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BRIEF REPORT

Selection history contributes to suboptimal attention strategies

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Abstract

Attentional control balances the competing drives of performance maximization and effort minimization. One way the attention system minimizes effort is through a bias to persist in the use of attentional control strategies that have been useful in the past. In the present study, we asked whether such selection history can result in the persistence of an attentional control strategy that is counterproductive, effectively competing with a more optimal strategy. Participants first completed a training in which one color target was encountered more frequently than another, and then completed a test phase in which they could search for one of two targets on any given trial, one of which would be more optimal to search for given the distribution of color stimuli. An attentional bias for the more frequent target color was observed in the training phase and the choice of which target to report was robustly optimal in the test phase, reflecting performance maximization. Importantly, participants also exhibited a tendency to report the target rendered in the previously more frequent target color in the test phase, even when the distribution of non-target colors made it suboptimal to do so. Our findings shed light on the fundamental question of why attentional control is sometimes suboptimal, demonstrating a role for selection history in the perseveration of previously employed attentional strategies even when such strategies produce suboptimal performance.

Keywords Selective attention · Visual search · Selection history · Strategy

Introduction

Attention determines which aspects of a complex visual scene receive cognitive processing and representation at capacity-limited stages of information processing (Desimone & Duncan, 1995). Studies have identified three significant factors influencing which stimuli are attended: physical saliency (Theeuwes, 1991, 1992), the relationship between the features of stimuli and features prioritized in accordance with task goals (Bacon & Egeth, 1994; Folk et al., 1992), and *selection history* (Anderson et al., 2021; Awh et al., 2012). Selection history reflects the influence of how attention has been allocated to different stimuli in the past and the outcomes experienced in association with such allocation. Examples of factors contributing to selection history include stimulus–reward associations (Anderson, 2016; Anderson et al., 2011), associations between stimuli and aversive outcomes (Anderson & Britton, 2020; Schmidt et al., 2015), the frequency of targets appearing at different spatial locations (Geng & Behrmann, 2002), the frequency of distractors appearing at different spatial locations (Failing et al., 2019; Wang & Theeuwes, 2018b), and the frequency with which a particular stimulus has served as a searched-for target (Cosman & Vecera, 2014; Kim & Anderson, 2019). A common consequence of selection history on a visual search is the prioritization of a particular stimulus or location, which can persist well after the association responsible for the attentional bias has been removed from the task (Anderson & Yantis, 2013; Britton & Anderson, 2020; Kim & Anderson, 2019).

In the overwhelming majority of studies examining selection history, participants are given specific instructions concerning which stimuli they should try to restrict their attention to, and the question is either whether participants are biased to attend to something that they have been instructed to ignore (Stilwell et al., 2019; Vatterott & Vecera, 2012) as a function of selection history or whether they are biased towards or away from attending to a particular location when searching (Britton & Anderson, 2020; Jiang et al., 2013; Wang & Theeuwes, 2018a, b). As noted by Anderson et al.

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(2021), these studies tend to focus on stimulus-driven and/or non-strategic attentional biases. Given this focus, in most studies examining selection history (and the control of attention more broadly), the displays to which participants are exposed are highly constrained, as is the manner in which the displays might be searched. In many real-life scenarios, in contrast, the visual displays to which individuals are exposed are dynamic and varied, particularly with respect to the arrangement and composition of different objects, and we have to decide what we want to find and how we might go about finding it. Prior studies have revealed a wealth of insights into how selection history influences *to what* and *where* people attend, but we know little about how selection history influences *how* people allocate their attention when they have some flexibility with respect to how search might proceed.

The Adaptive Choice Visual Search (ACVS) task (Irons & Leber, 2016, 2018; Kim et al., 2021) provides an experimental paradigm for examining the strategic control of attention, or how people choose to search. On a typical trial in the ACVS task, there are two task-relevant colors and one target rendered in each of those colors, either of which participants can identify to complete the search. Critically, the distribution of stimuli rendered in each of the task-relevant colors varies such that stimuli of one color are more abundant than the other. Participants get to choose how to search for one of the two targets, with the distribution of color stimuli making it such that searching among the stimuli of the less abundant task-relevant color is the more optimal strategy.

