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BRIEF REPORT

Late guidance resolves the search slope paradox in contextual cueing

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Abstract

Visual search is facilitated by statistical learning of repeated search contexts, termed 'contextual cueing'. Repeated displays are thought to enhance attentional guidance, but this has been challenged by the absence of search-slope differences between repeated and novel displays. Here we use eye-tracking to resolve this paradox by calculating a measure of when during search the contextual cueing benefit emerges. In 24 human participants we observe typical reaction time and fixation count benefits for repeated contexts, but no slope differences between repeated and novel search contexts. Eye-tracking showed that the attentional guidance benefit emerged over time, occurring later for larger set sizes, and producing similar response time benefits for small and large set sizes. We argue that repeated and novel contexts have similar slopes because learning benefits are confined to target-adjacent regions of roughly equivalent area across set sizes. This finding rules out one of the strongest pieces of evidence against an attentional account of contextual cueing.

Keywords Visual search · Attention · Eye movements and visual attention · Implicit memory

Introduction

Our knowledge of the likely locations of objects in the world is guided by their surrounding contexts. When returning to a familiar context, we tend to find objects in the same locations we have found them in in the past, making memory for the location of items a useful tool for locating those items in future. To use a familiar example, finding the wine glasses in one's own kitchen is generally much easier than finding them in someone else's kitchen. A similar phenomenon is observed in laboratory visual search tasks. When participants perform a visual search for a target among distractors, they are faster in finding that target if they have previously searched through the same arrangement of target and distractors than if they are presented with a novel display in which either the target or the distractors are displaced. The benefit for repeated contexts is termed 'contextual cueing' (Chun & Jiang, 1998). Spatial contextual cueing is a classic example of how scene statistics can guide implicit learning, but contextual cueing has also been observed with the target location predicted by distractor identity, motion direction, auditory cues, temporal sequences, background colour and texture, and natural scenes (Brockmole & Henderson, 2006b; Chun & Jiang, 1999; Kawahara, 2007; Kunar, Flusberg, & Wolfe, 2006; Makovski, Vázquez, & Jiang, 2008; Olson & Chun, 2001). It is a general phenomenon that has been observed across a range of age groups (e.g., Lyon, Scialfa, Cordazzo, & Bubric, 2014; Tummeltshammer & Amso, 2018) and studied in several neurological disorders (e.g., Chun & Phelps, 1999; Sisk, Twedell, Koutstall, Cooper, & Jiang, 2018; van Asselen et al., 2009, 2012; see Jiang, Sisk, & Toh, 2019 for review).

Given how broad and pervasive this form of statistical learning is, there has recently been strong interest in uncovering the mechanisms underlying this phenomenon (for reviews, see Goujon, Didierjean, & Thorpe, 2015, and Sisk, Remington, & Jiang, 2019). The two potential mechanisms that have received the most attention have been attentional guidance (e.g., Chun & Jiang, 1998; Harris & Remington, 2017), and response-related processes (i.e., response selection, preparation, or execution; e.g., Kunar, Flusberg, Horowitz, & Wolfe, 2007; Sewell, Colagiuri, & Livesey, 2018). Significant evidence has been found supporting the attentional guidance account. Paradoxically,

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however, guidance predicts shallower search slopes for repeated displays, which has not always been borne out by the literature. Here, we use eye-tracking to resolve this paradox and determine how an enhancement of attentional guidance could explain contextual cueing while simultaneously not affecting the slope of the search function.

Search slope is computed by dividing the difference in search time between set sizes by the difference in number of search items, to give an index of the time required to search each item. If the statistical learning occurring in contextual cueing improves search efficiency, then fewer items will be searched in repeated contexts relative to novel contexts. This would be expected to have most impact at larger set sizes and, as a result, to reduce the search slope in repeated contexts. Chun and Jiang (1998), in fact, found shallower slopes for repeated displays, which they interpreted as an enhancement of attentional guidance. Supporting this conclusion, eye-tracking evidence has repeatedly shown fewer eye fixations in repeated than novel contexts (Brockmole & Henderson, 2006a; Geringswald, Baumgartner, & Pollmann, 2012; Geringswald & Pollmann, 2015; Harris & Remington, 2017; Kroell, Schlagbauer, Zinchenko, Müller, & Geyer, 2019; Manelis & Reder, 2012; Manginelli & Pollmann, 2009; Peterson & Kramer, 2001; Tseng & Li, 2004; Zhao, Liu, Jiao, Zhou, Li, & Sun, 2012; Zhao & Ren, 2020). Critically, we (Harris & Remington, 2017) have recently shown that this is the case even under conditions in which there should be little room for attentional improvement, such as when exogenous cues are used to signal the location of the target, or when the target is a pop-out stimulus. Indeed, we found that the correlation between the contextual cueing effect observed in reaction times and that observed in the number of fixations was close to perfect ($r > .88$), leaving very little room for the contribution of mechanisms other than attentional guidance.

