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Spatial task relevance modulates value-driven attentional capture

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Abstract

Attention tends to be attracted to visual features previously associated with reward. To date, nearly all existing studies examined value-associated stimuli at or near potential target locations, making such locations meaningful to inspect. The present experiments examined whether the attentional priority of a value-associated stimulus depends on its location-wise task relevance. In three experiments we used an RSVP task to compare the attentional demands of a value-associated peripheral distractor to that of a distractor associated with the top-down search goal. At a peripheral location that could never contain the target, a value-associated color did not capture attention. In contrast, at the same location, a distractor in a goal-matching color did capture attention. The results show that value-associated stimuli lose their attentional priority at task-irrelevant locations, in contrast to other types of stimuli that capture attention.

Keywords Attentional capture · Attention: selective

Introduction

In the hallway of a cinema, a poster of a comedy film that previously made you laugh may stand out from a wall of posters and hold you there for a sweet flashback. While driving on the highway, a billboard advertising the burger from your favorite fast-food restaurant may steal your eyes away from the road. Visual stimuli like these capture attention due to their association with previously rewarding experiences. Studies that associated visual features with motivational value (e.g., monetary reward) through Pavlovian associative learning have found robust attentional priority for the value-associated features that can persist into subsequent unrelated tasks (Anderson et al., 2011a, 2012; Anderson & Yantis, 2013; Della Libera & Chelazzi, 2006; Failing & Theeuwes, 2014; Hickey et al., 2010a, 2010b; Hickey & van Zoest, 2012, 2013). Referred to as *value-driven attentional capture*, the phenomenon demonstrates how the reward-seeking human nature affects the deployment of attentional resources. While this attentional mechanism clearly embodies evolutionary significance in guiding behavior, it can conversely become detrimental if the value-associated stimulus appears as a distractor, to which sparing limited attentional resources runs counter to our purposes, or if the nature of the "reward" is unhealthy, such as with drugs of abuse. The detrimental impact of undesired counterproductive attentional bias towards value-associated stimuli makes it important to better understand the conditions under which it occurs. The present study investigated how task relevance modulates the effect. Specifically, we examined whether a rewarded stimulus can attract attention from a peripheral location that is outside the area of interest.

Attention has long been known to be guided by two distinct types of information. On the one hand, physically salient stimuli compete for attention in a bottom-up manner (Corbetta & Shulman, 2002; Itti & Koch, 2001; Theeuwes, 1992, 2010). Unique physical features such as color or shape (Theeuwes, 1992, 1994, 2010) and the abrupt onset of stimuli (Jonides & Yantis, 1988) all receive heightened attention across a scene. Studies using dynamic stimuli found that motion onset (Abrams & Christ, 2003; Smith & Abrams, 2018) and animated movement (Pratt et al., 2010) also capture attention. On the other hand, stimuli with visual features that match the observer's task goal are preferentially selected in a top-down manner (Anderson & Folk, 2010; Folk et al., 1992). For example, Folk et al. (1992) manipulated bottom-up salience independently from the participants' goal in a visual search task, and found that a physically salient color singleton did not have distracting effects when the participants were instructed to look for an abrupt-onset target, but captured attention when the target was instead defined by color (but see Theeuwes,

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1992). The complement was true for an abrupt-onset distractor, which only captured attention when the search target was defined by the same type of feature. These findings suggest that top-down motivation and bottom-up salience interact with each other to influence the deployment of visual attention.

The discovery of value-driven attentional capture demonstrated an additional manner in which humans allocate attentional resources. The paradigm that has been commonly used to study this phenomenon, introduced by Anderson et al. (2011a), includes two phases. In the initial value training phase, participants learn the association between certain visual features (e.g., color) and different amounts of value through trial-by-trial conditioning. They search for one of two color targets that appear among an array of distractors and report the orientation of a line segment inside the target with a key-press. Successful responses towards the two colors separately lead to feedback of relatively high or low monetary rewards. In the subsequent test phase, participants are told that color is irrelevant, and they will no longer receive reward – instead, they are to look for a shape singleton among an array of differently colored items. It is typically found that performance in the test phase is significantly impaired when one of the distractor items is a previously high-value-associated stimulus, compared to when it is a neutral color stimulus or a previously low-value-associated stimulus. Eye-tracking studies suggest that the performance cost is due to attentional capture by the value-associated stimulus: Participants' first saccades are more likely to land on the previously high-value-associated than the low-value-associated stimulus before redirecting to the target shape required by the task (Anderson & Yantis, 2012; Bucker et al., 2014; Failing et al., 2015; Hickey & van Zoest, 2012; Pearson et al., 2015; Theeuwes & Belopolsky, 2012).

The attentional priority of value-associated stimuli has been demonstrated in a wide range of tasks. For example, Failing and Theeuwes (2014) and Munneke et al. (2015) used a Posner cuing task where color cues marked the location of stimuli that would subsequently appear. Performance facilitation was observed when the target appeared at the location of a cue whose color was previously rewarded, while performance impairment was observed when the target appeared at the opposite location to a rewarded color cue. This, consistent with the oculomotor findings discussed earlier, demonstrated attentional capture by the rewarded stimuli. With an *additional singleton paradigm* (Theeuwes, 1992) where a salient color singleton competed for attention when the participants searched for a shape singleton target, Anderson et al. (2011b), Le Pelley et al. (2015), and Wentura et al. (2014) showed that the reward association of a color singleton can even boost its bottom-up salience to a more distracting level. The additive effect of reward on attentional priority modulated by salience suggests that it exerts a unique influence.

The performance cost in the presence of a value-associated stimulus has not only been found in visual attention tasks, but also in cognitive control tasks, suggesting that in addition to early attentional processing, the effect of reward history can extend to higher-order executive functions. Anderson et al. (2012) showed that when the flankers appeared in a value-associated color in a flanker task, participants were slower and less accurate to report the identity of the central target. Similarly, Grégoire and Anderson (2019) demonstrated in a Stroop task that participants were poorer at naming a word's color when the word named a value-associated concept. In order to test whether the effect of reward is transitory or makes enduring changes on attention, Anderson et al. (2011a) and Anderson and Yantis (2013) separately imposed a 4- to 21-day and a 6-month gap between the value training and test phases in their studies. It turned out that the attentional bias towards the stimuli that had previously offered monetary reward as long as 6 months earlier was robust enough to persist through the long interval. To test whether punishing saccades to rewarded stimuli could prevent value-driven capture, Pearson et al. (2015) asked participants to avoid looking at a reward-signaling distractor, as doing so would cause the omission of the reward that would otherwise have been delivered. However, even when being clearly aware of the omission contingency, the participants nevertheless fell prey to counterproductive capture by the rewarded stimuli. These findings together reflect that reward history can have fundamental and enduring effects across different stages of cognitive processing that is robust to extinction and resistant to conflicting goals.

In most existing studies, the value-associated stimuli were always presented at or near potential target locations, making them nevertheless meaningful to inspect. For example, in the test phase of the classical paradigm (Anderson et al., 2011a), the value-associated stimuli appeared randomly at one of the six locations within a search array, each of which was equally likely to contain a target stimulus. Most previous studies intended to avoid confounding value-driven attentional capture with goal-driven capture by presenting the rewarded feature on a distractor item that was never the search target (Anderson et al., 2011a, 2013; Anderson & Yantis, 2012, 2013). This feature-wise isolation from the task goal, however, is not enough to fully exclude the value-associated stimuli from an observer's attentional control setting if they are still presented in potential target locations. As a result, it remains unknown whether the attentional priority of a value-associated stimulus can persist in the absence of *any* relevance to the current task – that is, when the stimulus neither matches the task goal nor appears at a location of interest. Studying this question is meaningful to reveal the similarities and differences between value-driven attentional capture and other types of attentional bias. For example, the physical salience of bottom-up stimuli enables them to capture attention regardless of where they appear (Lamy & Zoaris, 2009). Similarly, stimuli that share features with top-down goals have also been shown to be capable of receiving preferential selection from outside the focus of attention: Using a *Rapid Serial Visual Presentation (RSVP) task* (see Joseph et al., 1997) where the target letter appeared in a central stream while some distractor flankers appeared in the periphery, Folk et al. (2002) found that flankers in a target-matching color were able to bias attention and disrupt the task even when physically separated from the target. These findings demonstrate the involuntary nature of some types of attentional bias, whose attentional priority is strong enough to overcome limited relevance to the concurrent activity. It is unknown, however, whether reward history stimuli also receive attentional priority that produces interference when at a task-irrelevant peripheral location. That is our focus in the present study.

