You see what you look for:
perceptual biases induced by targets and distractors in visual search

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ABSTRACT

Visual perception is, at any given moment, strongly influenced by its temporal context – what stimuli have recently been perceived and in what surroundings. We have previously shown that to-be-ignored items produce a bias upon subsequent perception that acts in parallel with other biases induced by attended items. However, our previous investigations were confined to biases upon a visual search target's perceived orientation, and it is unclear whether these biases influence perception in a more general sense. Canonical paradigms investigating so-called serial dependence have revealed biases in the perception of items not associated with any particular task. Therefore, we test here whether the biases from visual search targets and distractors affect the perceived orientation of a neutral test line, which is neither a target nor a distractor. To do so, we asked participants to search for an oddly oriented line among distractors and report its location for a few trials and then presented a test line irrelevant to the search task. Next, participants were asked to report the orientation of the test line. Our results indicate that in tasks involving visual search, targets induce a positive bias upon a neutral test line if their orientations are similar, while distractors produce an attractive bias for similar test lines and repulsive bias if the test line's orientations and the distractors' average orientation are far apart in feature space. In sum, our results show that both attention and proximity in feature space between previous and current stimuli plays a large role in determining the direction of the perceptual biases.

Introduction

Our visual system needs to process a large amount of complex visual information at any given moment. To make this task easier, the brain uses various heuristics based on knowledge about the environment. For example, we know that an object's appearance typically does not change dramatically from one moment to the next. This means that our visual system may ignore negligible changes in the visual input to promote stability. However, when objects do indeed change, such a bias could also highlight that change. One example of this is serial dependence (see, e.g., Fischer & Whitney, 2014; Pascucci et al., 2019). Fischer and Whitney (2014) presented two Gabor patches, one after the other, finding that orientation estimates for the second Gabor were biased toward the first one. They concluded that perception is tuned towards previous stimuli that have similar features and appear in the same locations and proposed that serial dependence promotes perceptual stability in our visual environment (see also Burr & Cicchini, 2014; Cicchini & Kristjánsson, 2015; Kiyonaga, Scimeca, Bliss, & Whitney, 2017 for review). Further investigations have since revealed that the perception of many other features, such as shape (Manassi, Kristjánsson & Whitney, 2019), motion coherence (Suarez-Pinilla, Seth, & Roseboom, 2018), numerosity (Fornaciai & Park, 2018), facial identity (Liberman, Fischer & Whitney, 2014) and even stimulus ensembles (Manassi et al., 2017; Pascucci et al., 2019), is systematically biased by information from the recent past.

Serial dependence in perception is thought to help us keep perception stable against minor changes that might arise due to internal or external noise. But the stimuli we encounter are not all equally important, and some can be ignored to enable us to concentrate on the object of interest at a given moment. For example, during visual search we need to pay attention to items similar to the potential target while simultaneously ignoring stimuli dissimilar to the target. This raises the question of whether and how these dissimilar items that need to be ignored affect our perception. Recent results (Fritsche, Mostert, & de Lange, 2017, and Fritsche & de Lange, 2019) have then suggested that proximity in feature space between the test stimulus and the inducer may determine whether biases from serial dependence are repulsive or attractive: An attractive orientation bias occurs when preceding targets and/or distractors have similar orientations. In contrast, a repulsive bias occurs when they have dissimilar orientations.

In a recent paper, we studied the effect of distractors upon the perception of attended items (targets) during visual search for an oddly-oriented line among distractors (Rafiei et al., 2020). In visual search, observers quickly learn the probability distributions of distractor sets (Chetverikov, Campana & Kristjánsson, 2016, 2017a, 2017c, 2020; Hansmann-Roth et al. 2019, 2020a, 2020b; Tanrikulu, Chetverikov & Kristjánsson, 2020). That is, they can learn which distractor features are more probable than others in surprising detail, and importantly, unlike the items typically used in serial dependence studies, observers learn to ignore them. Following this approach, Rafiei et al. (2020) employed repeated distractor presentations over several trials to ensure that participants learn the distractor features while judging an oddly oriented target's location. After a few search trials, participants were asked to report the target's orientation on the last visual search trial. We found that the target's perceived orientation was pushed away from the mean orientation of the distractors. Additionally, the search targets induced an attractive bias upon the perceived orientation of a subsequent visual search target, a result in line with serial dependence findings. This study demonstrated that the search task creates conditions for two perceptual biases that may operate simultaneously: a repulsive bias from distractors and an attractive bias from the targets.

While our findings in Rafiei et al. (2020) show how to-be-ignored items produce a perceptual bias that acts in parallel with another bias induced by attended items, our investigation was confined to biases upon the perceived orientation of the visual search target. We did not address whether the biases influence perception more broadly. This is important since canonical serial dependence paradigms have revealed changes to the perception of items not associated with any particular task. Here we address the question whether the biases from visual search targets and to-be-ignored distractors reported by Rafiei et al. (2020) can alter perceptual processing in a more general sense, or specifically whether the biases affect the perceived orientation of a neutral test line, which was neither a target nor a distractor. To do so, we asked our participants to search for an oddly oriented line among distractors and report its location for several adjacent trials. The specific targets and distractors varied from trial to trial, but their respective probability distributions remained stable within each block of search trials to ensure that the distractor feature distribution (and the targets) were well encoded. Next, participants were asked to report the orientation of a briefly presented test line in an adjustment task. We aimed to assess the biases induced by targets and distractors on the test line's perceived orientation that was, crucially, unrelated to the visual search task.