However, the finding of reduced search slopes for repeated contexts has been harder to reproduce than would be expected for such a strong attentional effect (Kunar et al., 2007; Makovski & Jiang, 2010; Rausei, Makovski, & Jiang, 2007; Wang, Haponenko, Liu, Sun, & Zhao, 2019). In particular, Kunar et al. (2007) performed ten contextual cueing experiments with set-size manipulations in each and found that nine of the ten experiments showed no significant slope differences between repeated and novel contexts. This seems a puzzling contradiction to the consistent evidence in support of attentional guidance described above. Based on these results, Kunar et al. (2007) suggested that perhaps contextual cueing is in fact due to the enhancement of response-related mechanisms. That is, once the target is found, a decision as to the target identity may be reached faster when the target appears in a repeated context. Subsequently, evidence both for and against this proposition has emerged (for review, see Sisk, Remington, & Jiang, 2019).

If contextual cueing is so strongly linked to attentional guidance, why are slope differences not always observed, even when contextual cueing effects are large and robust? A critical assumption behind search slope reduction is that the benefit of context repetition will be present from the very beginning of the trial, affecting all items in the search roughly equally. If, however, the benefit of repeated displays emerges later for high than for low set sizes (late guidance), then this will reduce the relative contextual cueing benefit in high set sizes and may serve to cancel out any slope differences between repeated and novel displays. Indeed, there is good reason to expect the contextual cueing benefit to emerge late within a search. Contextual cueing is known to be primarily influenced by the items located closest to the target (Brady & Chun, 2007; Olson & Chun, 2002). It is, therefore, reasonable to suspect that contextual cueing benefits may not emerge within an individual search episode until the eyes approach the target region. If the region is roughly the same size for large and small set sizes, then the amount of contextual cueing benefit will be the same, and produce equivalent slopes for repeated and novel displays.

In this study we used eye tracking combined with a set-size manipulation to explore if late guidance can explain the absence of slope differences. We first determined whether contextual cueing was reflected in a reduced number of fixations in both set-size conditions, which would indicate attentional guidance improvement despite any absence of slope differences. We then examined the time course of the gaze-target distance, determining whether there were differences between repeated and novel displays, and between set sizes, in the time required for the eyes to approach the target. If contextual cueing emerges more slowly within trials of the larger set size, this provides an explanation for the absence of slope differences that is still consistent with attentional guidance improvement being the primary mechanism underlying contextual cueing.

Method

Our experimental design was based on that of Kunar et al. (2007), Experiment 1.

Participants

Twenty-four participants between the ages of 18 and 34 years took part in this experiment (13 females; mean age = 21.92 years, SD = 3.32 years). This sample size was selected a priori as a large sample size for contextual cueing experiments (e.g., Kunar et al.'s (2007) set-size experiments all involved 8–13 participants). All participants had normal vision – participants with glasses or contact lenses were excluded as these can be problematic for the eye-tracking. This study was approved by the University of Queensland Research Ethics Committee, and all participants gave written informed consent prior to participating. Participants were paid $10/h for their time.

Apparatus and stimuli

Eye movements were tracked using an Eyelink 1000 (SR Research, Ontario, Canada) video-based infrared eye-tracking system with a spatial resolution of 0.01° of visual angle and a sampling rate of 500 Hz. Participants had their head supported by the eye-tracker's chin rest and forehead support and viewed the 19-in. CRT monitor from a distance of 60 cm. A USB keyboard was used for registration of manual responses. Event scheduling and response time measurement were controlled by Matlab, using the Psychophysics Toolbox.