Using the ACVS task, two studies have provided evidence for a role for selection history in the strategic control of attention. When participants have been rewarded for finding a target of a particular color in the past, they are biased to choose to search for a target of this particular color in a situation in which their strategy is otherwise non-optimal (Lee et al., 2022). Further, when participants are exposed to more imbalanced color distributions during a training phase, they are more likely to later adopt the optimal strategy in less imbalanced displays than are participants without this prior experience, suggesting that how participants have searched in the past contributes to strategy selection above and beyond the demands of the current search context (Kim et al., in press). In each of these cases, selection history either facilitated the optimality of visual search (Kim et al., in press) or it biased strategy selection that was otherwise non-optimal (Lee et al., 2022). To our knowledge, there have been no demonstrations of selection history leading to a decrement in the efficiency or optimality of strategic attentional control, with participants engaging in less optimal search strategies than they otherwise would as a function of selection history. Such a demonstration would require examination of strategic attentional control in a situation in which participants are otherwise generally optimal, which was not the case in Lee et al. (2022), where participants did not exhibit a systematic search strategy beyond an influence of reward history.

It has been hypothesized that one of the primary considerations governing the influence of selection history on the control of attention is effort minimization, with a bias to perseverate in allocating attention in ways that have proven beneficial in the past in order to reduce the effort needed to reappraise the situation and employ more effortful goal-directed attentional processing in order to complete a search (Anderson, 2021). Here, we asked whether such a bias could be powerful enough to produce a decrement in the optimality of the strategic control of attention. It is well established that people are far from optimal in how they choose to search as revealed by performance in the ACVS task (Irons & Leber, 2016, 2018). A program of research has begun to investigate the factors that contribute to this tendency to search non-optimally (Clarke et al., 2020; Irons & Leber, 2016, 2020), such as a tendency to avoid exerting the cognitive effort required to appraise the color distribution of the display prior to commencing search (Hansen et al., 2019). Perhaps one of the factors that contributes to the use of suboptimal search strategies is selection history. Prior research demonstrates that people will persist in whether they search for a target on the basis of its features or physical salience when either mode of searching is possible, even though in the latter case this results in unnecessary distraction by a physically salient non-target (Leber et al., 2009; Leber & Egeth, 2006a, b). In these situations, however, participants never actually choose how to search during the initial learning phase, such that selection history-dependent learning may be to some degree linked to how stimulus features are prioritized in much the same way as attention is biased towards prior target-defining features (Anderson et al., 2021), and observers also may not realize that the situation has changed such that they could choose to search otherwise. In the present study, we asked whether how participants *chose* to search during an initial training phase, in an effort to maximize their performance, could lead to *less optimal* choices concerning search strategy in a later test phase, providing direct evidence for a bias to persist in the selection of a search strategy even in situations in which this strategy now runs counter to the optimal strategy.

Methods

Participants

Thirty-four participants (20 females), between the ages of 18 and 35 years inclusive (M = 19.1, SD = 1.22) were recruited from the Texas A&M University community. All participants were English-speaking and reported normal or corrected-to-normal visual acuity and normal color vision. All procedures were approved by the Texas A&M Institutional Review Board. Written informed consent was obtained for each participant and all study procedures were conducted in accordance with the principles expressed in the Declaration of Helsinki. The final sample size (see Data analysis section below) matched that of Lee et al. (2022), informed by the same power analysis considerations ($d_z = 0.61$, $\alpha = 0.05$, Power ($1-\beta$) > 0.9), which was more conservative than that indicated by the larger effect sizes reported in Kim et al. (in press).

Apparatus

A Dell OptiPlex 7040 equipped with Matlab software and Psychophysics Toolbox extensions (Brainard & Vision, 1997) was used to present the stimuli on a Dell P2717H monitor. Participants viewed the monitor from a distance of approximately 70 cm in a dimly lit room. Manual responses were made using a Millikey SR-5 r2 button box.