Rafiei et al. (2020) proposed that the role the stimuli in the visual field play in attentional tasks determines whether any biases from presented stimuli are attractive or repulsive. They suggested that to-be-ignored objects (like distractors) lead to repulsive biases upon the target's perceived orientation, while attended stimuli (such as the previous targets) yield attractive biases upon subsequent perception. In Experiment 1, we tested whether similar effects would occur for a task-irrelevant line. The distance in feature space (orientation) between the target and distractors on the one hand, and the test line on the other, was random. In Experiments 2 and 3, we therefore addressed the role of distance in feature space between the test line on the one hand and the target and distractors more systematically in light of the findings of Fritsche et al., (2017) and Fritsche & de Lange, (2019). Finally, in Experiment 4, we tested the biases induced by neutral stimuli (which are neither search targets nor distractors). We cued the target location while keeping the task the same in other aspects so that participants did not need to search for the target. Therefore, the lines around the cued line did not serve as distractors anymore but were neutral with regard to the task. If their role as distractors is crucial for determining the direction of the biases, they should be eliminated or strongly diminished when the search is no longer required.

In sum, we had three aims in the current project. In Experiment 1, we studied biases produced by visual search upon a neutral test object. In Experiments 2 and 3, we investigated the effect that distance in feature space between the visual search targets and distractors and the task-irrelevant test line has on these biases. Finally, in Experiment 4, we tested how cueing the target location in the search (presumably eliminating the need for a search) would affect the biases from targets and distractors in the display upon the perceived orientation of the task-irrelevant test line.

Experiment 1

In Experiment 1, we tested whether the orientation of a target and distractors in a visual search task can lead to biases upon the perceived orientation of a task-independent test line presented following a series of visual search trials. In each block, participants were asked to perform a series of visual search trials (learning trials) to ensure that they had a representation of distractors (as in Chetverikov et al., 2016; see Chetverikov et al. 2019 for review). Next, a randomly-oriented test line was shown on the screen for 500 milliseconds. Finally, participants had to report the test line's orientation by adjusting a subsequently presented line located at screen center (see Figure 1).

Method

Participants

Twenty participants (eleven females and nine males, mean age = 32.35 years) were recruited for Experiment 1. All participants had a normal or corrected-to-normal vision and provided written informed consent that described the experimental procedure before starting the study. For all of the experiments here, before starting the test sessions, any participants who had never participated in our similar experiments underwent a training session, which was similar to the test session with the same number of experimental blocks. After completing the training session, participants were allowed to participate in the test. The training sessions and test sessions were held on two different days.

Stimuli and procedure

The stimuli were displayed at a viewing distance of 70 cm on a 24-inch Asus monitor with 1920×1080 pixel resolution. The experiment was programmed and carried out using Psychtoolbox-3 (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007) in MATLAB 2016a. We employed the FDL method (Chetverikov et al., 2016), where participants were asked to complete 4 to 5 visual search trials in each experimental block to ensure that they had learned the distractor distribution. On these visual search trials, participants searched for an oddly oriented line in the center of the screen in an array of 36 white lines (length = 1° of visual angle, v.a.), arranged in a 6×6 matrix (16 × 16 visual angle degrees in the center of a screen) on a gray background. We randomly added ±0.5° of v.a. to both the vertical and horizontal coordinates of the line positions to introduce some irregularity to the search array. If the target was in the upper three rows, participants were required to press the E key and press the D key (on a standard keyboard) when the target was in the lower three rows (see Figure 1).

We used both feedback and a scoring system to encourage participants to respond as quickly and accurately as possible on the search trials. If the provided response was incorrect, the word "*Error*" appeared in red on the screen for 1 second. The last trial score was presented in the top-left corner of the screen during the search trials, and a cumulative score was shown during the breaks. We employed the following formula to calculate the scores for correct answers: score = 10+(1-RT) *10 where RT stands for the response time in seconds, and the following equation determined the scores when responses were incorrect: score = -|10+(1-RT) *10| - 10. If the given response was correct and made in less than 2 seconds, the score was positive; otherwise, the score was negative.

After completing the search trials, the test line (a single oriented line) was presented on the screen for 500 milliseconds. In half of the blocks, the test line was shown at the last search target position, and in the rest of the blocks, it was displayed at a randomly chosen distractor position. The participants were asked to report the test line orientation by adjusting a bar located in the middle of the screen. Participants had 6 seconds to press the "M" or "N" keys to rotate the adjustment line clockwise or counter-clockwise, respectively.