Participants first saw a fixation display, composed of a blank grey screen (RGB: 200, 200, 200) with a small blue dot (RGB: 0, 0, 255; .8° x .8°) in the centre. Upon successful fixation (see *Procedure*), participants were presented with the search display, the appearance of which coincided with a 100-ms 500-Hz tone to indicate the beginning of the search period. Search stimuli were displayed at the intersection points between three concentric rings (9°, 15° and 23.5° diameter, respectively) and 16 equally spaced lines that radiated from the centre of the display (Fig. 1). This web-like pattern was black (RGB: 0, 0, 0; all lines 2 pixels thick) and presented on a grey background. Displays contained either eight or 12 search items (one of which was always a target). Search items subtended 0.8°, 1.3° or 2.1° when presented on the inner, middle or outer rings, respectively, and were presented within circles that masked the intersections of the web-like pattern (circles were 1.6°, 2.7° and 4.4° diameter when presented on the inner, middle and outer rings, respectively). Search stimuli were 4, 6 or 8 pixels thick when presented on the inner, middle or outer circles, respectively, and the background rings were all 6 pixels thick. The colour of the search stimuli was constant throughout the experiment, with each participant having stimuli presented in one colour selected randomly from the following eight colours: red (RGB: 255, 0, 0), green (RGB: 0, 255, 0), blue, yellow (RGB: 255, 255, 0), purple (RGB: 255, 0, 255), cyan (RGB: 0, 255, 255), orange (RGB: 255, 160, 0) and white (RGB: 255, 255, 255). Distractor stimuli were L shapes, rotated 0°, 90°, 180° or 270°, and targets were T shapes rotated either 90° or 270° such that they were lying on their right or left side. At the end of each trial participants were presented with a feedback display consisting of a grey screen containing the word 'Correct' or 'Wrong!' for correct and incorrect responses, respectively, in black text at the centre of the display. Incorrect trials also received a 500-ms 1,000-Hz tone coincident with the feedback display.

Procedure and design

Participants received written and verbal instructions for the search task, but received no information regarding the display repetitions. They were then calibrated with the eye-tracker's standard 9-point calibration. Following calibration, they received ten practice search trials to familiarise them with the task, followed by 512 search trials with a self-paced break every 64 trials that was always followed by recalibration of the eye-tracker. The 512 task trials were composed of 16-trial blocks, repeated four times per epoch for eight epochs. Each 16-trial block was composed of four 'repeated' displays of set-size 8, four 'repeated' displays of set size 12, four 'novel' displays of set-size 8, and four 'novel' displays of set-size 12. Each of the repeated displays was presented once per block and was identical across blocks except for the orientation of the target, which was selected randomly upon each presentation. The locations and orientations of all stimuli in the novel displays were randomly generated for each presentation, except the locations of the targets, which were repeated from block to block. The stimuli were controlled such that

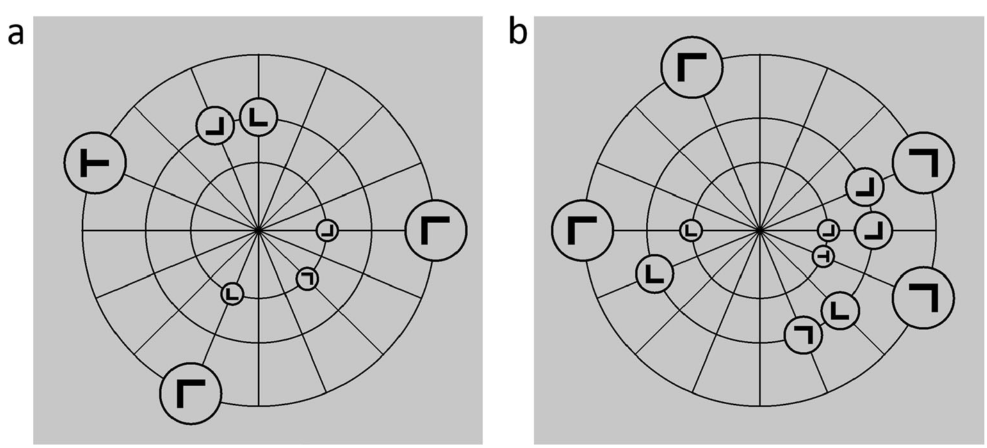

Fig. 1 Example stimulus displays from Set-Size 8 (**a**) and Set-Size 12 (**b**). Each participant saw the search stimuli in one of several possible colours (see main text), but the web-like pattern was always black

none of the 16 displays shared a target location with any other display (as implemented by Kunar et al., 2007).

Each trial of both practice and the main task began with a fixation control in which participants were required to fixate a blue dot at the centre of the display for 500 ms, unbroken by blinks or saccades, after which time the search array was presented. If 2 s passed without this 500-ms criterion being reached, the participant was calibrated anew and the trial began again with fixation control. Upon successful completion of the fixation control, search displays were presented for as long as was required for participants to make a manual response. They responded by pressing the '/' key with their right index finger if the target T was rotated to the right, and by pressing the 'Z' key with their left index finger if the target T was rotated to the left. Participants were asked to search as quickly and accurately as possible. Upon response participants were presented with a feedback display for 500 ms. Feedback was followed by a 500-ms inter-trial interval.