Stimuli

Each visual search array was composed of 54 colored squares (each approximately 1.1° × 1.1° visual angle) arranged in three concentric rings around the center of the screen. The inner ring had a radius of 7.3° and consisted of 12 boxes, the middle ring had a radius of 10.1° and consisted of 18 boxes, and the outer ring had a radius of 13.0° and consisted of 24 boxes. Each square in each ring was positioned equidistant from each other and contained a digit between 2 and 9, subtending 0.4° × 0.4°.

Task procedure

After consent, participants completed practice for the training phase. Practice consisted of 20 trials and participants had to obtain ≥ 85% accuracy to proceed. After the practice, participants completed a training phase consisting of three blocks of trials with 60 trials each. Then, participants performed a 20-trial practice for the test phase (with the same minimal accuracy criterion), followed by three blocks of test phase trials with 80 trials each.

Training phase

Trials in the training phase consisted of a fixation display (1,000 ms), search array (until response), and a blank intertrial interval (ITI; 1,000 ms). No time limit was used for the search array so that participants would be able to more fully learn the target color probabilities. Each trial had a red or blue box with a digit from 2 to 5 as a target and participants were informed that there would only be one target in each display. The color distribution was balanced between red and blue boxes on every trial: 20 red, 20 blue, and 14 green boxes (Fig. 1A). All the other red and blue boxes except for the target contained a digit from 6 to 9, and green boxes contained a digit from 2 to 9 to prevent participants searching for the digits regardless of the color. Participants reported the digit in the box by pressing a corresponding button on the button box. All digits inside non-target squares were assigned randomly using the aforementioned constraints. Target appeared in one color (red or blue) 80% of the time (48 trials per block, frequent target color) and 20% of the time for the other color (12 trials per block, rare target color); which color served as the frequent target color alternated across participants, and the order of trials was randomized. The location of the target was determined randomly on each trial, as was the digit within the target. If participants reported a wrong number, feedback consisting of the word “Missed” was inserted after the search array.

Test phase

Trials in the test phase consisted of a fixation display (1,000 ms), search array (6,500 ms or until response), and a blank ITI (1,000 ms). Each trial had two targets, one red and one blue box with a digit from 2 to 5 (Fig. 1A). Participants were instructed that they only had to report one of the two targets on a given trial and that they could choose which one to find and report. Participants reported the digit in the box with the corresponding button press that they had used for the training phase. With respect to the color distribution of red/blue boxes, the test phase included five search conditions: 20/20, 13/27, 27/13, 34/6 and 6/34 (in each case with 14 green boxes; Fig. 1C); there were 16 trials for each condition per block, the order of which was randomly determined. Prior research demonstrates that participants are increasingly likely to find and report a target of the less adundant color, which we will refer to as the *optimal target*, the more uneven the distribution of color stimuli becomes (Kim et al., in press). Participants received no instructions concerning the distribution of color stimuli or that it was more optimal to search through one of the two colors on a given trial, and of interest was whether the frequency with which participants would find and report the optimal target would differ as a function of whether its color was the more or less frequent target color during the prior training phase. The 20/20 trials were included to maximize sensitivity in case participants tended to strongly favor finding and reporting the optimal target color regardless of how uneven the color distribution was. The location of each target was randomly determined on each trial, and the digits within the non-targets were randomly determined in the same manner as in the training phase. The digit within each target was randomly determined with the constraint that the digit within each of the two targets could not be the same on a