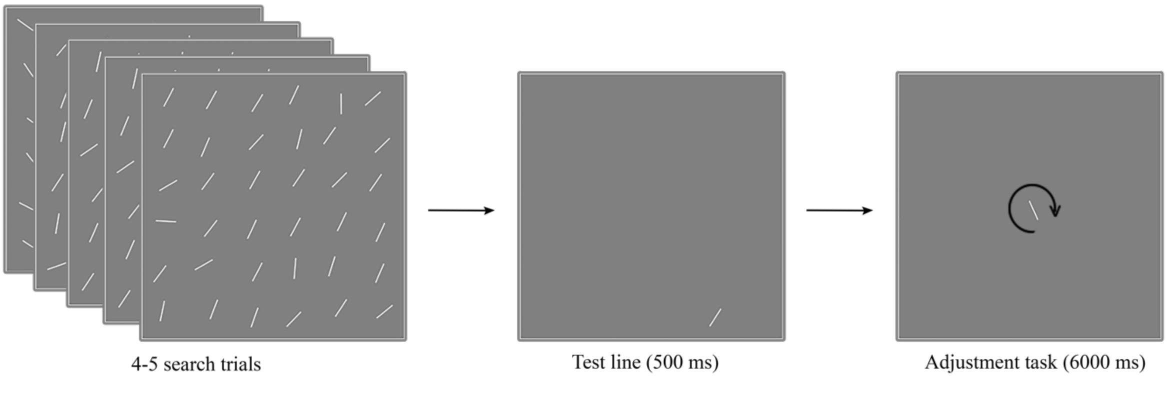

Figure.1. The design of Experiment 1. The figure shows one block consisting of the search display, the task-irrelevant test line, and the adjustment task. Firstly, participants were required to complete 4 to 5 visual search trials. They searched for an oddly oriented line (in the example shown above, the last trial's target is located in the first column, the fourth row) in the search array of 36 lines displayed in a 6×6 matrix. Next, a quasi-randomly oriented line (test line) was shown at a quasi-randomly chosen location. Finally, participants had to report the perceived test line orientation by adjusting a single bar presented at the screen center.

The mean distractor orientation on search trials was selected randomly from each block. The distractors were taken from a Gaussian distribution with a standard deviation of 15 degrees or a uniform distribution with a range of 0 to 180 (the distribution type remained constant within a block; its effect is not analyzed here). Within each block, the distractor distribution mean was kept constant to allow observers to learn the distractor distribution (as shown in previous experiments; see Chetverikov et al., 2019, for review). The target orientation was selected pseudo-randomly for each trial within 60° to 120° relative to the mean of the distractor distribution.

The distances in orientation space between the test line and the last search target and the test line and the distractors' mean were selected randomly (so the test line orientation was also selected randomly). Accordingly, in half of the blocks, the test line orientation was clockwise relative to the distractor's mean orientation and counter-clockwise in the rest of the blocks. Likewise, on half of the trials, the test line was clockwise relative to the target and counter-clockwise otherwise.

General data analysis

We excluded blocks with incorrect answers in the last search trial to ensure that we only investigated the blocks where we could be reasonably sure that participants had learned the orientation of the target and the distractor distribution. For estimating the effects of the previous target and distractor on the test line orientation judgment, we employed a hierarchical Bayesian model that integrates all of the participants' data in a single model and accounts for the parameter estimates' uncertainty. The model consisted of a mixture of two distributions of behavioral responses, x, each reflecting different types of responses on the adjustment task. The Gaussian distribution (with probability density $f_N(x;\mu,\sigma^2)$) represents variability and biases in adjustment errors, while the uniform distribution (spanning orientation space with probability density $f_U(x)=\frac{1}{180}$) maps the participants' random guesses (Zhang & Luck, 2008). The two distributions are mixed with the λ probability of an observation coming from a Gaussian distribution:

$$f(x;\theta,\mu,\sigma^2)=\lambda f_N(x;\mu,\sigma^2)+(1-\lambda)\,f_U(x)$$

Note that the Gaussian distribution is used here because the errors were relatively small so that the circularity of the orientation space is not a concern.

We modeled the mean of the Gaussian distribution (systematic biases) with a Bayesian hierarchical linear model as a function of the relationship between the distractors and the test line (clockwise vs. counter-clockwise; in the later experiments, we also added “no difference” or “orthogonal” conditions to the model as dictated by the experimental design) and the target to the test line relationship (clockwise vs. counter-clockwise; again, in the later experiments, we added “no difference” or “orthogonal” conditions where appropriate) as fixed effects. The differences between participants in terms of the overall mean error (the intercept in the model), the effects of targets and distractors (the slopes in the model), and the mixture proportions (λ) were modeled as random effects.

Results and discussion

Observers performance in the visual search task followed the expected pattern. Response times (RT; M = 895 ms, SD = 270) decreased within the block, $F(4, 76) = 18.52$, $p < .001$, $\eta^2_G = .02$, while the accuracy (M = 94.0% correct, SD = 3.3) remained relatively constant, $F(4, 76) = 0.79$, $p = .494$, $\eta^2_G = .01$, reflecting a typical attentional priming effect (Kristjánsson & Ásgeirsson , 2019). This suggests that observes obtained information about probable target and distractor features during the search.