Eye-tracking measures

While participants performed the search task, we recorded their eye movements. We analysed several gaze metrics in this study, including the number of fixations required to find the target, as a measure of attentional guidance, and the time from fixating the target to emitting a response, as a measure of the time required for response related processes. The time of target fixation was taken as the onset-time of the fixation nearest the target throughout the search. To follow up questions raised by Sewell et al. (2018), we also assessed the average fixation duration in each condition. Finally, we assessed the average within-trial time at which contextual cueing emerged by examining the distance between the eyes and the target across time (see *Results* for more description).

Results

Reaction time

Error rates were low ($M = 1.69\%$, $SD = 1.25\%$), and trials with incorrect responses were excluded from all analyses. Greenhouse Geisser correction was applied in all cases where the assumption of sphericity was violated. A repeated-measures ANOVA on participants' reaction times (Fig. 2a), with the factors Epoch (1–8), Set-Size (8, 12) and Repetition (repeated, novel), revealed a significant main effect of Epoch, $F(3.33, 76.47) = 30.84$, $p < .001$, $\eta^2 = .57$. There was also a significant main effect of Set-Size, $F(1, 23) = 166.34$, $p < .001$, $\eta^2 = .88$, reflecting faster responses on Set-Size 8 trials ($M = 1{,}172$ ms, $SD = 221$ ms) than on Set-Size 12 trials ($M = 1$ 446 ms, $SD = 242$ ms), and a significant main effect of Repetition, $F(1, 23) = 12.40$, $p = .002$, $\eta^2 = .35$, reflecting the expected faster responses to repeated displays ($M = 1{,}268$ ms, $SD = 253$ ms) relative to novel displays ($M = 1{,}350$ ms, $SD = 212$ ms). We also observed a significant Set-Size x Epoch interaction, $F(7, 161) = 5.90$, $p < .001$, $\eta^2 = .20$. None of the other interactions were significant, all $ps >= .772$. The absence of any Repetition x Set-Size interaction demonstrates that, despite observing a significant contextual cueing benefit (the main effect of Repetition), there were no significant slope differences between repeated and novel displays (Fig. 2b), consistent with the results of Kunar et al. (2007).

Eye-tracking

The same repeated-measures ANOVA as that reported above, now run on the number of fixations per trial, revealed results that were qualitatively the same as those observed in the reaction times (Fig. 3). We found significant main effects of Epoch, $F(4.12, 94.77) = 53.12$, $p < .001$, $\eta^2 = .70$, Set-Size, $F(1, 23) = 73.11$, $p < .001$, $\eta^2 = .76$, and Repetition, $F(1, 23) = 11.71$, $p = .002$, $\eta^2 = .34$. We also observed a significant Set-Size x Epoch interaction, $F(7,161) = 5.61$, $p < .001$, $\eta^2 = .20$. None of the other interactions were significant, all $ps >= .459$. Consistent with earlier studies, there were fewer fixations on repeated than novel displays. Thus, counter to the suggestion that a lack of slope difference reflects a lack of attentional guidance, the eye-movement results suggest that attentional guidance is the driving force behind contextual cueing despite the similar search slopes for repeated and novel displays.

Repeating this analysis for the time between fixating the target and emitting a response revealed a marginally significant main effect of Epoch, $F(2.51, 52.65) = 2.55$, $p = .075$, $\eta^2 = .11$, and a marginally significant effect of Set-Size, $F(1,21) = 3.94$, $p = .060$, $\eta^2 = .16$. No other effects approached significance, all $ps >= .229$ (Fig. 4). Consistent with Harris and Remington (2017), we found no significant difference in fixation-to-response time for targets in repeated compared to novel displays. These results are inconsistent with contextual cueing being produced by improvements in response-related processes.

Recently, Sewell et al. (2018) suggested that fewer fixations on repeated displays could be associated with a corresponding increase in the duration of those fixations. To explore this possibility, we ran the same ANOVA as above on participants' average fixation durations for each condition. This analysis revealed a marginally significant main effect of Epoch, $F(3.02, 66.51) = 2.33$, $p = .082$, $\eta^2 = .10$. None of the other main effects or interactions were significant, all $ps >= .197$ (Fig. 5).