Although there have been many investigations into the boundary conditions under which value-driven attentional capture can occur, inquiry into how task relevance modulates the effect has been sparse. The only attempts were conducted by MacLean and Giesbrecht (2015a, 2015b). They used a variation of the paradigm used by Anderson et al. (2011a). In their test phase, the value-associated colors could appear either within a search array of six circles, or outside of the array in a seventh circle perceptually segregated from the others. Each circle contained a letter or a digit. The display was presented for a short period of time and then disappeared. Participants were probed with two characters and asked to indicate which one of them had been present, after the offset of the scene. MacLean and Giesbrecht (2015a, 2015b) found that the value-associated color interfered with target identification when it appeared in the search array, consistent with value-driven attentional capture, but it had no effect when it appeared in the seventh, distractor-only circle. The results suggest that it is possible for individuals to exclude task-irrelevant locations from the search and to avoid value-based distraction there. However, in the MacLean and Giesbrecht's (2015a, 2015b) experiments, there was no evidence that *any* stimulus at the location of the isolated distractor would have captured attention. If subjects had effectively segregated the irrelevant location from the relevant ones, the irrelevant location simply might not have been processed at all – and thus the absence of an effect of value there may not be very informative about value-driven capture per se.

Several other studies have yielded findings that may also inform the issue, yet they produced the opposite results. In those studies, rewarded stimuli were able to overcome limited task relevance and produce interference at a task-irrelevant location, but these studies either encompassed cognitive processes other than spatial attentional orienting or used a weak manipulation of task relevance. For example, in a flanker task, Anderson et al. (2012) and Mine and Saiki (2015) found a greater compatibility effect caused by a high-value flanker than a low-value flanker when participants identified a central target letter. However, performance in such cognitive control tasks may reflect inhibition or facilitation of relatively late response-related processes, which differ from visual attentional processes that are thought to occur at a relatively early stage of processing. In another study by Kim and Anderson (2021), task relevance was manipulated by altering the probability that specific locations would contain distractors. In that case, task relevance of a location – in the form of distractor probability – did not alter the strength of value-driven capture. Other studies provided clear top-down guidance of spatial attention away from the reward signaling or previously rewarded distractor to make them "task irrelevant" (MacLean et al., 2016; Munneke et al., 2015, 2016; Wang et al., 2015). For example, MacLean et al. (2016) and Munneke et al. (2016) both used a search array containing the value-associated distractor, similar to that in the classical test phase (Anderson et al., 2011a), but provided valid endogenous cues indicating the location in the array in which the target would appear before the onset of the stimuli. While reasonable to ignore, the value-associated distractor, presented at a different location than had been cued, nevertheless captured attention. This effect of value could be due to an incomplete elimination of the task relevance of the distractor's location. That is, even though the target cue provided spatial certainty on a given trial, the trial-by-trial variation in target location may have prevented any location from being considered completely task irrelevant.

In order to more definitively test the effect of location-wise task relevance on value-driven attentional capture, we used a modified RSVP task, in which the value-associated color appeared as a peripheral flanker at a distance away from the central target. In our experiments, after the classical reward training, a letter stream was displayed at the center of the screen while occasionally a flanker in a previously value-associated color appeared in the periphery. The participants were required to find a target letter in a specified color that could appear at a random time in the central stream, while ignoring the irrelevant flankers. The accuracy in identifying the central target letter was used to index the attentional resources devoted to the flanker. In order to assess the extent to which *any* processing of the flankers was even possible, we also included a control condition in which the flanker matched the sought-for color, and hence was consistent with the participants' top-down goal. This permitted us not only to establish that the flanker was processed, but also to directly compare the strength of the attentional priority between a value-associated stimulus and a top-down stimulus.

Experiment 1

Experiment 1 examined whether value-driven attentional capture can occur at a task-irrelevant peripheral location. The experiment used a two-phase design similar to that used by (Anderson et al., 2011a), but with some changes in both phases. Virtual points were used instead of monetary reward. Awarding virtual points has been proven to be effective in triggering value-driven attentional capture (Albertella et al., 2019; Failing & Theeuwes, 2017). The present study adopted the point delivery method of Albertella et al. (2019). During the reward training phase, participants searched for two color targets. While one target color offered generous reward feedback for correct responses, the other target color was not followed by reward. Immediately after the completion of the training, the participants continued to the test phase, which consisted of an RSVP task with peripheral flankers. One of the peripheral flankers randomly adopted either the value-associated color or the RSVP target color across trials. The flankers appeared either shortly prior to or at the same time as the onset of the target letter in the central stream. Previous research has shown that under these conditions, a peripheral stimulus, if it captures attention, would cause the most impairment to performance when presented shortly before the target, whereas a flanker co-occurring with the target would barely have any distracting effect (Du & Abrams, 2008, 2010; Folk et al., 2002; Leblanc & Jolicoeur, 2005). Top-down stimuli have been shown to be able to capture attention in the periphery (Folk et al., 2002). Therefore, it was expected that the participants' performance would be significantly impaired when there was a lag between a goal-matching flanker and the central target, compared to when the two appeared at the same time. The attentional priority of a value-associated flanker could be similarly measured by comparing performance in the two lag conditions, as well as by contrasting to the performance pattern in the top-down condition. If a value-associated stimulus receives attention in the periphery, poorer performance in the flanker-target lagged condition should be observed than in the no-lag condition. Alternatively, if the attentional priority of a value-associated stimulus does not exert any interference from a task-irrelevant location, participants' letter identification performance should remain intact regardless of the flankers' temporal relation to the central target.

Methods

Participants

Power analysis was performed in GPOWER (Erdfelder et al., 1996) for sample size estimation. Based on the effect size $\eta^2 p$ = .167 from a previous study using a similar flankered RSVP task (Du & Abrams, 2008), the analysis showed that with an alpha = .05 in order to achieve a power of 0.90 in a 2 × 2 interaction, the projected sample size needed is approximately N = 56. Therefore, 57 undergraduate students (22 males, 33 females, two unreported) at Washington University in St. Louis were recruited to participate in the study, which was conducted online, for course credit. The participants were all between 18 and 24 years in age (*Mean* = 19.29, *SD* = 1.17), and all reported normal or corrected-to-normal vision and normal color vision. Informed consent was obtained from each of them.

Apparatus

The experiment was programmed in PsychoPy (v2020.1.3; Peirce, 2007). Data were collected through the online research platform Pavlovia (https://pavlovia.org). Participants used their own electronic devices to complete the study. At the beginning of the experiment, to obtain the display parameters of the monitor in use, the participants were asked to resize a credit card image on the screen to match that of a physical card. The sizes of all visual stimuli appearing later in the experiment were calibrated independent of the screen size and resolution so as to be equivalent for all participants.

Procedure

The training phase of the value-driven attentional capture task (Anderson et al., 2011a) was modified to award virtual points instead of money. The test phase used an RSVP task with peripheral flankers. The experiment consisted of two phases, and took around 30 min in total to complete. The participants were allowed to take short breaks between blocks but were told that they should only participate if they were able to commit themselves for the entire session without interruption.

