in novel, but not repeated, trials. In a similar paradigm (Peterson & Kramer, 2001b), when a pre-mask distractor was introduced after the contextual cueing effect was established, this distraction impeded performance more so on novel compared to repeated trials, resulting in a greater contextual cueing effect after the appearance of unexpected distraction. Speculatively, the difference between Peterson and Kramer (2001b) and our study might rely on the nature of distraction, as colour singleton and the abrupt onset of pre-mask manipulations might serve as different types of stimulus-driven attentional capture. For example, as the distraction effect used in Peterson and Kramer relied on the use of a pre-mask before the presentation of the configuration, it's possible that the timing of attentional capture relative to the influence of memory is critical (Sisk et al., 2019; e.g., Theeuwes et al., 2000; Zinchenko et al., 2020), such that benefits from contextual cueing might operate on a longer time-scale compared to the more immediate distracting effect of colour singleton. For example, recent work using event-related electroencephalogram (EEG) potentials has suggested that repeated displays can prime participants' attention and evoke attention-related components as early as 160 ms after stimulus onset. Although beyond the scope of the current work, future research might explore time-dependent interactions between stimulus-driven and memory-guided attention by, for example, varying the onset of distractors in a parametric manner.

Taken together, although previous studies have highlighted specific situations wherein stimulus-driven attention and memory-guided attention might interact in various ways, our results are in line with a parallel account. That is, it bears similarity to past work showing independent effects of an unexpected attentional capture in search configurations beyond the current task goal (Conci & Müller, 2012; Horstmann, 2015; Horstmann & Herwig, 2015; Johnson et al., 2001; Theeuwes, 1992, 1994; Theeuwes et al., 2000; Yantis & Jonides, 1984). Interestingly, it has been proposed that goal-directed influences on attention might operate after perceptual distraction (Theeuwes et al., 2000). Our findings here are putatively consistent with such an account wherein memory-guided attention, although not explicitly goal-relevant, might occur after the impact of perceptual distraction. A promising direction for future research, then, might be to further explore the relative temporal dynamics of stimulus-driven, memory-guided, and goal-directed attention in a single paradigm.

Beyond the evidence for an additive, non-interactive influence of both memory and stimulus-driven attentional capture discussed above, we did find evidence for a role of memory in trials without singleton presence. That is, after the appearance of colour singletons, all trials, except Repeated No-singleton trials, showed increased RT. Notably, even novel trials *without* singletons had increased reaction times after singletons were introduced in the experiment. It is worth noting that a potential limitation of the current study concerns the small number of trials in certain bins (e.g., a maximum of 8 trials per participant would fall into each of the Novel conditions for Blocks 6–10 in both experiments). Although this increases the likelihood of statistical noise influencing our findings, the key results were observed across two experiments, each with sample sizes greater than those used in past works which found significant effects employing similar paradigms (e.g., Conci & von Mühlenen, 2009, Experiment 2; Zinchenko et al., 2018, Experiment 1b). Further, this effect regarding Novel No-singleton trials was not related to the singleton status of the immediately preceding trial, suggesting that that the influence of singleton trials on Novel No-singleton trials was not immediate or on the trial-to-trial level but was rather more general or sustained in nature. Interestingly, only Repeated No-singleton trials did not show an increased RT. It is possible that the increased uncertainty introduced by the distractors produced delays in other decision processes, such as the criteria used to respond, which was then offset by the contextual cueing effect for repeated trials. Such interpretations, however, remain speculative here and await future research which can target the relationship between more sustained task dynamics and memory-guided attention.

In this study, we have followed the theory that selective attention can be controlled by more than the traditional dichotomy of influence: stimulus salience and task goals. Memory-guided attention, although often categorized within the top-down control of task goals, has recently gained more recognition as an important and separate, third influence of selective attention (for related reviews, see Chen & Hutchinson, 2019; Chun & Turk-Browne, 2007; Hutchinson & Turk-Browne, 2012; Logan, 2002; Võ & Wolfe, 2015; Woodman & Chun, 2006). Although our study cannot speak to whether memory is a separate influence from top-down attentional control, our results provide helpful insights to its independence from stimulus-driven attention, as the two influences could operate largely in a non-interactive, parallel manner.

In summary, the present study demonstrates how memory-guided and stimulus-driven attention unfold in a visual search paradigm. When an unexpected colour singleton replaced part of a learned context, there was no evidence that the learned representation was significantly changed nor that learned context prevented stimulus-driven distraction. Notably, attentional capture due to colour singletons increased search times on novel trials without singleton presence. That is, although our paradigm did not suggest a direct interaction between memory-guided and stimulus-driven attention, it is possible that sudden changes in attentional capture might introduce global-level uncertainty in a memory-dependent manner. Future research is needed, however, to fully unpack the mechanism of this intriguing relationship between such large-scale task dynamics and attention guided by past experience.

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