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Selection history-driven signal suppression

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ABSTRACT
The control of attention is influenced by current goals, physical salience, and selection history. Under certain conditions, physically salient stimuli can be strategically suppressed below baseline levels, facilitating visual search for a target. It is unclear whether such signal suppression is a broad mechanism of selective information processing that extends to other sources of attentional priority evoked by task-irrelevant stimuli, or whether it is particular to physically salient perceptual signals. Using eye movements, in the present study we highlight a case where a former-target-colour distractor facilitates search for a target on a large percentage of trials. Our findings provide evidence that the principle of signal suppression extends to other sources of attentional priority beyond physical salience, and that selection history can be leveraged to strategically guide attention away from a stimulus.

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The control of attention is now widely believed to reflect the joint influence of three distinct factors: current goals (goal-directed attention), the physical properties of objects (stimulus-driven attention), and past experience or selection history (Awh, Belopolsky, & Theeuwes, 2012). In this context, selection history has taken on an increasingly broad definition and includes history as a former search target (e.g., Grubb & Li, 2018; Kim & Anderson, 2019b; Sha & Jiang, 2016) as well as past experience linking stimuli with rewarding (e.g., Anderson, Laurent, & Yantis, 2011; Anderson & Halpern, 2017; Hickey, Chelazzi, & Theeuwes, 2010; Sali, Anderson, & Yantis, 2014) and aversive outcomes (e.g., Anderson & Britton, 2019; Schmidt, Belopolsky, & Theeuwes, 2015). One prominent hypothesis has been that each of these sources of attentional priority contribute to activation in a common spatiotopically organized priority map, where priority sums and competes for selection (Awh et al., 2012).

Under certain task conditions, attention can appear predominantly goal-directed or predominantly stimulus-driven, with physically salient stimuli either being efficiently ignored or robustly capturing attention. Over decades of attention research, this complexity has generated considerable debate and controversy (see Gaspelin & Luck, 2018). A suggested resolution to this seemly two-sided literature has centred upon the concept of signal suppression, positing that under conditions conducive to strong top-down modulation, priority signals evoked by physically salient stimuli (an "attend-to-me signal"; Sawaki & Luck, 2010) are not simply ignored but actively suppressed (Gaspelin, Leonard, & Luck, 2015, 2017; Gaspelin & Luck, 2018). More broadly, proactive suppression of stimuli known to be task-irrelevant has been hypothesized to reflect an important component of the selection process in visual search (e.g., Arita, Carlisle, & Woodman, 2012; Geng, 2014; Geng, Won, & Carlisle, 2019). Whether or how mechanisms of signal suppression might be applied to attentional priority signals evoked by stimuli as a function of selection history remains unclear.

Concerning the influence of reward in selection history, value-driven attentional priority has demonstrated a striking ability to resist inhibitory control (e.g., Anderson, Folk, Garrison, & Rogers, 2016; Kim & Anderson, 2019c; Munneke, Belopolsky, & Theeuwes, 2016; Pearson, Watson, Cheng, & Le Pelley, 2019; Wang et al., 2015; although see Gong, Yang, & Li, 2016). It has been hypothesized that such resistance to inhibitory control reflects the influence of an attention mechanism that more broadly biases the organism in favour of stimulus-evoked approach

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behaviour (Anderson, 2017). From this evidence, it appears that top-down control via signal suppression may be particular to priority signals evoked by task-irrelevant stimuli that are not reward-related.

However, other influences of selection history have not been explored in the context of the signal suppression hypothesis. The influence of selection history that is independent of the outcome of selection – that is, history as a sought target in visual search – provides a potentially more promising candidate for signal suppression to act upon. Like attentional capture by physically salient stimuli, attentional capture by former-target-colour stimuli can vary substantially across experiment contexts, at times robust (e.g., Grubb & Li, 2018; Sha & Jiang, 2016) and at times difficult to detect at all (e.g., Anderson & Halpern, 2017; Roper & Vecera, 2016; Sali et al., 2014). Unlike with attention to physically salient stimuli (Gaspelin et al., 2015, 2017), however, when and why such differences are observed remain poorly characterized. We hypothesized that the effectiveness of signal suppression might contribute to variability in the robustness of selection history-driven attentional capture, such that previous demonstrations contain some mix of trials on which stimuli that share a feature with a former target either capture attention or are suppressed in a manner that facilitates search.