Training phase The trial events of the training phase are illustrated in Fig. 1 (panel A). The stimuli were presented against a black background. Each trial started with a fixation display of 500 ms, and then a search array of six circles (2.5 cm diameter) was presented along the circumference of an invisible ring with a diameter of 10 cm. Five of the circles appeared in the colors pink, cyan, white, orange, and purple. Two target colors were randomly chosen from the set {red, green, blue}. One of the chosen colors was assigned to be the *rewarded color*, and the other was the *non-rewarded color*. The sixth circle of the array appeared in the rewarded color on one-half of the trials, and in the non-rewarded color on the other half. Only one target color appeared on each trial. Each circle contained a short line segment (0.7 cm) inside. The line in the critical circle was either horizontal or vertical, while the lines in the other five circles were either left or right tilted by 45°. Participants were instructed to look for the circle in either target color and report the orientation of the line segment in it by pressing the "F" key for a vertical line and the "J" key for a horizontal line. The corresponding line orientation and response keys were printed at the bottom of the screen as a reminder throughout the experiment. Speed and accuracy were both emphasized. The search array was presented for

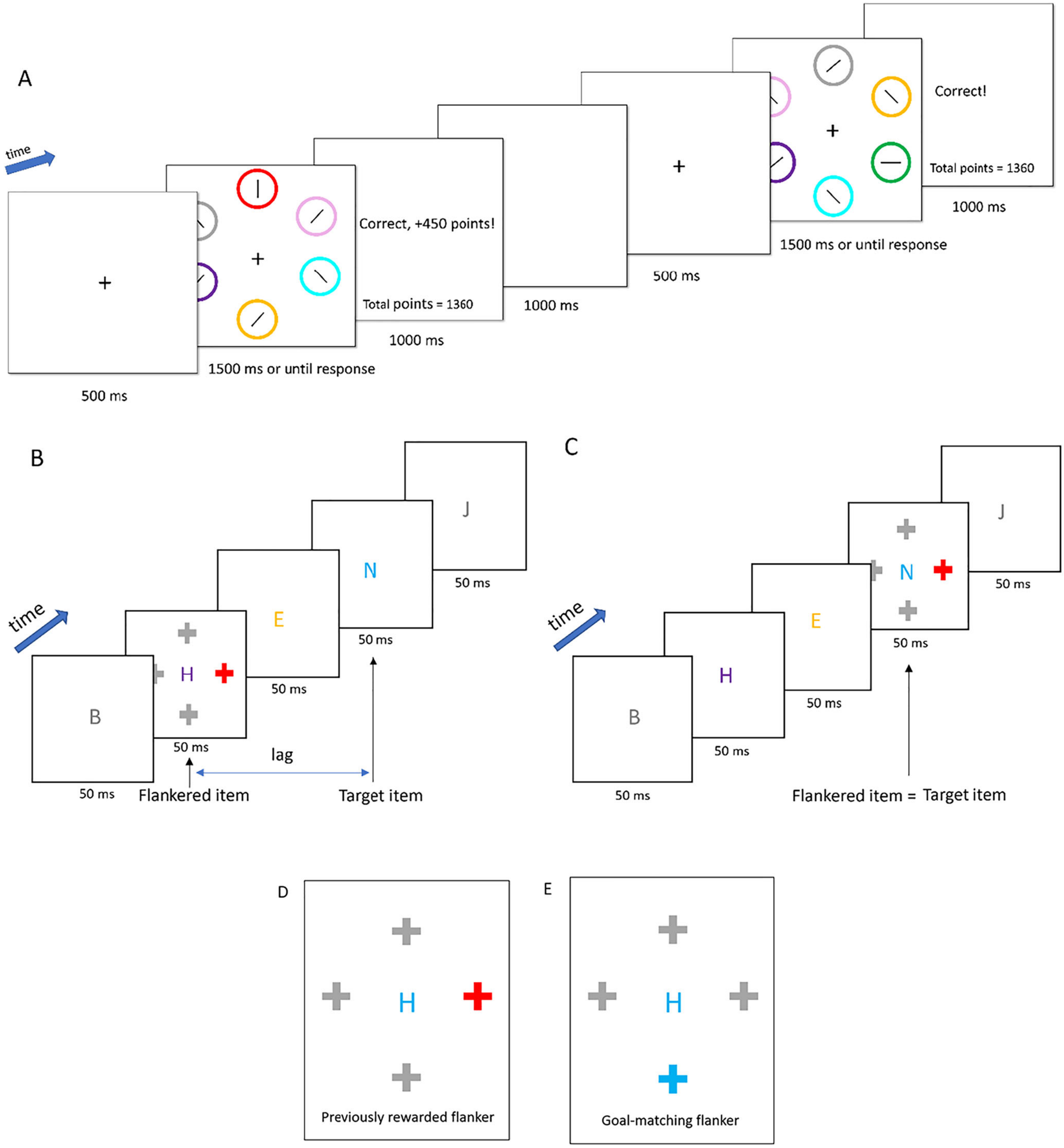

Fig. 1 Sequence of trial events in the training phase and example of conditions in the test phase. **a** In the training phase, participants searched for a circle in one of the two target colors (red and green in the example), and reported the line orientation (vertical or horizontal) inside the target with key-presses. Correct responses towards the rewarded circle (red in the example) were followed by points reward feedback, while correct responses towards the non-rewarded circle (green in the example) were followed only by accuracy feedback. (**b** and **c**) In the test phase, participants looked for a target letter in a pre-defined color (blue in the example) among a temporal sequence of differently colored letters (with a 50-ms blank screen in-between every two letters, not shown in the image), and reported its identity. One flanker appeared in the sequence, consisting of three gray crosses and one colored cross. **b** The flanker either appeared two frames before the target letter or (**c**) simultaneously with the target letter. **d** The flanker was in a previously rewarded color on one-half of the trials, and (**e**) was in a goal-matching color on the other half

1,500 ms or until response. After a correct response to a rewarded target, feedback with the virtual points reward for that trial and the total cumulative points was displayed for 1,000 ms. The number of points was calculated based on the participant's reaction time (RT; in milliseconds) on that trial (points = 1,000 – RT). The faster one responded, the more points they could receive. However, an incorrect response or a response longer than 1,000 ms was not awarded points, but was followed by an error or "too slow" message. Responses to a non-rewarded target were only followed by accuracy feedback, but never any points reward. The next trial started after a 1,000-ms delay. At the end of each block, every 6,000 points earned would unlock a virtual medal. Participants viewed a medal-awarding GIF, and were able to check their medal collection record. There was a total of four collectable virtual medals to unlock, in incremental level of honor: bronze, silver, gold, platinum. After a 12-trial practice block of line orientation judgement, and a 24-trial practice block of the visual search task, participants completed 180 training trials divided into four blocks. By design, approximately 80% of the participants were able to accumulate enough points to unlock all four of the medals by the end of the training.

Test phase The test phase was administered immediately following the training and is summarized in Fig. 1 (panels B–E). Participants were told that they would no longer receive points reward in this phase. The stimuli were presented against a black background. Each trial began after a spacebar press. A stream of 15 uppercase letters (1.5 cm in height, randomly selected from 23 letters in the alphabet, excluding I, O, and S) were presented one after another each for 50 ms at the center of the screen. In between every two letters, there was a 50-ms interval with a blank screen – however, the flanker remained displayed for 100 ms. All but one of the letters (the target) appeared randomly in gray, pink, or orange; two consecutive letters never appeared in the same color. Participants were instructed to look for (and then identify) the sole letter in the stream in a specified target color. For every subject, the RSVP target color was specified to be the remaining color in the set {red, green, blue} that had not been previously chosen as target colors in the training. The target letter randomly appeared in the eighth through 12th position in the temporal sequence. A flanker display also appeared once in the stream on each trial. The flanker consisted of four bold plus signs (1.2 × 1.2 cm) 4 cm above, below, to the left, and to the right of center for 100 ms. Three of the flankers were gray, while one of the flankers was either a previously rewarded color, or a color that matched the specified target color. The flanker appeared at one of two intervals relative to the appearance of the target letter: either two items before the target (200 ms, flanker-target lag 2) or simultaneously with the target (flanker-target lag 0). After the presentation of the letter stream, participants were prompted to report the identity of the target letter by pressing one key on the keyboard, and they were encouraged to make their best guess if unsure about the answer. There was no time pressure for entering a response. After an answer was keyed-in, the participants could start the next trial by pressing the spacebar. After a practice block of 24 trials, the participants completed a total of 160 letter recognition trials divided into four blocks.