We then analyzed the role of observed distractors and targets on the perception of an independent test line. In the adjustment task, observers were relatively precise, M = -0.004°, SD = 12.16°. As shown in Figure 2, the previous target effect had an attractive effect (b = -1.08, 95% HPDI = [-2.01, -0.14], where HPDI stand for the highest posterior density interval, a form of credibility interval defining the plausible range within which the unobserved parameter might vary) and the distractor effect was numerically repulsive (b = 0.54, 95% HPDI = [-0.43, 1.51]). To further test the effect of distractors and the target, we compared the full model with the restricted distractors-only (dropping the target effect) and target-only (dropping the effect of the distractors) models. The full model provided a better fit than both the distractors-only (logBF = 7.05; logBF stands for log-transformed Bayes factor with positive values here indicating evidence in favor of the full model) and target-only models (logBF = 0.74). So, as seen before in Rafiei et al. (2020), the distractor sets led to a repulsive serial dependence effect while the target caused an attractive effect upon the test line's perceived orientation. Importantly here, this was observed for the task-irrelevant test line but not the target of the search. However, the credibility interval for the distractor effect includes zero, and the logBF factor for the target-only model is small, indicating that we cannot draw solid conclusions from it.

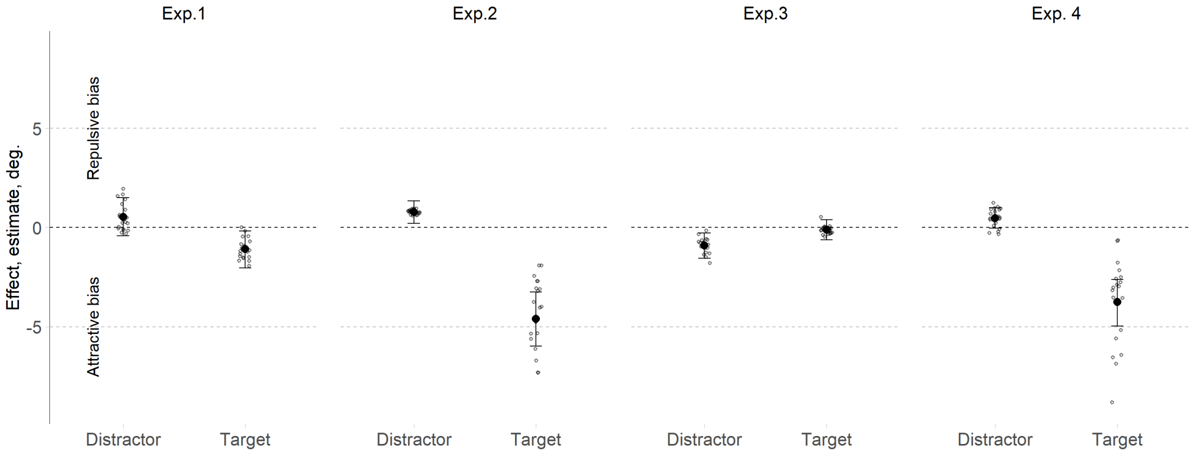

Figure 2. The target and distractor effects on adjustment error in the reported test line orientation. Small gray dots represent the individual observers, and large dots represent the population-level effects. The lines display 95% credibility intervals. Effect estimates (y-axis) shows the magnitude of the biases (in degree) produced by distractors and targets, while the x-axis shows the sources of the biases (distractors and targets).

Additionally, we ran an exploratory analysis of target- and distractor-to-test distances as continuous variables without splitting trials into clockwise/counter-clockwise groups (shown in Supplementary Fig. 1). The results suggest that the target effect is similar to what we observed in Rafiei et al. (2020), positive biases created by test lines relatively similar to the targets, and no bias from test lines dissimilar to the targets. For distractors, in contrast, the biases were repulsive and became stronger with decreasing similarity. However, due to the task's nature, the orientations of targets and distractors are not fully independent, and hence, the effect of their similarity to the test line (the target must be dissimilar to distractors). Therefore, we treated this analysis as exploratory and tested the effect of similarity in the follow-up experiments.

Experiment 2 and 3

The results of Experiment 1 suggested that while to-be-ignored objects (in our case distractors during visual search) lead to repulsive serial dependence effects upon perception, while the attended items (targets) formed an attractive bias. Importantly, this occurs not only for visual search targets but also for a task-irrelevant test line, indicating that this is not simply a task-based bias but causes general biases upon perception. Yet, the evidence for the distractor effect was not significant. In Experiments 2 and 3, we looked at proximity in feature space as a potential moderating factor for both target and distractor effects.

Some recent studies have shown that proximity in feature space between what we have recently perceived and what we are currently observing can determine the direction of serial dependence produced by the preceding items (whether the biases are attractive or repulsive). Fritsche et al. (2017) showed that two stimuli could induce opposite biases, depending on their distances in feature space. In Experiments 2 and 3, we, therefore, manipulated the distances in feature space between the distractors and test line and between the target and the test line to investigate the effect of proximity in feature space on the biases produced by our visual search stimuli.