The results described above are clearly in-line with an attentional guidance account of contextual cueing. Our results fully replicate the collection of findings that give rise to the paradox of increased guidance without reduced search slope.

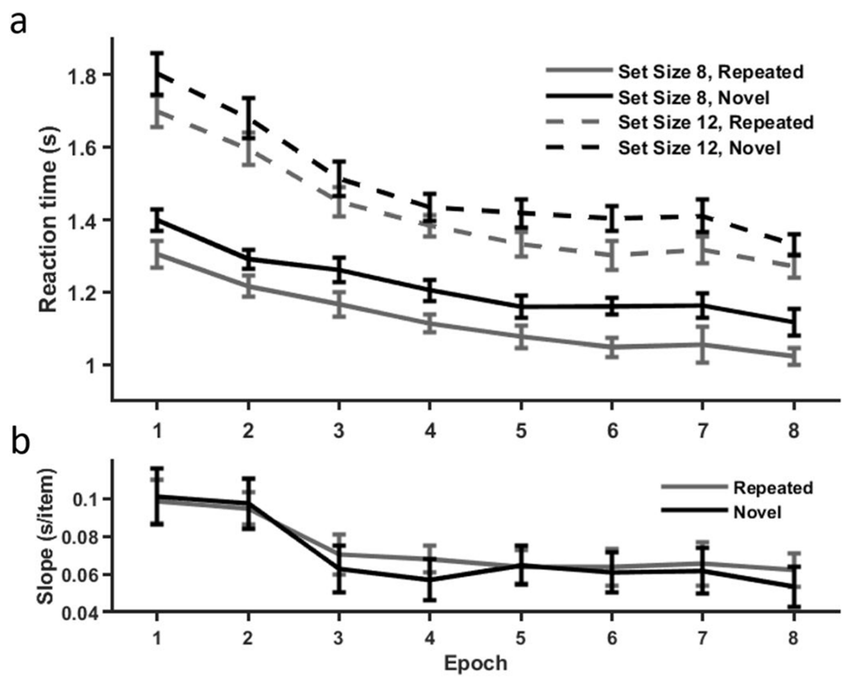

Fig. 2 Average reaction time. Results show faster responses for repeated than novel displays at both set sizes (**a**) but no difference in slope between repeated and novel displays (**b**)

Gaze time-courses

To test our hypothesis that contextual cueing benefits emerge later in search through larger displays, we examined the distance between participants' gaze and the target as a function of time throughout the trial. The time at which the average search time-courses diverge between repeated and novel displays gives us an index of the average time at which the benefit due to display repetition emerged. By comparing the time-course of repeated-novel differences between Set-Size 8 and Set-Size 12 we can assess any differences in the latency at which contextual cueing emerged throughout search.

For this analysis we normalised distances for each trial by the distance between the fixation point (the starting position)

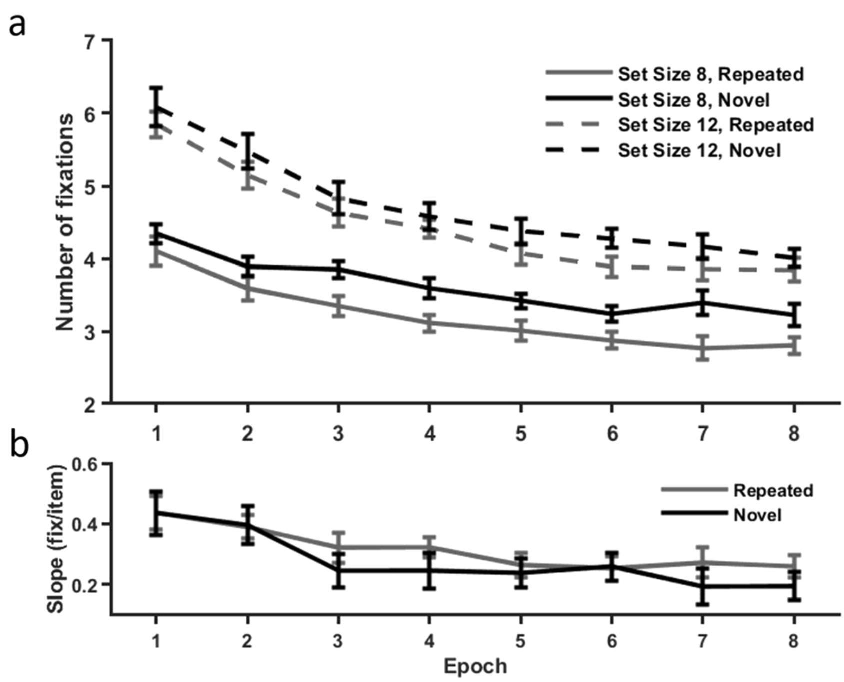

Fig. 3 Average number of fixations per trial. Results show fewer fixations for repeated than novel displays at both set sizes (**a**) but no difference in slope between repeated and novel displays (**b**)