To gain further insight into these issues, we conducted an experiment in which participants first searched for a colour-defined target repeatedly over trials in a training phase, and then completed a test phase in which former-target-colour stimuli appeared as distractors. Under such conditions, for reasons that are not clear, sometimes these distractors impair search for a shape-defined target (e.g., Grubb & Li, 2018; Sha & Jiang, 2016) and sometimes they do not (e.g., Anderson & Halpern, 2017; Roper & Vecera, 2016; Sali et al., 2014). Importantly, in the present study, the task required fixation of the target and eye position was continuously measured, providing a sensitive measure of competition for selection that has been shown to provide a robust indicator of signal suppression (Gaspelin, Leonard, & Luck, 2017), with a well-defined time course in which distractor-evoked attentional priority is typically initially elevated and then suppressed over time (e.g., Pearson et al., 2016; van Zoest & Donk, 2005). Given a similar time course, we hypothesized that selection history-driven attention may reflect a combination of trials on which signal suppression is not engaged quickly enough, resulting in slowed search and/or oculomotor capture by the former-target-colour distractor, and trials on which signal suppression is robust, speeding search compared to distractor-absent trials. To test this hypothesis, we measured both the rate of oculomotor capture by former-target-colour distractors and the speed of target selection on trials on which the target was the first stimulus fixated, predicting evidence for attentional capture in the case for the former and signal suppression in the case of the latter, with the combination of the two producing a negligible influence on saccadic reaction time consistent with the at times null effect of such distractors on manual response time (e.g., Anderson & Halpern, 2017; Roper & Vecera, 2016; Sali et al., 2014).

We were interested in similar questions with respect to former-target-colour distractors previously associated with reward, particularly given their apparent robustness to inhibitory control (Anderson et al., 2016; Kim & Anderson, 2019c; Munneke et al., 2016; Pearson et al., 2019; Wang et al., 2015) and controversy concerning the relationship between attentional capture driven by selection history with and without reward history (e.g., Anderson & Halpern, 2017; Grubb & Li, 2018; Kim & Anderson, 2019a, 2019b; Roper & Vecera, 2016; Sali et al., 2014; Sha & Jiang, 2016). To this end, we modeled our experiment closely after a task previously used to examine attentional capture by previously reward-associated stimuli (Anderson & Kim, 2019a, 2019b), with the only difference being the absence of reward feedback; we examined the same measures of performance in these prior experiments (Anderson & Kim, 2019a, 2019b), with particular emphasis on the speed of target selection on trials on which the target was the first stimulus fixated, as this was not examined in prior work.

Methods

Participants

Twenty-four participants were recruited from the Texas A&M University community. Participants were compensated with course credit. All reported normal or corrected-to-normal visual acuity and normal colour vision. All procedures were approved by the Texas A&M University Institutional Review Board and conformed with the principles outlined in the Declaration of Helsinki. The sample size was informed by a power analysis. The effect size for attentional bias from a former target was set at $d = 0.88$, matching the smallest effect size reported by Sha and Jiang (2016) for the comparison of distractor present versus absent. With $\alpha = 0.05$ and $\beta > 0.9$, a minimum sample size of 16 was indicated; we chose a sample size of twenty-four to match that reported in Sha and Jiang (2016).

Apparatus

A Dell OptiPlex equipped with Matlab software and Psychophysics Toolbox extensions (Brainard, 1997) was used to present the stimuli on a Dell P2717H monitor. The participants viewed the monitor from a distance of approximately 70 cm in a dimly lit room. Eye position was monitored using an Eye Link 1000-plus desktop mount eye tracker (SR Research). Head position was maintained using an adjustable chin and forehead rest (SR Research).

Training phase

Each trial consisted of a fixation display, a search array, and a blank inter-trial-interval (see Figure 1(A)). The fixation display remained on screen until eye position was registered within 1.1° of the centre of the fixation cross for a continuous period of 500 ms. The search array was then presented for 1000 ms or until a fixation on the target was registered. The search array consisted of six coloured circles, one of which was red or green on each trial. The colour of the other five circles was drawn randomly from the set {blue, cyan, purple, orange, yellow, white} on each trial without replacement. Each circle was approximately 3.6° visual angle in diameter, placed at equal intervals along an imaginary circle with a radius of 10.2°. The inter-trial-interval (ITI) lasted 3000 ms, matching the total duration of blank intervals plus reward feedback in Anderson and Kim (2019a, 2019b). If the participant failed to fixate the target before the timeout limit, the word "Miss" was presented for 1000 ms during the inter-trial-interval.