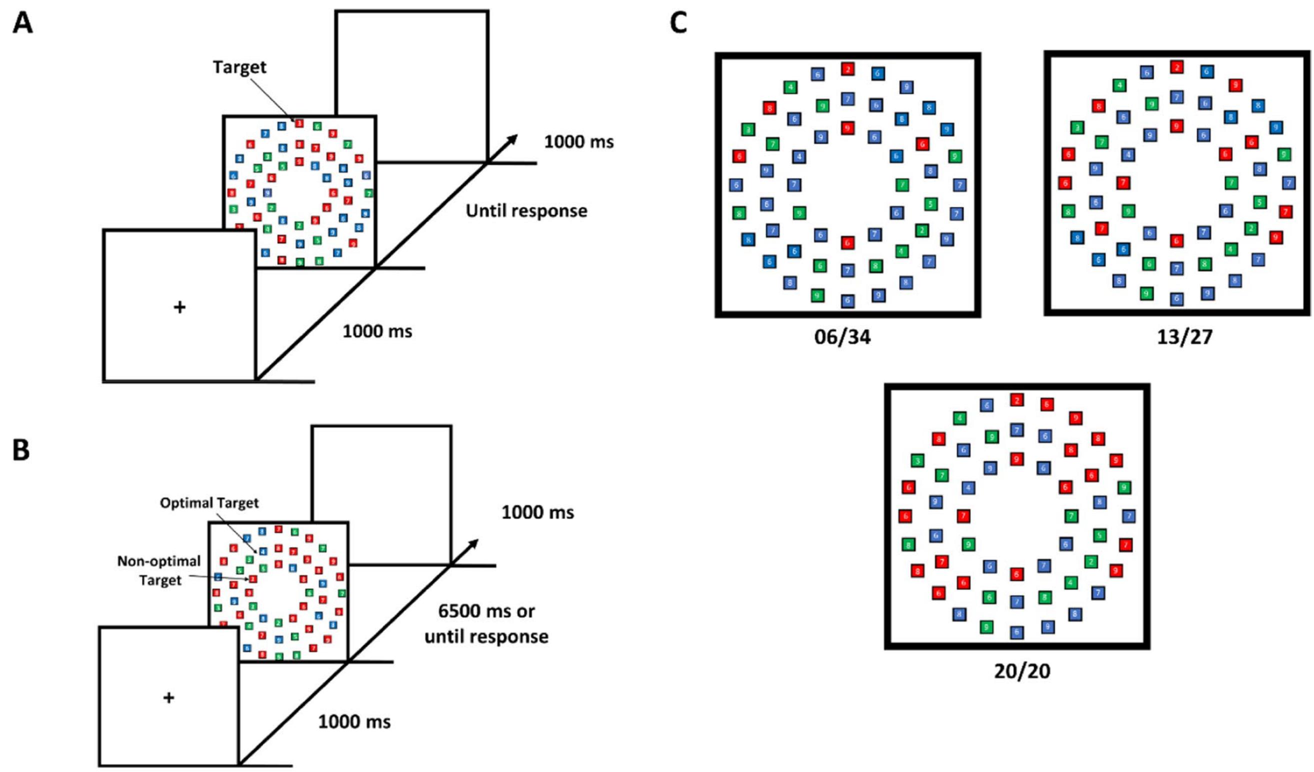

Fig. 1 Experiment task and search conditions. **A** Sequence of a trial in the training phase, **B** sequence of a trial in the test phase, and **C** search conditions in the test phase. The color distribution for 06/34 and 13/27 are depicted with red as the less adundant color, but participants were also exposed to displays in which the color distributions were flipped and blue was the less abundant color

given trial, such that which digit the participant reported was diagnostic of which color target they had found. If participants reported a number that did not correspond to a red or blue target on a trial, they received the same error feedback as in training, and if participants did not report any number within 6,500 ms, they were presented with feedback consisting of the words "Too Slow."

Data analysis

We excluded data from three participants who withdrew from the experiment prior to completion. Thus, 31 datasets were analyzed.

Results

Training phase

Participants found and reported the target significantly faster when it was rendered in the freqeunt target color, confirming an influence of the probability manipulation on color-based attentional priority, $t(30) = 3.11$, $p = 0.004$, $d_z = 0.56$ (Fig. 2A). No difference in accuracy was observed between the frequent ($M = 98.2\%$, $SD = 3\%$) and rare target color conditions ($M = 98.3\%$, $SD = 2.9\%$), $t(30) = 0.46$, $p = 0.65$.