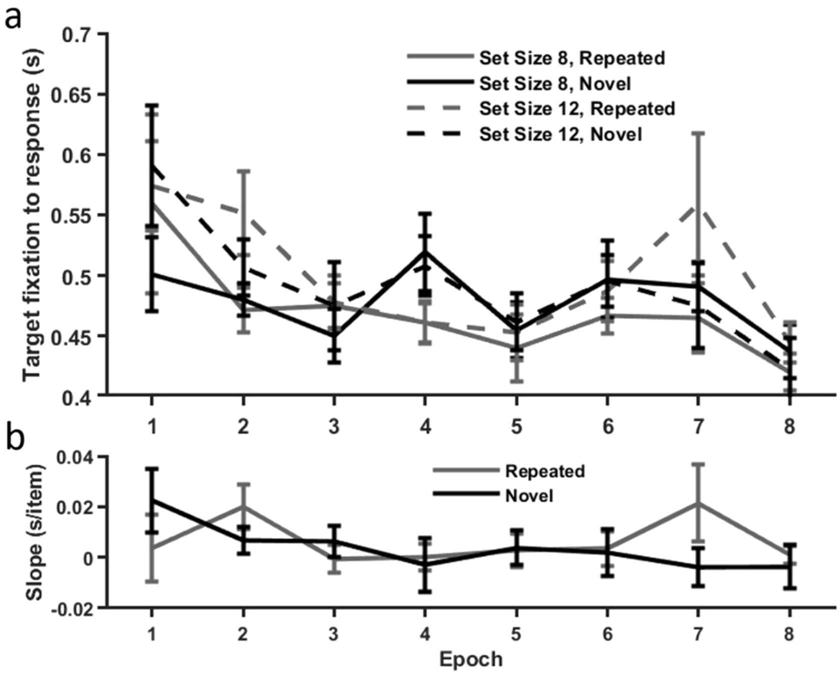

Fig. 4 Average time between fixating the target and emitting a response. Results show no difference between repeated and novel displays at either set size (**a**) and no difference in slope between repeated and novel displays (**b**)

and the target. We performed this analysis across all trials from Epoch 2 onwards, so as to exclude those trials in Epoch 1 in which contextual cueing had not yet fully emerged (however, highly similar results were obtained if we were to include Epoch 1). On each trial, average distance from the target was calculated for successive 50-ms bins from the onset of the search display. Repeated measures *t*-tests revealed significant differences between the average gaze position of repeated and novel displays for Set-Size 8 from 650 ms to 1,000 ms, and for Set-Size 12 from 1,050 ms to 1,250 ms (Fig. 6a). The onset latency of contextual cueing was deemed to be the time at which the difference between the gaze position for repeated and novel displays reached 50% of its maximum (highly similar results were achieved by using the time