Method

Participants

Twenty participants (thirteen females and seven males, mean age = 31.3 years for Experiment 2, and seventeen females and three males, mean age = 28 years for Experiment 3) were recruited for each experiment. All participants had the normal or corrected-to-normal vision and provided written informed consent before starting the tests, which briefly explained the experimental procedure.

Stimuli and procedure

The methods in Experiments 2 and 3 were overall similar to Experiment 1. In Experiment 2, the test line orientation was close to the target orientation and far away from the mean of the distractor distribution. The mean orientation of distractors for each block was picked randomly (from 0° to 180°), and the test line orientation was selected so that it ranged from 70° to 110° (in 4° steps) away from the distractor distribution mean with an equal number of trials within each distance bin. On the last visual search trial within each block, the target orientation had either a 10°, 0° or -10° distance to the test line (counterbalanced). On the trials preceding this last trial, the target was selected from a uniform distribution with 60° to 120° distances from the distractor mean.

Since we aimed to address the role of relations in feature space between targets and distractors on the one hand and the test line on the other, in Experiment 3, in contrast with Experiment 2, the test line orientation was close to the mean of the distractors and far from the target. The mean distractor orientation was selected randomly from 0° to 180°, as in Experiment 2. Next, the test line orientation was picked from 10°, 0°, or -10° distances to distractors. The distractors were, therefore, close to the test line in feature space. The target orientation was also chosen from 70° to 110° (in 4° steps) from the test line orientation.

Results and discussion

In both Experiments 2 and 3, priming effects were observed, suggesting that observers learned target and distractor characteristics within each block. In Experiment 2, the RT ($F(4, 76) = 6.11$, $p = .016$, $\eta^2_G = .02$, $M = 825$, $SD = 200$) decreased and accuracy ($F(4, 76) = 2.94$, $p = .045$, $\eta^2_G = .02$, $M = 93.4$, $SD = 3.9$) increased significantly over the visual search trials. In Experiment 3, the priming effects for accuracy ($F(4, 76) = 3.66$, $p = .015$, $\eta^2_G = .01$, $M = 92.7$, $SD = 4.5$), and RT were also significant ($F(4, 76) = 9.41$, $p = .002$, $\eta^2_G = .02$, $M = 729$, $SD = 160$).

The target and distractor effects on adjustment error for Experiments 2 and 3 are shown in Figure 2. Overall, the adjustment error was similar to Experiment 1 ($M = 0.17°$, $SD = 14.28°$ for Exp. 2 and $M = 0.004°$, $SD = 10.38°$ for Exp. 3). Both attention and proximity in feature space between the inducers (targets and distractors) and the test line clearly affected the direction and magnitude of the serial dependence effects (Figure 2). In Experiment 2, the targets (close to the test line in feature space) caused attractive bias ($b = -4.61$, 95% HPDI = [-5.96, -3.22]), and the distractors (far away from the test line) caused repulsive bias ($b = 0.78$, 95% HPDI = [0.24, 1.35]). Comparing the restricted models (dropping the target or distractor effect) against the full model, we found that the full model provided a better fit in both comparisons (full model vs. target-only: logBF = 3.41; full model vs. distractors-only: logBF = 15.58).

In contrast with Experiment 2, in Experiment 3, where the test line was similar to distractors and differed from targets, the direction of serial dependence for distractors was reversed – the distractors induced an attractive bias ($b = -0.92$, 95% HPDI = [-1.56, -0.27]), while the target-induced bias was close to zero ($b = -0.12$, 95% HPDI = [-0.63, 0.39]). The full model provided a slightly worse fit than the distractors-only model (logBF = -0.21) but predicted the data better than the target-only model (logBF = 4.79). Therefore, the results for experiment 3 indicate that, in opposition to Experiment 2, the distractors played a larger role in shaping the adjustment error than the targets and created attractive and not repulsive biases.

Overall, the results of Experiment 2 and 3 show that proximity in feature space between what we have already perceived and what we observe determines the direction of the biases from visual search distractors and targets. This means that attention (or whether an item is a target or distractor) is not the only factor determining the direction of the biases. In Experiment 2, the targets induced an attractive bias and the distractors a repulsive bias (like in Experiment 1), while in Experiment 3, this was reversed; the distractors produced an attractive bias upon the perception of the orientation of the test line even though they were to be ignored. On the other hand, the attended stimuli (the targets) did not affect the test line's perceived orientation. Therefore, Experiments 2 and 3 argue strongly that feature-space proximity plays a large role in determining bias direction.

Experiment 4

The results of Rafiei et al. (2020) suggested that attention plays a role in shaping biases from serial dependence. Distractors that must be ignored led to a repulsive bias, while attended targets introduced attractive biases. This conclusion was supported in Experiments 1 and 2 here. However, the results of Experiment 3 complicate this story since they show that proximity in feature space between what we have perceived previously (targets or distractors) and what we currently perceive modulates the direction of the biases. In Experiment 4, we aimed to assess attention's role in forming perceptual biases by converting the distractors from to-be-ignored stimuli to neutral ones by cueing the target location.