Test phase

To examine the effect of the selection history of the optimal target color and the distribution of color stimuli on the rate of reporting the optimal target (optimality), we conducted 2 × 2 analysis of variance (ANOVA) with color distribution (13/27 vs. 6/34) and whether the optimal target color was the previously more frequent target color in the training phase (frequent vs. rare). There was a main effect of selection history, $F(1,30) = 10.86$, $p = 0.003$, $\eta^2_p = 0.266$, with participants being less optimal when the optimal target was in the rare target color. There was also a main effect of color distribution, $F(1,30) = 20.24$, $p < 0.001$, $\eta^2_p = 0.403$, with participants being more optimal when the color distribution was more skewed, replicating our previous findings concerning the influence of color distribution on optimality (Kim et al., in press). The interaction between these two factors was not significant, $F(1,30) = 0.16$, $p = 0.691$, suggesting that participants were generally less likely to choose to search for a target of the previously rare target color regardless of the color distribution (Fig. 2C). The rate of reporting the optimal

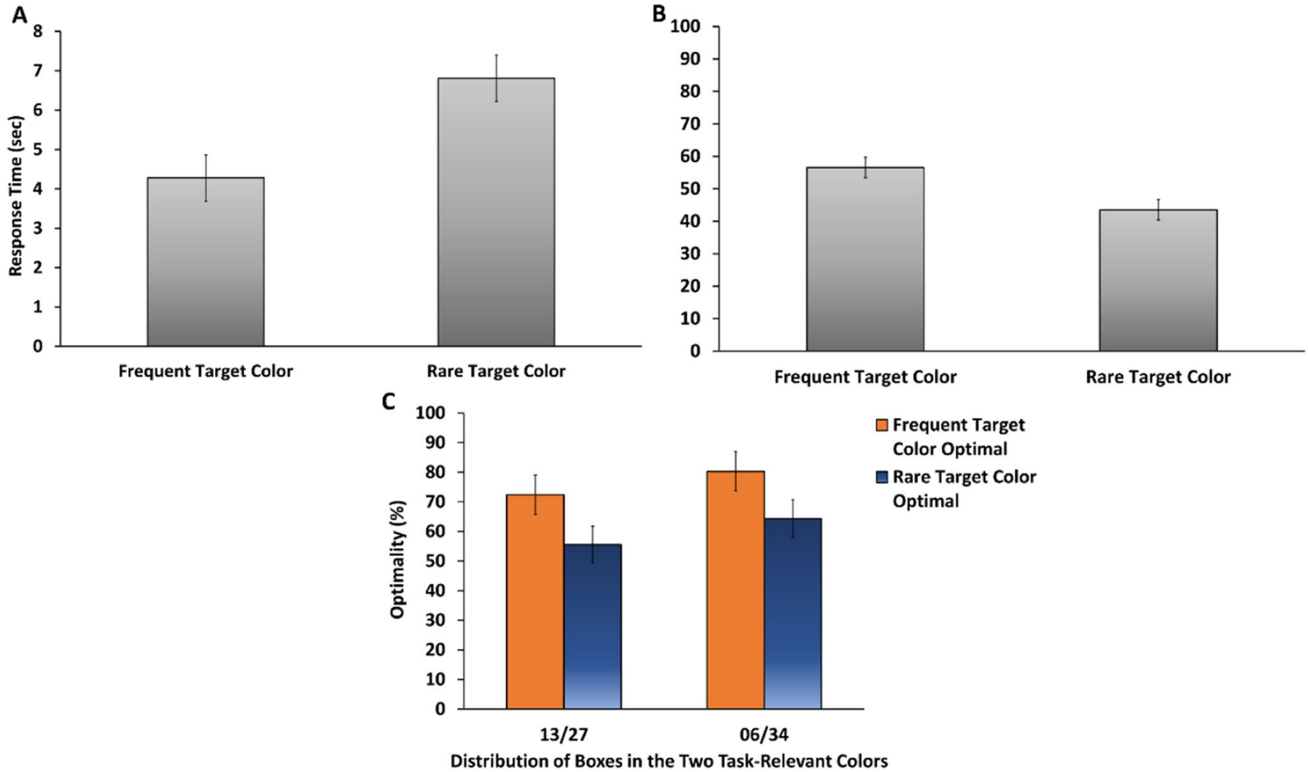

Fig. 2 **A** Response time for trials with targets in the frequent and rare target color in training phase, **B** choice rate of reporting a target in the frequent and rare target color on trials with a 20/20 color distribution in the test phase, and **C** the rate of reporting the optimal target (optimality) on trials with a skewed color distribution. Error bars reflect the within-subjects SEM