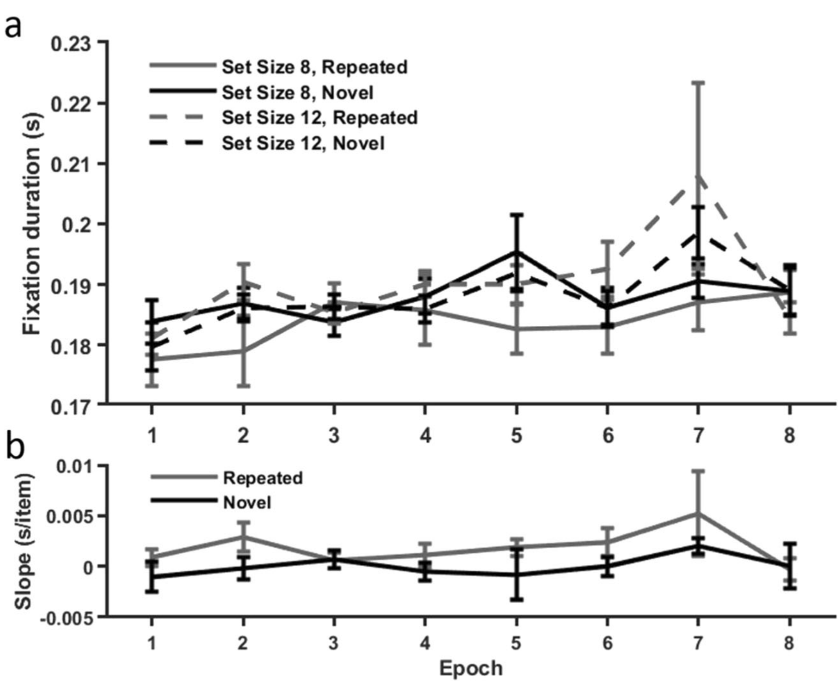

Fig. 5 Average fixation duration. Results show no difference between repeated and novel displays at either set size (**a**) and no difference in slope between repeated and novel displays (**b**)

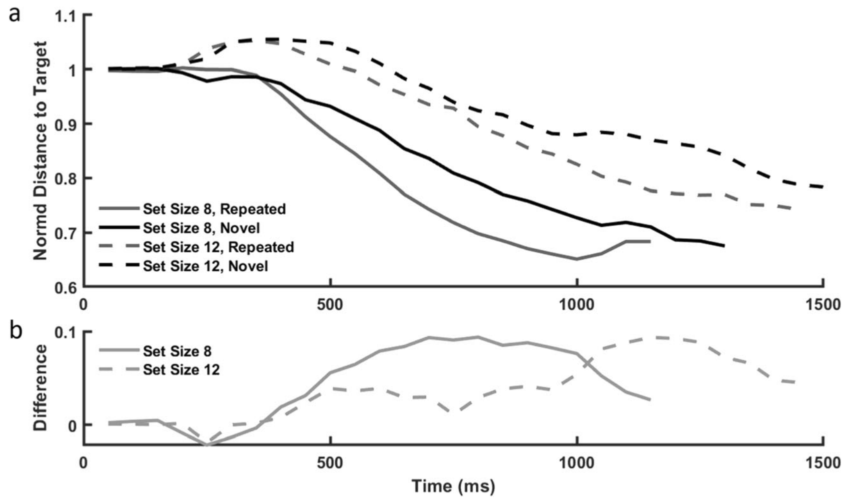

Fig. 6 Gaze time-courses. The gaze approaches the target earlier on repeated displays than novel displays for both set sizes (**a**), but this difference emerges earlier for Set-Size 8 than for Set-Size 12 (**b**). Time courses end at average reaction time for each condition in (**a**) and at the earlier of the two average reaction times in (**b**)

of maximum difference; i.e., peak latency). One participant was excluded from analysis for never having a positive difference in the Set-Size 12 condition, making it impossible to determine the time at which they reached 50% of maximum difference. A Jack-knifed latency analysis (Miller, Patterson, & Ulrich, 1998; Ulrich & Miller, 2001) comparing the latencies of contextual cueing onset for Set-Size 8 and Set-Size 12 demonstrated that contextual cueing was evident in the distance of the gaze from the target significantly earlier in Set-Size 8 trials (M = 482ms) than in Set-Size 12 trials (M = 978ms), $t(22) = 5.40$, $p < .001$, Cohen's d = .28 (Fig. 6b).

Discussion

Here we provide a resolution of the search-slope paradox in contextual cueing. The paradox arises because repeating a search context results in a faster search associated with fewer eye movements than observed for a novel context, indicating enhanced attentional guidance, but without the shallow search slopes expected from improved attentional guidance. We resolve this by using eye-fixation data to show that benefits from repeated displays emerge later with larger set sizes. The benefits of improved attentional guidance appeared only during the final ~500 ms of search, affecting about the same number of items regardless of overall set size. These results are consistent with the idea that benefits of repetition are found in a region local to the target (Brady & Chun, 2007; Olson & Chun, 2002) that is equivalent in size, regardless of the number of search items. The failure to find shallower search slopes with set size was one of the final strong pieces of evidence against attentional guidance as the mechanism behind contextual cueing. By resolving this paradox, we provide compelling support that contextual cueing is produced by increased efficiency in attentional guidance.

We were able to show that the contextual cueing benefit in both set sizes was associated with a reduced number of fixations in repeated search contexts, consistent with improved attentional guidance as the source of contextual cueing. These results are consistent with past behavioural (Geyer, Zehetleitner, & Müller, 2010), eye-tracking (e.g., Harris & Remington, 2017; Peterson & Kramer, 2001; Tseng & Li, 2004) and EEG results (the N2pc component; Johnson, Woodman, Braun, & Luck, 2007; Schankin & Schubö, 2009, 2010). We found no evidence for a response-related account of contextual cueing. Although past studies have produced evidence consistent with a response-related account (e.g., Kunar et al., 2007; Schankin & Schubö, 2009, 2010; Zhao et al., 2012; Wang et al., 2019), this evidence has generally been weak and inconsistent (e.g., Zhao & Ren, 2020), and of too small a magnitude to explain the majority of the contextual cueing effect (Harris & Remington, 2017).