Method

Participants

As in the preceding experiments, we recruited twenty participants (twelve females and eight males, mean age = 30.95 years). All had normal or corrected to normal vision and signed informed consent where the experimental procedure was outlined briefly.

Stimuli and procedure

In Experiment 4, the methods were similar to Experiment 2, where the targets were close to the test line orientation, and distractors were far from it. However, in this experiment, the crucial difference is that the target location was cued by a small dot presented for a short period (500 milliseconds) before the visual search trial started. The light-gray dot size was 3 pixels, which was shown 30 pixels (0.54° visual angle) above or below the target line center for 500 milliseconds. We reasoned that if participants were cued to the target location, they would not need to search for the target among the distractor lines, which would therefore not need to be actively rejected as nontargets. The task was to report the target position relative to the cueing dot, so participants were to press the "D" key if the target appeared below the cue and "E" if the target appeared above it. After completing 4-5 such trials in each block, an irrelevant test line was then presented, followed by the adjustment line like in previous experiments.

Results and discussion

In Experiment 4 adjustment errors were similar in magnitude to previous experiments ($M = 0.25°$, $SD = 9.93°$). The targets produced an attractive bias in the perceived orientation of the test line (b = -3.76, 95% HPDI = [-4.89, -2.57]; see plot for Expeeriment 4 in figure 2). In contrast, the effect of distractors was repulsive but close to zero (b =0.48, 95% HPDI = [-0.02, 1.01]). The model comparisons showed that the full model, which included both effects, fit the data better than both the distractors-only (logBF = 13.21) and targets-only models (logBF = 1.65).

The results of Experiment 4 suggest that the role of proximity in feature space may be more important than the role of attention. When the distractors were converted to "neutral" stimuli through the use of a pre-cue, the distractors still produced a repulsive bias in perceived test line orientation. We speculate that parts of the biases that we see reflect stimulus-based, not attentional factors; in other words that even though the distractors do not play a distracting role, they nevertheless bias subsequent perception through merely being present on the screen.

General Discussion

In Rafiei et al. (2020), we demonstrated for the first time how attended and ignored stimuli in visual search task create perceptual biases. We argued that at least two opposite biases influence perception of a search target at a given moment. Positive serial dependence pulls the target toward previous target features, and a negative bias pushes targets away from distractors. Here, we set out to address three questions regarding perceptual biases created by targets and distractors during visual search upon a neutral test object's perception. Our main conclusions are:

1) There were biases from both preceding targets and distractor sets upon a neutral test line. Overall, attended items (targets) produce stronger serial dependence than ignored ones (distractors).

2) Both attention and proximity in feature space play critical roles in determining the perceptual biases from serial dependence, and our results cast light on the role that attention plays in serial dependence (see Fischer & Whitney, 2014; Fritsche & DeLange, 2019).

3) We tested how cueing the target location (presumably eliminating the need for search) affected serial dependence biases. Even when the distractors were not "to-be-rejected" items anymore but were irrelevant to the task (and dissimilar to the test item), they still produced repulsive biases. These results show that even if their attentional role is weakened, distractors still cause biases, arguing for a lower-level perceptual bias from the repeated distractors.

What functional role do the biases play in perception?

The first thing to note is that the current results show that serial dependence biases from visual search operate on perception generally, not just on the search relevant items. Rafiei et al. (2020) reported similar biases on the perceived orientation of a search target as a function of the previous trial target and current distractors. However, those results could reflect that observers do not recall the search target but report their search template instead. Our current results suggest that this is unlikely. The biases created by the search task affect neutral items, and reporting the search template instead of the neutral item would make little sense in this scenario. Search templates can nevertheless play a mediating role in the observed biases (see below).

Secondly, the to-be-ignored items induce a perceptual bias acting in parallel with positive biases induced by attended items. The latter is often described as serial dependence and is assumed to stabilize and preserve continuity in perception in the spirit of the continuity field proposed by Fischer & Whitney (2014). Serial dependence is thought to help us deal with familiar conditions by ignoring minor changes in already perceived items and maintaining continuity in perception over time (Cicchini & Kristjánsson, 2015; Liberman, Zhang & Whitney, 2016).

Pascucci et al. (2019) argued that perception is at any moment shaped by two contrasting history-based forces: sensory adaptation (as in classic after-effects such as the tilt or motion after-effects; Gibson, 1937; Wohlgemuth, 1911) and past decisions. According to their account, repulsive forces (such as seen in various low-level negative after-effects) push perception away from recently perceived stimuli. Conversely, attractive forces dominate human perception during sequences of perceptual decisions, biasing the present sensory input so that it appears more similar to past visual input than it actually is, serving as compensation for sensory adaptation. This mechanism might explain the repulsive biases we observed. However, this similarity effect (similar distractors create attractive biases while dissimilar ones create repulsive biases) does not fit the typical pattern of sensory adaptation (stronger repulsive biases for similar inducers, weak, often attractive or no biases for dissimilar ones, see reviews in Clifford, 2014; note, however, that Solomon et al., 2004, observed a pattern of results that is more similar to what we found). This explanation can nevertheless be tested in future research into the effects of different roles that items play in this interdependence.