color target was significantly greater than chance (50%) in all search conditions except for trials with the 13/27 distribution in which the optimal target was the rare color, $t(30) = 1.28$ $p = 0.211$ (other *t*s > 2.85, *p*s < 0.009, d_zs > 0.50). The same ANOVA performed over accuracy revealed only a main effect of color distribution, $F(1,30) = 15.52$, $p < 0.001$, $\eta^2_p = 0.341$; the main effect of selection history, $F(1,30) = 2.40$, $p = 0.132$, and the interaction were not significant, $F(1,30) = 3.68$, $p = 0.065$. Accuracy was overall high and inconsistent with a speed-accuracy tradeoff (see Table 1).

Using the 20/20 condition, we next examined the influence of selection history over time. Overall, participants reported the previously frequent color target more often than the previously rare color target on these trials, $t(30) = 2.08$, $p = 0.047$, $d_z = 0.373$ (Fig. 2B). Next, we divided trials into six bins over time. There was a main effect of bin, $F(5,150) = 3.64$, $p = 0.004$, $\eta^2_p = 0.108$, that was well accounted for by a linear trend, $F(1,30) = 13.13$, $p = 0.001$, $\eta^2_p = 0.304$, in which the bias to report the frequent color target gradually extinguished over trials (Fig. 3D). The bias in favor of the previously frequent target color was significant in each of the first three blocks, *p*s < 0.007, becoming non-signficant by the fourth block, $p = 0.410$.

Next, we examined how use of the optimal strategy of reporting the target of the less adundant color might have varied over time. We divided trials into six bins and computed the overall proportion of trials in which the optimal color target was reported. As with the prior analysis concerning selection history, there was a main effect of bin, $F(5,150) = 4.44$, $p = 0.001$, $\eta^2_p = 0.129$, that was well accounted for by a linear trend, $F(1,30) = 9.74$, $p = 0.004$, $\eta^2_p = 0.245$. In this case, the proportion of targets reported in the optimal color gradually increased throughout the task, suggesting a learning curve in the use of the optimal strategy (Fig. 3A). Participants were,

Table 1 Mean accuracy (SD) by trial condition in the test phase

		Frequent target color optimal		Rare target color optimal	
Color distrubtion	20/20	13/27	06/34	13/27	06/34
	96.5% (3.6%)	96.4% (4.7%)	97.6% (4.1%)	94.4% (6.2%)	98.2% (3.5%)