Design

The three colors in the set {red, green, blue} were randomly assigned to be the rewarded, non-rewarded, or test-phase target color across the participants. In the training phase, the location of each colored circle and the orientation of the line segments were randomized independently. The target circle equally often appeared in the rewarded color or the non-rewarded color, and equally often contained a horizontal or a vertical line, presented in a random order.

In the test phase, the identity of the target letter and the temporal position of the target were selected randomly. The two independent variables were the lag between the flanker and the target onset (two items or no lag), and the flanker color (previously rewarded or goal-matching). A random location (up, down, left, or right) was selected to carry the colored flanker on each trial. Trial order was randomized.

Results

Participants had to achieve an overall accuracy of 70% or higher in the training phase and 40% or higher in the test phase to remain in the analyses. Seven participants' data were removed for failing to meet these criteria. For the remaining 50 participants, individuals' mean RTs of each cell condition from the two phases were calculated. Trials with RTs more than 2 standard deviations beyond an individual's cell mean were trimmed. This exclusion criterion resulted in 3.93% of the total trials removed from the training phase data, and 2.90% from the test phase data.

Training phase

The mean RT results from the training phase are shown in Fig. 2 (left panel). Data from the training phase were submitted to paired sample t-tests separately on RT and accuracy with the independent variable being target value (rewarded or non-rewarded). Participants were significantly faster to respond to a rewarded target (626 ms) than a non-rewarded target (665 ms), $t(49) = 4.556$, $p < .001$, $d = .644$. This RT advantage to rewarded stimuli was not achieved at the sacrifice of accuracy: participants were also slightly but not significantly more accurate to respond to a rewarded (89.5%) than a non-rewarded target (88.5%), $t(49) = 1.527$, $p = .133$, $d = .216$.

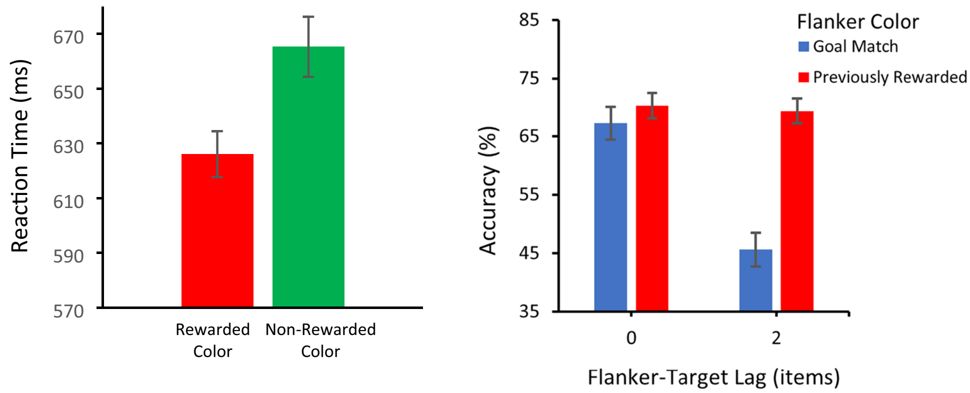

Fig. 2 Mean reaction time in the training phase (**left panel**) and mean accuracy in the test phase (**right panel**) of Experiment 1. Error bars indicate within-subject standard errors

Test phase

The mean accuracy results from the test phase are shown in Fig. 2 (right panel). In tasks like the present one, peripheral distractors typically have no effect when they appear simultaneously with the target, and have maximal effect when they appear shortly before the target (Du & Abrams, 2008). Because of that, attentional capture by the distractor would be indicated by poorer performance in the lag-2 condition compared to the lag-0 condition here. Data from the test phase were submitted to a 2 flanker-target lag (two items or no lag) × 2 flanker color (previously rewarded or goal matching) repeated-measures ANOVA separately on RT and accuracy. Participants were significantly less accurate at identifying the letter when the flanker distractor appeared two items before the target (57.5%) than when it appeared simultaneously with the target (68.9%), $F(1, 49) = 31.430$, $p < .001$, $\eta^2_p = .391$, indicating that overall the distractors were indeed attention-capturing. Accuracy was also significantly lower when the flanker appeared in a goal-matching color (56.5%) than a previously rewarded color (69.9%), $F(1, 49) = 65.158$, $p < .001$, $\eta^2_p = .571$. Critically, the interaction between flanker-target lag and flanker color was significant, $F(1, 49) = 49.739$, $p < .001$, $\eta^2_p = .504$. Post hoc comparisons show that while the goal-matching flanker significantly reduced accuracy in the two-item lag condition compared to the no-lag baseline, $t(49) = 8.679$, $p < .001$, $d = 1.326$, this difference was not significant for the previously rewarded flanker color, $t(49) = .397$, $p = .853$, $d = .128$. In other words, the goal-matching color captured attention but the previously rewarded color did not.

Responses in the test phase were unspeeded, but the test phase RT results align with the accuracy findings. Participants were significantly slower to respond when the flanker distractors appeared two items before the target (527 ms) compared to at the same time (489 ms), $F(1, 49) = 15.310$, $p < .001$, $\eta^2_p = .242$. The main effect of distractor type was not significant, $F(1, 49) = 2.629$, $p = .111$, $\eta^2_p = .052$: RT did not differ between when the flanker was in a previously rewarded color (502 ms) or a goal-matching color (515 ms). The interaction between flanker-target lag and flanker color was also not significant, $F(1, 49) = 3.136$, $p = .083$, $\eta^2_p = .061$, suggesting that there was no speed-accuracy tradeoff.

We separately conducted the analyses for each possible assignment of the three colors (red, green, and blue) to the three roles (reward, no-reward, or test-phase target). All six color-stimulus combinations produced the same pattern as the overall results, suggesting that the effect was not driven by a particular color.

Bayesian analysis Because the present experiment failed to find an effect of the value of the flanker, Bayesian analyses were conducted to further establish the absence of an effect. Bayesian paired-samples t-tests were performed in JASP (JASP Team, 2020) on test phase accuracy and RT specifically in the previously rewarded flanker condition. Consistent with the results of the classical t-tests, Bayesian analyses supported that the RSVP task accuracy, $BF_{01} = 5.877$, and RT, $BF_{01} = 1.989$, did not differ regardless of whether the rewarded flanker preceded or accompanied the target. The Bayesian factors, according to convention, separately indicate moderate and weak evidence favoring the null hypothesis. An absence of value-driven attentional capture is therefore endorsed by the Bayesian analyses.

Discussion

Experiment 1 compared the attentional priority of a previously rewarded stimulus to a top-down stimulus at a peripheral location. It was found that the participants' letter identification accuracy for the central target was not affected by the presence of a previously rewarded color, but was compromised when the designated target color appeared at a peripheral location under the same display conditions. These results show that under conditions in which a goal-matching stimulus is able to capture attention at a location out of the focus of attention, a previously value-associated stimulus is unable to do so, revealing a key difference between the attentional prioritization of goal-matching and previously rewarded stimulus features. Importantly, the present experiment showed that flankers matching the top-down goal were indeed capable of capturing attention under exactly the same conditions in which there was no effect of value, eliminating one of the limitations of prior investigations of the issue by MacLean and Giesbrecht (2015a, 2015b).

Additionally, it is worth noting that the flankers in the present task might have been considered to all be task-relevant because they provided temporal information about the appearance of the central target. Nevertheless, in previous experiments neutral-colored flankers have been found to have no distracting effect (e.g., Du & Abrams, 2008), and if the temporal information here rendered all of the distractors to be task-relevant, then interference would have been expected even for the value-associated color, contrary to the results.