Participants were instructed to fixate ("look directly at") the red or green circle on each trial as quickly as possible. Red and green target circles appeared equally-often across trials within a block, with each colour appearing equally-often in each of the six stimulus positions. Participants completed four blocks of 60 trials each, with the order of trials randomized separately for each block. Eye position was calibrated at the beginning of each block using 9-point calibration.

Test phase

Each trial consisted of a fixation display (until fixation was acquired for a continuous period of 500 ms), a search array (1000 ms or until a fixation on the target was registered), a 1000 ms blank interval, and, in the event of an incorrect response, a feedback display (1000 ms). Each trial concluded with a 500 ms blank interval (Figure 1(B)). Targets were now defined as the unique shape, either a diamond among circles or a circle among diamonds (equally-often), which participants were instructed to fixate. The colours of the shapes were irrelevant to the task, and participants were instructed to ignore colour. The feedback display consisted of the word "Miss" presented at the centre of the screen. To maximize sensitivity to attentional capture by the distractors, participants were not required to fixate the target first in order avoid receiving "Miss" feedback (i.e., they only needed to fixate the target within the 1000 ms limit).

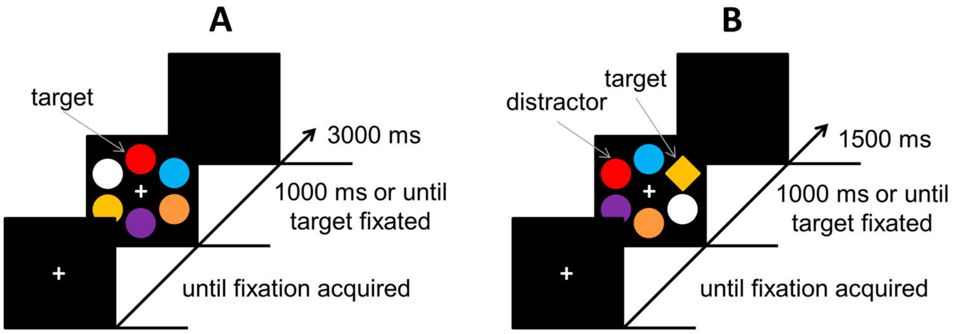

Figure 1. Example trials illustrating stimuli and time course. (A) Training phase. (B) Test phase.

One of the non-target shapes was rendered in the colour of a former target on two-thirds of trials (one-third of trials for each of the two prior target colours). On the remaining one-third of trials, none of the shapes were rendered in the colour of a formerly reward-predictive target (distractor-absent trials). Stimuli other than the former-target-colour distractor were drawn from the same colour set used for non-targets in the test phase, and the same stimulus positions were used. Targets and distractors appeared equally-often in each of the six possible stimulus positions across trials within a block. Participants completed two or three blocks (as the 60-min experiment session allowed) of 90 trials each, with the order of trials randomized separately for each block. Eye position was calibrated at the beginning of each block using 9-point calibration.

Data analysis

We measured which of the six shape stimuli was initially fixated on each trial (i.e., the first stimulus fixated), along with time to fixate the target (i.e., response time, RT). Fixation of a stimulus was registered if eye position remained within a region extending 0.7° around the stimulus for a continuous period of at least 50 ms (100 ms on the target to trigger the termination of the stimulus array). RT was measured from the onset of the search array until a target fixation was registered. Percentage of initial fixations on a distractor were taken over all trials within the respective condition, collapsing across distractor colour to compare performance on distractor-present vs. distractor-absent trials. On distractor-absent trials, in order to quantify the probability of initially fixating a distractor for the sake of comparison, one of the non-targets was dummy-coded as the distractor on each trial using the same parameters that were used to define the position of the former-target-colour distractors on distractor-present trials (i.e., same counterbalance of position relative to the target position).[1] RT was measured both averaging over all trials in each condition as well specifically on trials in which the target was the first stimulus fixated. Oculomotor dwell time on former-target-colour distractors and other non-targets was also computed, which was taken as the average duration that the eyes remained within the fixation window surrounding each stimulus for a given fixation, computed over all trials.