We speculate that our findings may be related to what has been called tuning of target templates through the history of both distractors (Chetverikov et al., 2020; Geng, Won, & Carlisle, 2019) and targets (Hansmann-Roth, Geng, & Kristjánsson, 2020c; Manassi, Kristjánsson & Whitney, 2019; see Geng & Witkowski, 2019 for review and see Fischer, Czoschke, et al., 2020 for evidence of context-based serial dependence). Visual search templates can be optimally tuned through perceptual history to help us find items similar to the target. As Bravo and Farid (2016) put it: “rather than being a faithful, unbiased representation of the target, the target template is a biased representation that reflects the information necessary to perform the search task.” Bravo and Farid (see also Navalpakkam & Itti, 2007) argued that the template is adapted to the task at hand, and we propose that recent perceptual history plays a crucial role in determining this bias. The representations (or templates) are dynamic – dependent on the context, and our current findings may cast light on how the templates are biased. Importantly, our results suggest that the search templates can bias perception of irrelevant items and that these biases serve the purpose of making the objects of interest in each case more salient (assuming that the biases occur relatively early during processing so identifying items matching the biased search templates becomes easier during later processing). Manassi et al. (2019) reported interesting findings with respect to this in a visual classification task. They found that visual classification of single objects was serially dependent, biasing classification towards previously perceived objects, but only between similar objects and within a limited spatial window, showing the three characteristics proposed for continuity fields (featureal, temporal and spatial tuning). We speculate that this reflects the biasing of templates. The intriguing question is, therefore, whether parallel template biases can be found for distractor-based repetition effects.

Effects of attention and proximity in feature space

In Experiment 1, where feature space distances between test line orientation and the target on the one hand and target orientation and distractor orientation on the other, were selected randomly, the target caused attractive biases while there were hints of a repulsive bias from distractors. Experiments 2 and 3 then indicated that feature space proximity plays a crucial role in determining bias direction. In Experiment 2, where target orientation was close to the test line orientation, the targets caused attractive biases, but when the same targets in Experiment 3 were far from the test line, there was no significant bias. Conversely, the distractors produced a repulsive bias upon perceived test line orientation when they were far from each other in feature space (Experiment 2) but produced an attractive bias when they were close to the test line orientation in feature space in Experiment 3. This shows an interactive relationship between feature space proximity and whether items are attended targets or distractors to ignore.

Bliss et al. (2017, see also Fritsche et al., 2017; Samaha et al., 2019) reported attractive biases upon orientation estimations when preceding stimuli had similar orientations to the current ones in a serial dependence paradigm involving an inducer and a test stimulus. Additionally, Fritsche et al. (2017) reported repulsive biases when the inducer and the test were dissimilar. Later, Fritsche and de Lange (2019) found that the attractive bias was strongly reduced when observers attended to a different feature of the previous stimulus than orientation, arguing for a role of attention in determining perceptual biases. This is similar to previous findings suggesting that serial dependence occurs only for attended items (Fischer & Whitney, 2014; Forniciai & Park, 2018; Liberman, Zhang & Whitney, 2016). In contrast, repulsive biases in Fritsche and de Lange (2019) were not affected by feature-based attention. Our results partly agree with these findings but, in other ways, go against them. As in Fritsche et al. (2019), we found attractive biases from items similar to the test and repulsive biases from items dissimilar from the test. Furthermore, we also found that attention strengthens the attractive biases from similar items. However, in our experiments, the repulsive biases were not observed for dissimilar targets, only for dissimilar distractors. Additionally, Experiment 4 suggests that the bias from distractors is weakened when they are not a part of the task. In sum, our findings suggest that both attractive and repulsive biases are affected by attention but in different ways.

Context effects and ensembles

Previous results have revealed strong effects upon response times in visual search, both from targets (Maljkovic & Nakayama, 1994) and distractors (Kristjánsson & Driver 2008; Saevarsson et al., 2008; see Kristjánsson & Ásgeirsson, 2019 for a recent review). The current results add a crucial component to such visual search effects in showing how they affect a task-irrelevant item's perception. While we speculate that similar mechanisms facilitate search and cause the perceptual biases we see here, mapping their connection requires further research.

Our results also add to our understanding of these processes by demonstrating how both attended items and items that need to be ignored influence perception. The distractor effect here is interesting in light of the finding that perception of a visual ensemble (e.g., a set of Gabor patches) is sequentially dependent on previously perceived ensembles (Manassi et al., 2017; see Pascucci et al., 2019, experiment 7, for related findings). Our current findings reinforce this, suggesting that not only attended but also distracting ensembles create perceptual biases.