Experiment 2

Experiment 1 showed that distractors with features matching the top-down goal produced interference while distractors that matched previously rewarded stimuli did not. As noted earlier, attentional capture in similar tasks is typically indexed by the diminution in performance for peripheral distractors presented shortly before the target relative to those presented simultaneously with it (e.g., Du & Abrams, 2008). Importantly, there was no effect of lag for the previously rewarded color distractor, leading to the conclusion that it had not captured attention. However, in the test phase of Experiment 1 we included only rewarded color but not non-rewarded color flankers. Previous studies have suggested that the effects of value are relative – that is that a high-value stimulus is deemed to be high in value because it is more valuable than another stimulus. For example, S. Kim and Beck (2020) compared the effect of a reward to a higher and a lower reference value and found that the relative value, rather than the absolute value, determined the priority in attentional allocation. Importantly, in most previous studies of value-driven capture, both the high- and low-value colors from the training phase were presented in the test phase. One exception to this was reported by Sali et al. (2014), who showed that the high-value color in isolation can indeed induce attentional capture. Nevertheless, because the non-rewarded color was not included in the test phase of Experiment 1, it remains possible that the rewarded color was no longer regarded as valuable, and that might account for our failure to find an effect of value there. To examine that possibility, and to bolster the conclusions from Experiment 1, we repeated the experiment here with the addition of a new flanker condition: In addition to a flanker matching the top-down goal color, and one matching the previously rewarded color, we also included a flanker that matched the previously non-rewarded color from the training phase.

Methods

Participants

Similar criteria to those in Experiment 1 were used in a power analysis. In order to achieve a power of 0.90 in a 2 × 3 interaction, the projected sample size needed is approximately N = 34. To account for foreseeable subject removal, 38 undergraduate students (15 males, 22 females, one other) at Washington University in St. Louis were recruited to participate in the study, which was conducted online, for course credit. The participants were all between 18 and 24 years in age (*Mean* = 19.34, *SD* = 1.10), and all reported normal or corrected-to-normal vision and normal color vision. Informed consent was obtained from each of them.

Procedure and design

Experiment 2 was identical to Experiment 1, except for some changes in the test phase. In addition to the previously used two flanker color conditions (previously rewarded and goal-matching colors), Experiment 2 further included a third condition containing the previously non-rewarded color from the training phase. On each trial, a flanker distractor randomly appeared in one of the three colors (red, green, or blue). Each color was equally likely to be selected as the flanker color. As in Experiment 1, colors were randomly assigned to conditions for each subject. The flanker-target lag was manipulated in the same way as in Experiment 1: flankers were equally often presented two items before the target or simultaneously with the target. Trial order was randomized.

Results

The same participant removal and data-cleaning criteria as in Experiment 1 were used in Experiment 2. Seven participants were removed from analysis for failing to meet the accuracy standard in either phase of the experiment. The same data-cleaning method as in Experiment 1 was used on the data of the remaining 31 participants. The trial-trimming criterion resulted in 4.41% of the total trials removed from the training phase data, and 3.30% from the test phase data.

Training phase

The RTs from the training phase are shown in Fig. 3 (left panel). Data from the training phase were submitted to paired-sample t-tests separately on RT and accuracy with the independent variable being target value (rewarded or non-

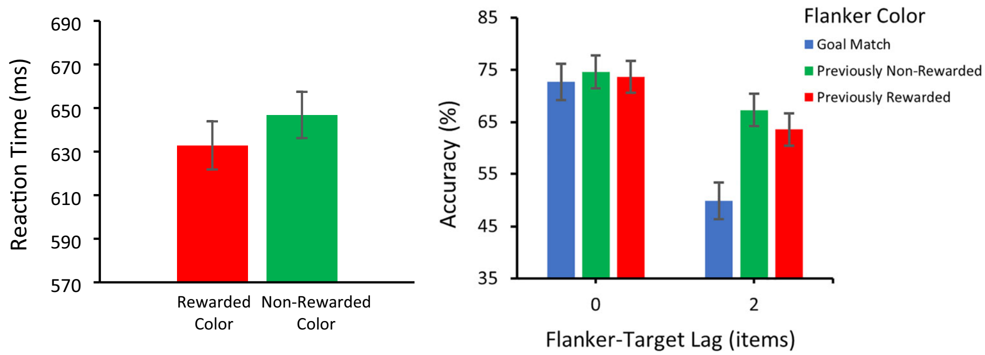

Fig. 3 Mean reaction time from the training phase (**left panel**) and mean accuracy in the test phase (**right panel**) of Experiment 2. Error bars indicate within-subject standard errors

rewarded). Participants were slightly but not significantly faster to respond to a rewarded target (633 ms) than a non-rewarded target (647 ms), t (30) = 1.647, p = .110, d = .296. Analysis of accuracy shows that the participants were also slightly but not significantly more accurate to respond to a rewarded (88.9%) than a non-rewarded target (88.8%), t (30) = .116, p = .909, d = .021.

Test phase

The accuracy from the test phase is shown in Fig. 3 (right panel). Data from the test phase were submitted to a 2 flanker-target lag (two items or no lag) × 3 flanker color (previously rewarded, previously non-rewarded, or goal matching) repeated-measures ANOVA separately on accuracy and RT. Participants were significantly less accurate at identifying the letter when the flanker distractor appeared two items before the target (60.3%) than when it appeared simultaneously with the target (73.7%), $F(1, 30) = 19.404$, $p < .001$, $\eta^2_p = .393$, as was observed in Experiment 1 and is typical in similar RSVP tasks. The main effect of flanker color was also significant, $F(2, 60) = 21.067$, $p < .001$, $\eta^2_p = .413$. Post hoc t-tests adjusted for familywise error show that accuracy was significantly lower when the flanker appeared in a goal-matching color (61.3%) than a previously rewarded color (68.7%), t (30) = 4.719, $p < .001$, d = .445, or a previously non-rewarded color (71.0%), t (30) = 6.219, $p < .001$, d = .586. Accuracy in the latter two conditions did not differ, t (30) = 1.501, p = .139, d = .141. Critically, the interaction between flanker-target lag and flanker color was significant, $F(2, 60) = 10.508$, $p < .001$, $\eta^2_p = .259$. Post hoc comparisons show that while a goal-matching flanker significantly impaired accuracy in the two-item lag condition compared to the no-lag baseline, t (30) = 6.188, $p < .001$, d = 1.384, this difference was not significant for a previously rewarded flanker, t (30) = 2.773, p = .075, d = .612, or a previously non-rewarded flanker, t (30) = 1.983, p = .365, d = .444.

The test phase RT results align with the accuracy findings. A 2 flanker-target lag (two items or no lag) × 3 flanker color (previously rewarded, previously non-rewarded, or goal matching) repeated-measures ANOVA shows that the participants were significantly slower to respond when the flanker distractors appeared two items before the target (473 ms) compared to at the same time (438 ms), $F(1, 30) = 5.769$, $p = .023$, $\eta^2_p = .161$. The main effect of flanker color was not significant, $F(2, 60) = .592$, $p = .556$, $\eta^2_p = .019$: RT did not differ between when the flanker was in a previously rewarded color (458 ms), a previously non-rewarded color (449 ms), or a goal-matching color (461 ms). The interaction between flanker-target lag and flanker color also was not significant, $F(2, 60) = 1.975$, $p = .148$, $\eta^2_p = .062$, indicating that the accuracy results are not likely to be contaminated by a speed-accuracy tradeoff.

We separately conducted the analyses for each possible assignment of the three colors (red, green, and blue) to the three roles (reward, no-reward, or test-phase target). All six color-stimulus combinations produced the same pattern as the overall results, suggesting that the effect was not driven by a particular color.