What might be the mechanism underlying the late attentional guidance we observed? As the number of display items increases there is increased probability of overlap in item locations between displays. As such, one possibility is that larger set sizes require more time for display-wide recognition processes to complete, owing to the greater noise across displays (Makovski & Jiang, 2010). Alternatively, display repetition may produce a configural memory of the target and the nearest distractors (see, Brady & Chun, 2007; Olson & Chun, 2002), with improved guidance occurring only when the gaze lands near the local target configuration. Because gaze prior to landing in the target region proceeds uninformed by learning, it lands within the target region later for large compared to small set sizes. Under this account, the contextual cueing effect for repeated displays is driven only by the search within the target region. Assuming the target region is roughly the same area for large and small set sizes, equivalent contextual cueing effects are observed.

One remaining result that conflicts with the attentional guidance account of contextual cueing is the diffusion modelling of Sewell et al. (2018). These authors mapped the various accounts of contextual cueing (attentional guidance, decision threshold, and a novel perceptual processing account) to separate parameters of a drift-diffusion process (non-decision time, boundary separation, and drift rate, respectively), and examined, on a single-participant basis, which parameters differed in repeated relative to novel displays. They found that the fits to the data for the majority of participants were significantly better by assuming contextual cueing affects parameters associated with either a decision threshold or perceptual processing account. Very few participants produced results in line with the attentional guidance account. This is hard to square with the majority of the results we have reviewed. However, it is important to consider that the drift diffusion model was developed to model the underlying mechanisms in single decisions. Sewell et al. (2018) treat the entire search process as affecting only the non-decision parameter, even though search involves multiple decisions regarding the target/distractor status of a range of items over a large span of time. Diffusion models have not yet been validated to determine whether properties such as search time do in fact load onto the non-decision time. Thus, it is currently unclear whether the results of Sewell et al. (2018) do in fact relate to the cognitive mechanisms that they propose.

Sewell et al. (2018) also proposed that contextual cueing could produce a reduced number of fixations without this reduction being the source of the contextual cueing benefit if the reduction in number of fixations occurs with a corresponding increase in the duration of fixations. This kind of fixation-related speed accuracy trade-off could produce the illusion of attentional guidance when search is, in fact, no quicker. This would create room for response-related factors to explain the contextual cueing effect that we have shown is well explained by reduced number of fixations (Harris & Remington, 2017). Contrary to this suggestion, our analysis of fixation duration showed no difference between repeated and novel displays, suggesting that a reduced number of fixations does in fact contribute a large proportion of the reaction time benefit for repeated contexts.

Interestingly, Zhao and Ren (2020) recently showed that first eye-movement latency is reduced under contextual cueing. Although this effect was too small to explain more than a small percentage of the overall contextual cueing effect, it may indicate some early recognition of repeated displays. Our results suggest that this recognition does not aid search, however, until late in the trial. Alternatively, it may be that the shortened latency to begin search was only present on those trials in which the target was recognised immediately, making even the beginning of the search correspond to the 'late' search period on those trials.

To summarize, in this work we resolve the paradox of how contextual cueing can be produced by enhanced attentional guidance without producing slope differences between repeated and novel search contexts. The resolution to this puzzle is that the attentional guidance benefit does not apply uniformly to every item in the display, but instead emerges throughout the search, and emerges later in search through larger set-sizes. Thus, although the search goes on longer through larger set sizes, the period of enhanced attentional guidance is similar for both set sizes, producing similar absolute benefits to reaction time, and no difference in slope between repeated and novel displays. This finding rules out one of the final major pieces of evidence against an attentional guidance account of contextual cueing.

Open practices statement The experiment reported in this article was not formally preregistered. Neither the data nor the materials have been made available on a permanent third-party archive as the experiment was run without ethical approval for making the data and materials publicly available; requests for the data or materials can be sent via email to the lead author at anthmharris@gmail.com

Author contributions AMH and RWR developed the study concept and design. Data collection and analysis were performed by AMH. The manuscript was drafted by AMH and RWR. All authors approved the final version of the manuscript for submission.

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