Potential relations with visual working memory

Whether serial dependence reflects working memory function is hotly debated (see, e.g., Lorenc, Mallet & Lewis-Peacock, 2021 and Kiyonoga et al., 2017 for reviews). Interestingly, Rademaker, Bloem, De Weerd, and Sack (2015) showed that when observers have to remember the first of two sequentially presented Gabor patches, the remembered orientation of the Gabor was biased towards the second irrelevant stimulus. Similarly to our conclusions here, Rademaker et al. argued that both attended and ignored information (in their case in working memory) is used to maintain continuity within the visual environment. Golomb (2015) found that for two simultaneously presented stimuli, memory is biased away from a distractor when it is similar to the test item but towards it when it is dissimilar (see also Chunbaras et al., 2019; Bae & Luck, 2019). What is interesting about these findings is how feature space and attentional role are both critical for the biases of the representations as is the main finding here.

Serial dependence as a general feature of perceptual mechanisms?

The wide-ranging spectrum of findings on serial dependence effects that we scratch the surface of here raises the intriguing question of whether serial dependence is a general characteristic of perceptual mechanisms. Serial dependence is unlikely to solely reflect low-level activity. For example, areas of the prefrontal cortex show activity modulations from serial dependence in working memory (Barbosa et al. 2020; although there is also evidence for serial dependence in earlier visual areas, John-Saaltink et al., 2016; van Bergen & Jehee, 2019). Cicchini, Benedetto & Burr (2020) have recently proposed that the priors that presumably play a crucial role in serial dependence arise in higher-level visual processing, propagating information down to earlier sensory processing levels. This interesting possibility invites speculation that the detailed characteristics of SD may differ depending on particular circumstances. For example, whether the effects are positive or negative, large or small, and their temporal profiles may differ depending on the network involved in analyzing particular aspects that SD is seen for. A similar proposal regarding the nature of potentially related history effects (attentional priming) has recently been made (Kristjánsson & Ásgeirsson, 2019).

Summary and Conclusions

The most important result here is that visual search can induce biases in the perceived orientation of a test line that is unrelated to the search task. Our results also indicate that these biases are strongly determined by both attention and similarity between the search stimuli and the test item. Overall, we speculate that our results provide a glimpse of the bag of tricks that the visual system uses to optimize perception over time. These tricks may be diverse depending on the context and may not always follow simple operational principles but can be highly task-dependent. Biases from previous stimuli may be a general feature of perceptual mechanisms and their diverse manifestations may reflect the operational characteristics of the particular neural mechanisms involved in each case.

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Open Practices Statement

The preprint of this paper is available at https://psyarxiv.com/sah9n. Additionally, the experiment's scripts and the code that we use to analyze the collected data in our experiments are available at https://osf.io/ndmju/.

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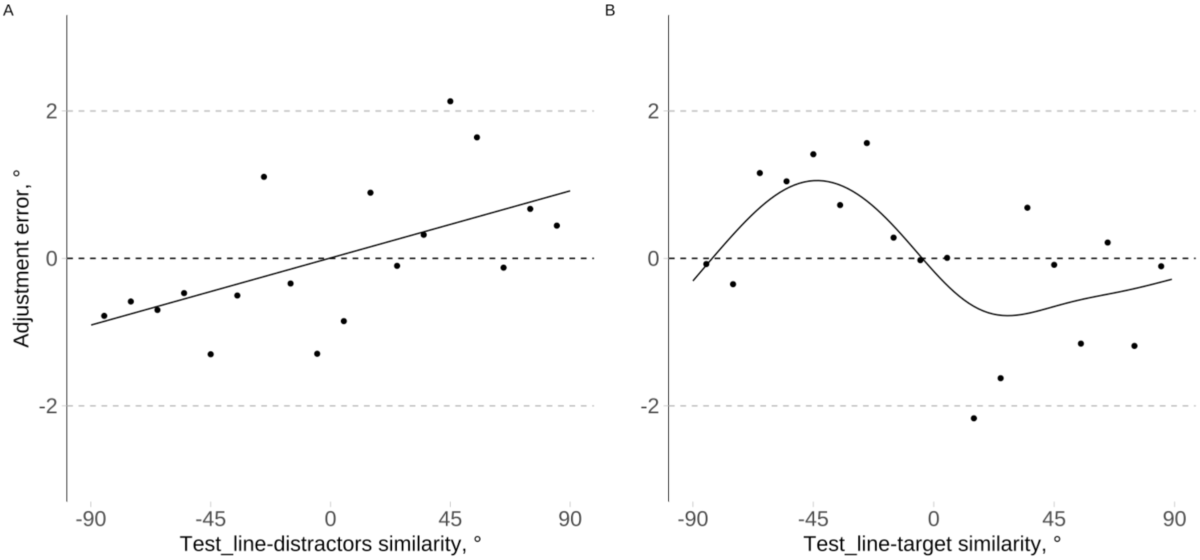
Supplementary information



Supplementary Fig.1. The effect of target and distractors to test line distances in feature space on test line perception. The above exploratory analysis suggests that the target's attractive bias is strong when they are close to the test line orientation in feature space, and the distractor effect is in the strongest state when it is far away from the test line orientation in feature space.