Bayesian analysis Because the present experiment failed to find evidence for value-driven attentional capture, a Bayesian approach was used to further establish the absence of an effect. To specifically examine value-driven attentional capture, the Bayesian analyses specifically focus on the flanker conditions in the two previously trained colors from reward learning. A 2 flanker-target lag (two items or no lag) × 2 flanker color (previously rewarded or previously non-rewarded) Bayesian repeated-measures ANOVA was conducted in JASP (JASP Team, 2020) to specifically quantify the evidence in favor of the absence of value-driven attentional capture. The test phase accuracy data were best represented under a model that includes the factor of flanker-target lag, $BF_{01} = .006$. According to convention, the Bayesian factor indicates strong evidence supporting this model compared to the null model, which is consistent with the significant main effect of lag condition in the classical analysis. On the contrary, the model that includes the factor of flanker color received less support compared to the null model, $BF_{01} = 3.345$, with a moderate level of evidence favoring the null model. This also aligns with the non-significant main effect of flanker color in the classical analysis and supports the conclusion that previously rewarded and previously non-rewarded flankers had equivalent effects. Following the principle of marginality (Nelder, 1977), the model with both factors and their interaction term was compared to a new null model that incorporates the main effect of the two factors. BF_{01} was 3.503, indicating moderate evidence favoring the new null model without the interaction term. The overall results suggest that the absence of an effect of value is likely to be true.

The same Bayesian repeated-measures ANOVA was conducted on test phase RT. The data were best represented under the null model. The model that includes the factor of flanker-target lag leads to a BF_{01} of 1.184, indicating weak support for the null model. Similarly, the model that includes the factor of flanker color yields a BF_{01} of 4.321, indicating moderate level of support for the null model. The model with both factors and their interaction terms was compared to a new null model that incorporates the main effect of the two factors. The BF_{01} of 3.084 suggests moderate support for the new null model. The weak to moderate support for null models in these model comparisons is consistent with an absence of value-driven attentional capture.

Discussion

As in Experiment 1, a goal-matching flanker was found to impair performance when it shortly preceded the target compared to accompanying the target, but distractors that matched the previously rewarded and the previously non-rewarded colors had no effect. The results replicate the findings from Experiment 1 and further rule out the possibility that the omission of a previously non-rewarded distractor during the test phase might have affected capture by the reward-associated distractor. The Bayesian analysis did suggest that both the rewarded and the non-rewarded distractors captured attention to some extent (although not differentially). That result could be due merely to the distracting effects of the sudden-onset distractors in the periphery regardless of their color (but see Du & Abrams, 2008). The finding may also reflect the effects of selection history (Awh et al., 2012) because both rewarded and non-rewarded colors had been repeatedly selected as targets in the training phase. Nevertheless, the effect was clearly very small compared to the effects of the goal-matching color, and importantly there was no difference between rewarded and non-rewarded colors.

One potential limitation of the present experiment is that the value training phase did not show significant performance differences between the rewarded and the non-rewarded colors in either RT or accuracy. This does not necessarily mean that the color-value association was not learned because the absence of an effect during training has been reported in a number of studies that did observe significant effects of reward in the subsequent test phase (Anderson et al., 2011a; Anderson & Yantis, 2013; Laurent et al., 2015; Suh & Abrams, 2020). Nevertheless, it is possible that the value-associated color failed to capture attention in the test phase here because the value had not been learned in the first place. The next experiment addressed this possibility.

Experiment 3

Experiment 3 was conducted to address the concern from Experiment 2 that there was no confirmation of the effectiveness of the value manipulation. Here, we repeated Experiment 2, but included a traditional test of value-driven capture during the test phase in addition to the RSVP task that was used in Experiment 2. For the traditional test, we used an additional singleton paradigm, in which the previously rewarded or non-rewarded color appeared as a color singleton among a search array, while participants searched for a shape singleton. This paradigm has been used to successfully demonstrate value-driven attentional capture in several studies (Anderson et al., 2011b; le Pelley et al., 2015; Wentura et al., 2014). In the experiment, we interspersed blocks of the additional singleton task with blocks of the RSVP task (identical to that used in Experiment 2). This allowed us not only to confirm that value had been effectively learned in training, but also to examine any diminution in the value-color association over time during the test phase.

Methods

Participants

With the same design as in Experiment 2, we followed the same projected sample size of approximately N = 34. Thirty-four undergraduate students (11 males, 21 females, two others) at Washington University in St. Louis participated in the study, which was conducted online, for course credit. The participants were all between 18 and 24 years in age (*Mean* = 19.84, *SD* = 1.08), and all reported normal or corrected-to-normal vision and normal color vision. Informed consent was obtained from each of them.

Procedure and design

Training phase The training phase of Experiment 3 was similar to that of the first two experiments, except for a few changes aimed to improve learning of the color-value associations. Before the training started, the participants were explicitly told about the mapping between the two color-value pairs (reward contingency was also made explicit to participants in Albertella et al., 2019). We also increased the training from four blocks of 180 trials to six blocks of 270 trials. In addition to the previously used four medals, two additional “diamond” and “elite” medals were added to accommodate the lengthened task.

Test phase The test phase consisted of interspersed blocks of the RSVP task, which was identical to that used in Experiment 2, and blocks of the additional singleton task. Participants were told that they would not receive points reward in these two tasks. Trial events in the additional singleton task are illustrated in Fig. 4. In the task, the stimuli were presented against a black background. On each trial, after a fixation display of 500 ms, six shapes appeared along the circumference of an invisible ring (diameter: 10 cm). On one-half of the trials, five of the shapes were circles (2.5 × 2.5 cm), while one shape had a unique form of a diamond (2.2 × 2.2 cm). On the other half of the trials, the shapes were five diamonds and a unique circle. The distractor condition differed across trials. On one-third of the trials, all six shapes were gray. On the other two-thirds of the trials, while five of the shapes were gray, one of the non-singleton shapes appeared in either the previously rewarded color or the previously non-rewarded color. The two previously trained colors appeared equally often, and the order of the three trial types was random. Similar to the training, each shape contained a short line segment (0.7 cm), that was either horizontal or vertical in the unique shape, and tilted to the left or the right by 45° in the other shapes. Participants were told to look for the shape singleton and report the orientation of the line in it by pressing the “F” or the “J” key, but to ignore the task-irrelevant color singleton. Speed and accuracy were both emphasized. The search array remained on the screen for 1,500 ms or until response. Different search array layouts, distractor types (rewarded distractor, non-rewarded distractor, and distractor absent), and the line orientation were independently presented in a random order. An error message was displayed for 500 ms after an incorrect or too slow response. The next trial started after a 1,000-ms delay.

At the beginning of the test phase the participants performed 24 practice trials separately for the RSVP and the additional singleton tasks, and then began the formal test with a block of the RSVP task. At the end of each block, after a short break they were guided to switch to the alternative task, with a brief reminder of the instructions for that task. There was a total of seven blocks of 168 trials of the RSVP task, and seven blocks of 126 trials of the additional singleton task, administered in alternate blocks.

Results

Each participant had to simultaneously meet the accuracy criteria of 70% or higher in the training phase, 40% or higher in the RSVP task, and 70% or higher in the additional singleton task to remain in the analyses. Four participants’ data were removed for failing to achieve the required accuracy in at least one of the three phases. The same data-cleaning method as in the previous experiments was used on the data of the remaining 30 participants. The trial-trimming criterion resulted in 3.96% of the total trials removed from the training phase data, 3.69% from the RSVP task data, and 3.84% from the additional singleton task data.