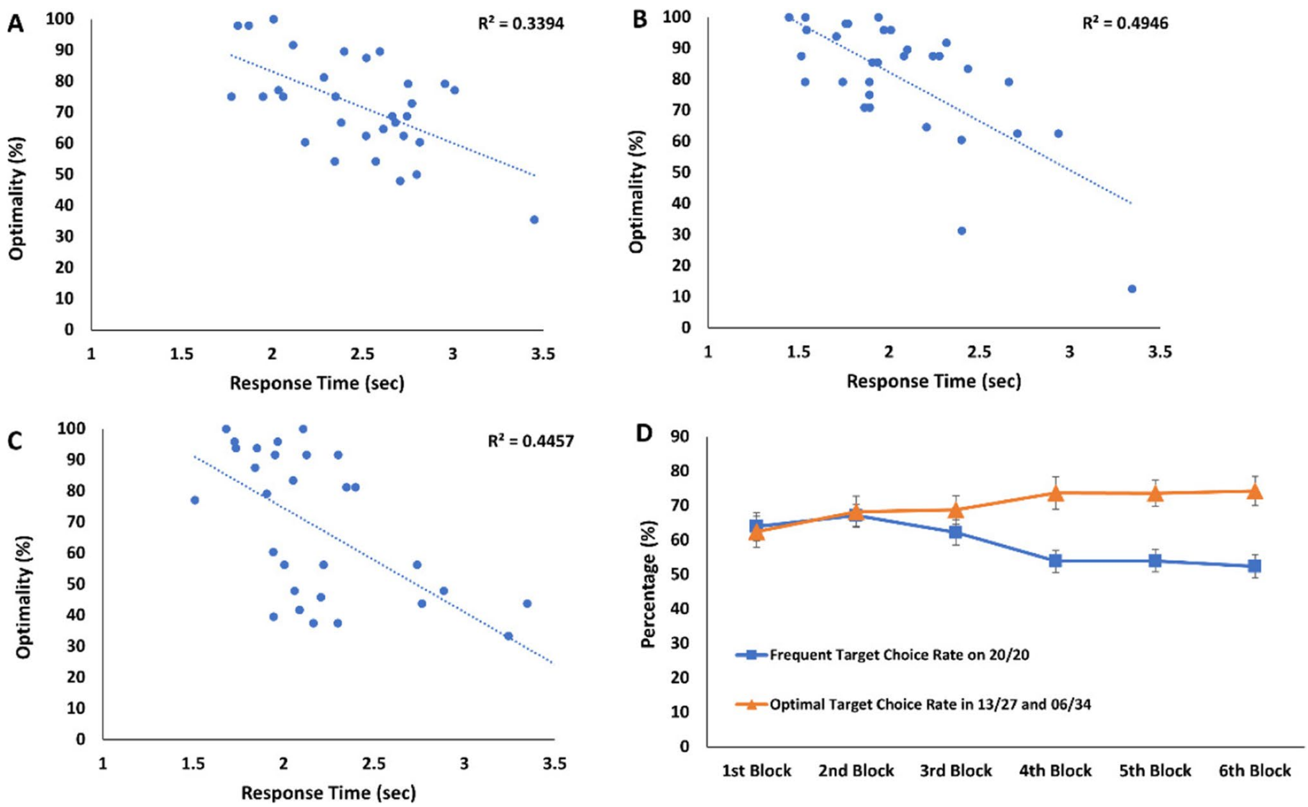

Fig. 3 Correlation between the frequency of reporting the optimal color target (optimality) and response time for **A** 13/27 trials in which the frequent color target was optimal, **B** 06/34 trials in which the frequent color target was optimal, and **C** 06/34 trials in which the rare color target was optimal. **D** Frequency of reporting the frequent color target on 20/20 trials and the optimal color target for trials with a skewed color distribution over block. Error bars reflect the SEM

however, above-chance optimal in their search as early as the first block of trials, $p = 0.005$.

Finally, we examined whether the use of the optimal strategy was in fact beneficial to performance by correlating the frequency with which the optimal target was reported with response time (RT). If using the optimal strategy is beneficial to task performance, more frequent adoption of this strategy should result in a faster time to report the target on average. Consistent with this, the frequency with which the optimal target was reported was significantly negatively correlated with RT in all three conditions in which the optimal target was reported more frequently than chance, rs < -0.57, ps < 0.001 (Fig. 3A–C). This analysis lends independent support to the idea that the frequency of finding and reporting the target of the less adundant color is a reflection of the optimality of the strategic control of attention (see also Kim et al., in press).

Discussion

Although a plethora of studies have probed the mechanisms through which selection history influences to *what extent* or *where* a person is biased to direct their attention (Anderson et al., 2011; Geng & Behrmann, 2005; Schmidt et al., 2015; Wang & Theeuwes, 2018a), very few studies have investigated the role that selection history might play in biasing *how* a person searches, or the strategic control of attention (Kim et al., in press; Lee et al., 2022). Of the studies demonstrating an effect of selection history on the choice of which of two targets to search for, the effect of selection history is either neutral with respect to task performance or it facilitates more optimal searching (Kim et al., in press; Lee et al., 2022). People often search suboptimally (Irons & Leber, 2016, 2018), and in the present study we examined whether selection history might contribute to this tendency. More specifically, we asked whether people would perseverate in adopting an attentional strategy that was previously advantageous, even when it is disadvantageous in the current task context and participants otherwise exhibit a tendency to search optimally.