Results

Present study

A fixation on the target was registered within the timeout limit on 92.7% of all trials. Former-target-colour distractors were significantly more likely to draw initial eye movements than a non-target, $t(23) = 5.33$, $p < 0.001$, $d = 1.09$ (Figure 2(A)), indicating robust oculomotor capture. Mirroring this increase in oculomotor capture, initial fixations on the target were less frequent for distractor-present trials ($M = 71.6\%$) compared to distractor-absent trials ($M = 75.1\%$), $t(23) = -2.55$, $p = 0.018$, $d = 0.52$. Collapsing across all trials, there was no cost in RT associated with the former-target-colour distractors, $t(23) = -0.58$, $p = 0.571$ (Figure 2(B)), with the Bayes Factor supporting the null hypothesis, $BF_{01} = 4.01$ (Rouder, Speckman, Sun, Morey, & Iverson, 2009). This is surprising in the context of the robust oculomotor capture observed and stands in contrast to the reliable RT cost associated with high-value distractors previously observed using this task (Anderson & Kim, 2019a, 2019b; see also Anderson & Yantis, 2012). For trials in which eye

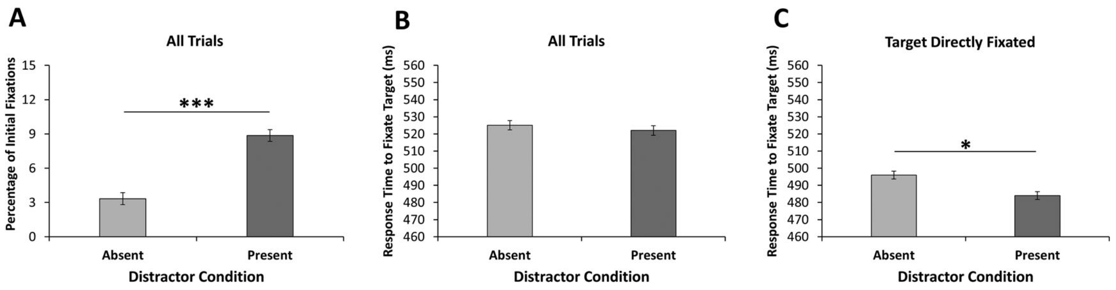

Figure 2. Behavioural data. (A) Percentage of initial fixations on the former-target-colour distractor (dummy-coded on distractor-absent trials). (B) Response time to fixate the target across all trials (C) Response time to fixate the target specifically on trials in which the first stimulus fixated was the target. Error bars reflect the within-subjects SEM. *$p < 0.05$, ***$p < 0.001$.

movements were initially directed toward the target, however, participants were in fact significantly *faster* to fixate the target on distractor-present trials, $t(23) = -2.74$, $p = 0.012$, $d = 0.56$ (Figure 2(C)). Oculomotor dwell time did not significantly differ between former-target-colour distractors and non-targets ($M = 177$ vs. 174 ms, respectively), $t(23) = 0.34$, $p = 0.73$, suggesting that differences in the time to disengage from the distractors did not meaningfully contribute to overall RT in this task.

Relation to value-driven attention

In this particular implementation of the test phase (where the task is to fixate the target), the influence of previously reward-associated distractors on RT has not been examined specifically on trials in which eye movements were initially directed to the target. Although high-value distractors are associated with an overall cost in RT across all trials (Anderson & Kim, 2019b), this specific comparison was not reported in prior studies (Anderson & Kim, 2019a, 2019b). To provide a parallel analysis to the approach adopted in the present study, using the larger dataset provided by Anderson and Kim (2019a)[2], we compared RTs between the high-value distractor vs. distractor-absent conditions for trials in which eye movements were initially directed to the target. The experiment of Anderson and Kim (2019a) was exactly identical to the present study, with the exception that reward feedback was delivered during what served as the ITI in the present study and some participants only completed two blocks of the test phase due to time constraints. In contrast to the present study, and consistent with the pattern previously observed using a manual response task (Anderson & Yantis, 2012), high-value distractors were associated with an RT cost even on trials in which the target was the first and only stimulus fixated, $t(55) = 3.44$, $p = 0.002$, $d = 0.46$[3], suggesting that the signal suppression observed in the present study may not extend to all components of selection history (in this case, the modulatory role of learned value).