Training phase

The mean RT results of the training phase are shown in Fig. 5 (left panel). Data from the training phase were submitted to paired sample t-tests separately on RT and accuracy. Participants were significantly faster to respond to a rewarded target (597 ms) than a non-rewarded target (651 ms), t (29) = 6.953, p < .001, d = 1.269. The RT advantage to rewarded

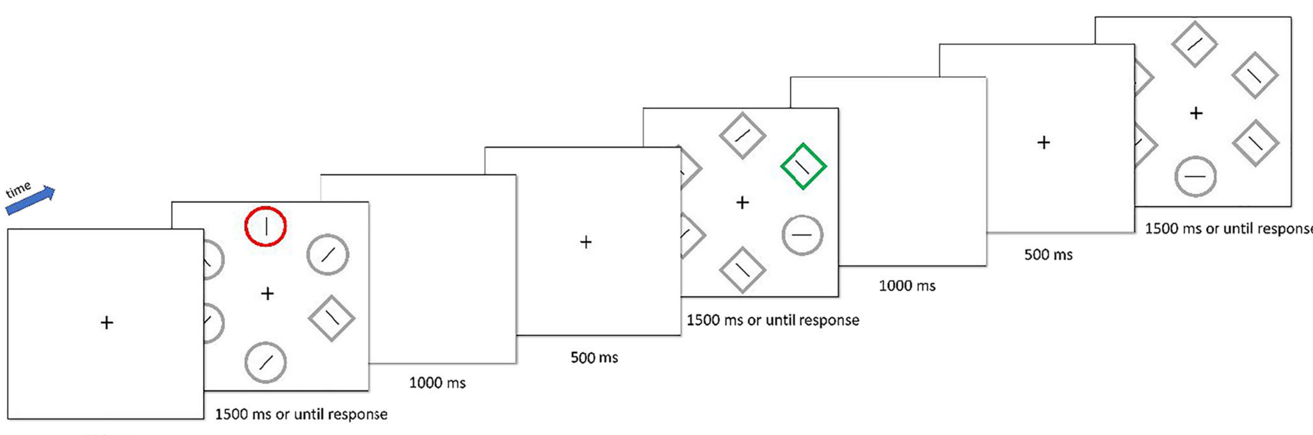

Fig. 4 Sequence of events in a trial of the additional singleton task. Participants searched for a unique shape, which could be a diamond among circles (as in the first trial in the figure) or a circle among diamonds (as in the second and third trials), and reported the orientation (horizontal or vertical) of the line inside it with a key-press. They were told to ignore a stimulus in a unique color, as the target would never be in a unique color. A trial contained either no color singleton or a colored singleton that matched either the previously rewarded color or the previously non-rewarded color. The three types of trials were presented equally often, in a random order

stimuli was not achieved at the cost of accuracy: Participants were also slightly but not significantly more accurate to respond to a rewarded (88.1%) than a non-rewarded target (86.8%), t (29) = 1.329, p = .194, d = .243.

RSVP test phase

The mean accuracy results from the RSVP task are shown in Fig. 5 (right panel). Data from the RSVP task were submitted to a 2 flanker-target lag (two items or no lag) × 3 flanker color (previously rewarded, previously non-rewarded, or goal matching) repeated-measures ANOVA separately on accuracy and RT. Participants were significantly less accurate at identifying the letter when the flanker distractor appeared two items before the target (62.7%) than when it appeared simultaneously with the target (70.9%), $F(1, 29) = 12.603$, $p = .001$, $\eta^2_p = .303$. The main effect of flanker color was also significant, $F(2, 58) = 10.110$, $p < .001$, $\eta^2_p = .259$. Post hoc tests adjusted for familywise error show that accuracy was significantly lower when the flanker appeared in a goal-matching color (62.4%) than a previously rewarded color (70.0%), t (29) = 4.312, $p < .001$, d = .453, or a previously non-rewarded color (68.1%), t (29) = 3.260, p = .004, d = .342. Accuracy in the latter two conditions did not differ, t (29) = 1.053, p = .297, d = .111. Critically, the interaction between flanker-target lag and flanker color was significant, $F(2, 58) = 12.646$, $p < .001$, $\eta^2_p = .304$. Post hoc comparisons show that while a goal-matching flanker significantly impaired accuracy in the two-item lag condition compared to the no-lag baseline, t (29) = 5.792, $p < .001$, d = 1.027, this difference was not significant for a previously rewarded flanker, t (29) = 0.523, p = 1.000, d = .093, or a previously non-rewarded flanker, t (29) = 2.011, p = .485, d = .357.

The RT results from the RSVP task align with the accuracy findings. A 2 flanker-target lag (two items or no lag) × 3 flanker color (previously rewarded, previously non-rewarded, or goal matching) repeated-measures ANOVA shows that the participants were significantly slower to respond when the flanker distractors appeared two items before the target (489 ms) compared to at the same time (468 ms), $F(1, 29) = 7.071$, $p = .013$, $\eta^2_p = .196$. The main effect of flanker color was not significant, $F(1, 29) = 1.335$, $p = .271$, $\eta^2_p = .044$. RT did not differ between when the flanker was in a previously rewarded color (473 ms), a previously non-rewarded color (476 ms), or a goal-matching color (490 ms). The interaction between flanker-target lag and flanker color also was not significant, $F(2, 58) = .327$, $p = .722$, $\eta^2_p = .011$, suggesting that there is no speed-accuracy tradeoff.

We also examined the time-course of capture during the RSVP test phase. Figure 6 shows the *accuracy capture index* (lag 0 accuracy minus lag 2 accuracy) as a function of trial block during the test phase, separately for each type of distractor. These data were submitted to a 3 flanker color (previously rewarded, previously non-rewarded, or goal matching) × 7 block repeated-measures ANOVA. The main effect of flanker color was significant, $F(2, 58) = 12.646$, $p < .001$, $\eta^2_p = .304$. Post hoc tests adjusted for familywise error show that capture was significantly greater when the flanker appeared in a goal-matching color (17.1%) than a previously rewarded color (1.5%), t (29) = 4.878, $p < .001$, d = .891, or a previously non-rewarded color (6.0%), t (29) = 3.50, p = .002, d = .639. Capture for previously rewarded and previously non-rewarded colors did not differ, t (29) = 1.378, p = .174, d = .252. Neither the main effect of block, $F(6, 174) = .274$, $p = .949$, $\eta^2_p = .009$, nor the interaction between flanker color and block, $F(12, 348) = .293$, $p = .990$, $\eta^2_p = .010$, were significant, showing that the strength of capture by the goal matching color and the absence of capture for the previously rewarded and non-rewarded colors remained consistent over time during the test phase.

Additional singleton test phase

The RT and accuracy results as a function of block are shown in Fig. 7. These data were submitted to a 3 distractor type (distractor absent, rewarded distractor, and non-rewarded

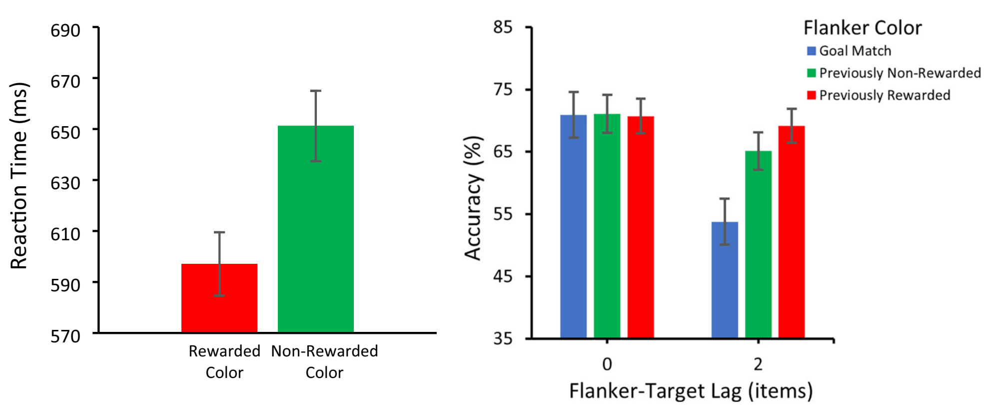

Fig. 5 Mean reaction time in the training phase (**left panel**) and mean accuracy in the test phase (**right panel**) from Experiment 3. Error bars indicate within-subject standard errors