A single target appeared much more frequently in one particular color during a training phase, and in a subsequent test phase participants could report a target of either this color or a color that appeared much less frequently as a target during training. The distribution of color stimuli varied in the test phase, such that one of the two task-relevant colors was less adundant, making it more optimal to search among stimuli of this less adundant color. Participants were sensitive to the probability of the target appearing in each of the two task-relevant colors during training, more quickly finding and reporting a target of the more frequent color, suggesting elevated attentional priority to this more frequent target color. Importantly, in the test phase, we found that although participants were generally optimal, more frequently reporting the target of the less abundant color, they were significantly less optimal when the optimal target color was also the previously less frequent target color. That is, selection history competed with the use of the optimal attentional strategy.

Analyses correlating the use of the optimal strategy with RT provided evidence that searching for and reporting the target of the less abundant color was in fact beneficial to performance. Participants were less likely to engage this beneficial strategy as a function of selection history. Participants seemed to gradually adopt the optimal attentional strategy with increasing frequency, and the probability of finding and reporting a target rendered in the previously more frequent target color dissipated throughout the course of the test phase, suggesting that the influence of selection history extinguished gradually.

Our findings bear some resemblance to the phenomenon of Einstellung, whereby individuals perseverate in a suboptimal strategy for solving a problem when that strategy has proven useful in the past (Leber & Egeth, 2006a; Luchins, 1942). In the present study, we extend this principle to the strategic control of attention, lending unique insights into why people sometimes search suboptimally. In this context, however, it is interesting that the influence of selection history extinguished as gradually as it did. One might have expected a much more rapid decline in the bias to find and report a target of the previously more frequent target color in a context in which participants were generally optimal (and thus clearly capable of recruiting the optimal strategy). The general "problem" was also clearly shifted, with participants being explicitly informed that they could find a target of either color on a given trial, so any perseveration in attentional strategy would not have been the result of a failure to realize that the task demands had changed. Indeed, participants exhibited a preference for the optimal strategy from the first block of trials, yet were biased to search for the previously more frequent target color for at least the first three blocks. Rather, our data appear most consistent with a bias to default to an attentional strategy that has proven beneficial in the past, which competes with priorities built on an assessment of the current demands of the trial.

Our findings extend research demonstrating that participants exhibit a tendency to maintain the scope or "window" of attentional focus from one trial to the next, even when this tendency is suboptimal in that it promotes greater vulnerability to attentional capture (Chen & Chen, 2021; Theeuwes et al., 2004) – here, we demonstrate a learning-dependent bias in the control of attention that (a) is unambiguously related to an attentional strategy (participants must choose how to search) and (b) perseverates for multiple blocks of trials, reflecting a shift in how visual information is prioritized. The extent to which participants might have more rapidly overcome the observed selection history bias if they were informed about the distribution of trials during the training phase or given explicit instruction concerning how to search, rather than needing to rely on experience to generate a strategy, is unclear. We would hesitate to generalize our findings beyond situations in which participants are tasked with generating their own attentional strategies from experience, although such situations have high ecologically validity and are important to study, as people are rarely instructed in how to search through displays in the real world.

In summary, our findings support the idea that the strategic control of attention is subject to selection history-dependent influences, complementing the findings from Lee et al. (2022) and Kim et al. (in press). Our findings go an important step further, however, in demonstrating that the influence of selection history can shift people away from an otherwise more optimal search strategy. In this respect, our study has important implications for our understanding of suboptimal attentional performance. When participants search suboptimally, they may be engaging in strategies that have benefited them in other contexts, being slow to update their strategies even when a former strategy conflicts with a more optimal one.

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Declaration

Conflicts of interest The authors declare no conflicts of interest.

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