Discussion

In the present study, former-target-colour distractors robustly drew eye movements but did not produce a measurable interference cost in target selection. Rather, when oculomotor capture (which occurred on less than 10% of distractor-present trials) was averted, the presence of a former-target-colour distractor actually facilitated performance, consistent with signal suppression (e.g., Gaspelin & Luck, 2018; Gaspelin et al., 2015, 2017; Sawaki & Luck, 2010). This contrasts with the pattern observed for previously reward-associated distractors (reanalysis of Anderson & Kim, 2019a), which interfere with target selection even when oculomotor capture is averted (see also Anderson & Yantis, 2012). These findings have several important implications, which we address in turn.

First and foremost, our findings suggest that attentional capture driven by status as a former target is subject to signal suppression (e.g., Gaspelin & Luck, 2018; Gaspelin et al., 2015, 2017; Sawaki & Luck, 2010), at least on a significant portion of trials, which would extend the principle of signal suppression beyond the processing of physically salient stimuli. This suggests that signal suppression is a broad mechanism of selective information processing that can be applied to other sources of attentional priority, perhaps reflecting suppression of the locus of activation on a shared priority map (see Awh et al., 2012). Although the mechanism underlying the signal suppression observed in the present study is unclear, it may be related to the signal suppression observed for task-irrelevant but physically salient distractors – a form of proactive attentional control (see Geng, 2014) thought to aid in the avoidance of anticipated distraction (Gaspelin & Luck, 2018; Gaspelin et al., 2015, 2017; Sawaki & Luck, 2010). Should this be the case, experience-driven priority would serve as a second source of priority or “attend-to-me signal” (Sawaki & Luck, 2010) capable of being the target of signal suppression, a possibility ripe for further investigation.

It is important to note, however, that evidence for signal suppression is only indirect in the present study. Although the speed of target selection is a well-established measure of covert attention to non-targets (e.g., Geng & DiQuattro, 2010; Hickey, van Zoest, & Theeuwes, 2010), which was significantly reduced on distractor-present trials compared to distractor-absent trials, this finding is not uniquely consistent with the suppression of covert attentional bias. Our finding that former-target-colour distractors can at times benefit search performance is novel, although other interpretations that do not necessarily implicate signal suppression need to be considered. For example, it is possible that the presence of a former-target-colour distractor more strongly engages compensatory goal-directed attentional control mechanisms, which in turn more efficiently guide attention to the target. Another possibility is that participants more quickly reject the former-target-colour distractor as a potential saccade target without suppressing it in priority map representations.

Second, our findings offer a possible context for why experience-driven attention is at times robust (e.g., Grubb & Li, 2018; Sha & Jiang, 2016) and at times difficult to detect (e.g., Anderson & Halpern, 2017; Roper & Vecera, 2016; Sali et al., 2014). The underlying priority signal may itself be robust in each case, particularly in its ability to elicit eye movements on a significant minority of trials. However, the differential effectiveness of suppressive mechanisms could give rise to an overall difference in observed behavioural performance costs.

Third, our findings concerning the apparent absence of such signal suppression in the case of value-driven attention dovetail nicely with recent findings that value-driven attention is not subject to certain forms of suppression frequently observed for physically salient stimuli in the absence of prior reward training (e.g., Anderson et al., 2016; Kim & Anderson, 2019c; Munneke et al., 2016; Pearson et al., 2019; Wang et al., 2015). Such a divergent pattern of results is consistent with the hypothesized link between value-driven attention and the facilitation of approach behaviour (Anderson, 2017). More broadly, our findings are consistent with a fundamental distinction between value-driven attention and experience-driven attention as advocated by Anderson and colleagues (Anderson & Britton, 2019; Anderson, Chiu, DiBartolo, & Leal, 2017; Kim & Anderson, 2019a, 2019b), in this case with each being differently subject to inhibitory control processes.

Notes

1. For distractor-present trials, a non-target other than the former-target-color distractor was fixated on 3.5% of trials (after dividing total fixations by 4 for 4 non-target stimuli present in the display), which was not significantly different from the 3.3% of non-target fixations on distractor-absent trials (*p* = 0.67), and either measure produces the same statistical conclusions when compared to fixations on the former-target-color distractor.
2. Note that the participants in these two studies overlapped, with those reported in Anderson and Kim (2019b) reflecting the participants who returned to complete a test-retest design, and so the analysis reported here reflects all available data.
3. The same result is obtained if the third block is randomly dropped for some participants using a resampling procedure to equate the frequency of two vs. three blocks across studies.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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