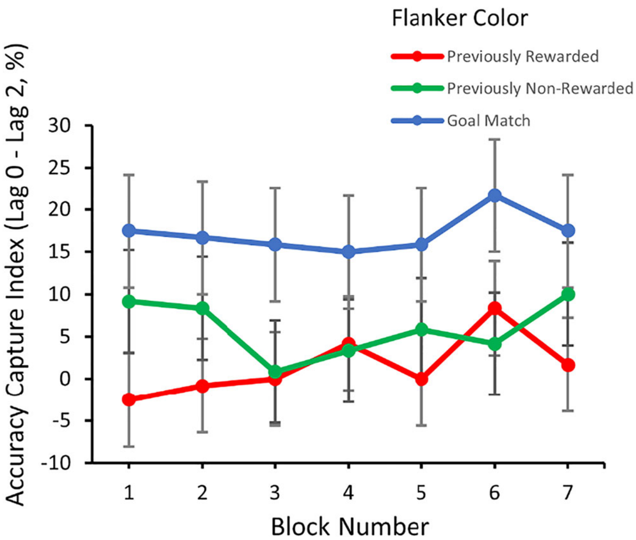

Fig. 6 Accuracy capture index (difference in accuracy at lag0 and lag2) for each type of flanker as a function of trial block in the test phase of Experiment 3. Error bars indicate within-subject standard errors

distractor) × 7 block repeated-measures ANOVA. In the RT results, the main effect of distractor type was significant, $F(2, 58) = 61.885$, $p < .001$, $\eta^2_p = .681$. Post hoc t-tests adjusted for familywise error were then conducted to compare the differences between conditions. Participants were fastest when the distractor was absent (703 ms), and were significantly slower when a previously non-rewarded distractor appeared (765 ms), t (29) = 7.411, $p < .001$, $d = 1.353$. A previously rewarded distractor (795 ms) further slowed the participants down compared to a non-rewarded distractor, t (29) = 3.480, $p < .001$, $d = .635$, revealing value-driven attentional capture. The main effect of block was also significant, $F(6, 174) = 15.584$, $p < .001$, $\eta^2_p = .350$. RT gradually decreased from Block 1 to Block 7, indicating a learning effect. The interaction between distractor type and block was not significant, $F(12, 348) = 1.030$, $p = .421$, $\eta^2_p = .034$, suggesting that the RT differences between conditions did not wane across time.

The additional singleton task accuracy data showed similar patterns. The main effect of distractor type was significant, $F(2, 58) = 19.242$, $p < .001$, $\eta^2_p = .399$. Post hoc t-tests adjusted for familywise error showed that the participants were significantly less accurate in the presence of a previously rewarded distractor (82.9%) than in the presence of a previously non-rewarded distractor (91.1%), t (29) = 6.144, $p < .001$, $d = 1.122$, or with no distractor present (88.0%), t (29) = 3.817, $p < .001$, $d = .697$. When a previously non-rewarded distractor was present, participants' accuracy was not impaired but was even better than when the distractor was absent, t (29) = 2.326, $p = .024$, $d = .425$. The main effect of block was also significant, $F(6, 174) = 2.640$, $p = .019$, $\eta^2_p = .082$. Accuracy increased from Block 1 to Block 7, indicating a learning effect. The interaction between distractor type and block was not significant, $F(12, 348) = .943$, $p = .504$, $\eta^2_p = .031$, suggesting that the accuracy differences between conditions did not vary across time.

We separately conducted the analyses for each possible assignment of the three colors (red, green, and blue) to the three roles (reward, no-reward, or test-phase target). All six color-stimulus combinations produced the same pattern as the overall results, suggesting that the effect was not driven by a particular color.

Bayesian analysis To further evaluate the strength of the value-driven attentional capture effect, the same Bayesian analyses as in Experiment 2 were conducted on the RSVP task data. A 2 flanker-target lag (2 items or no lag) × 2 flanker color (previously rewarded or previously non-rewarded) Bayesian repeated-measures ANOVA was conducted separately on accuracy and RT. The accuracy data were best represented under the model that incorporates the factor of flanker-target lag, $BF_{01} = .700$, indicating weak support for this model over the null model. As in Experiment 2, this finding may reflect a capture effect caused by the transients associated with distractor onset, or by effects of selection history due to the repeated selection of both rewarded and non-rewarded colors in the training phase. On the contrary, the model that incorporates the factor of flanker color was suboptimal compared to the null, $BF_{01} = 3.124$, supported by a moderate level of

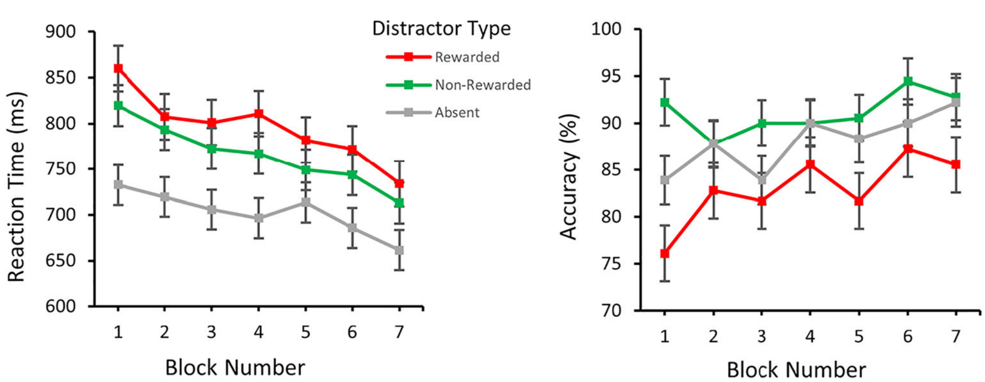

Fig. 7 Mean reaction time (**left panel**) and mean accuracy (**right panel**) as a function of trial block in the additional singleton task from Experiment 3, separately for the three different distractor types. Error bars indicate within-subject standard errors

evidence. Following the principle of marginality (Nelder, 1977), the model with both factors and their interaction term was compared to a new null model that incorporates the main effect of the two factors. The data were better represented under the model without the interaction, BF_{01} = 2.036, supported by anecdotal to moderate level of evidence. These results provide support for an absence of difference between the distraction effect of a rewarded color and a non-rewarded color.

The same 2 flanker-target lag (2 items or no lag) × 2 flanker color (previously rewarded or previously non-rewarded) Bayesian repeated-measures ANOVA was conducted on RT of the RSVP task. The data were best represented under the null model. The model that includes the factor of flanker-target lag leads to a BF_{01} of 1.403, indicating weak support for the null model. Similarly, the model that includes the factor of flanker color yields a BF_{01} of 4.996, indicating moderate level of support that the null model is better. The model with both factors and their interaction terms was compared to a new null model that incorporates the main effect of the two factors. The BF_{01} of 3.409 suggests moderate evidence for the new null model. The Bayes analysis on RT again supports a true absence of value-driven attentional capture.

Discussion

As in Experiments 1 and 2, we found here that a peripheral distractor that matched the sought-for target color impaired identification of the target letter in the RSVP stream while a distractor matching the previously rewarded color in the same location had no effect. These results further confirm the inability of rewarded stimuli to capture attention when they appear in task-irrelevant locations. Importantly, the present experiment also included a measure of the effectiveness of value learning throughout the test phase. This measure revealed robust capture by the valuable color throughout the test phase when that color appeared in potentially relevant locations (for the search in the additional singleton task). Taken together the results reveal important limitations of the effects of value on attention.

Experiment 4

Value driven attentional capture is believed to be context dependent: Rewarded stimuli have been shown to capture attention only in contexts matching that of the prior learning experience (Anderson, 2014). This opens the possibility that our failure to find value-driven capture in Experiments 1–3 occurred because the RSVP task used in the test phases invoked a different context from the visual search task used in the training phases (or because RSVP tasks more generally are immune to effects of value-driven capture, but see below). Indeed, in most prior studies of value-driven capture, the test and training phases employed very similar visual search tasks. Nevertheless, a few previous studies have demonstrated the occurrence of value-driven capture in RSVP tasks. For example, Failing and Theeuwes (2015) and Le Pelley et al. (2017) presented a rapid series of scenes to participants and found that previously rewarded scenes significantly interfered with subsequent target scene detection. However, in those experiments the reward training also involved evaluation of scenes – permitting a similar context for both the training and test phases, unlike in the present experiments. To address this concern, we conducted an additional experiment very similar to Experiments 1–3, however here, instead of presenting the previously rewarded-color stimuli in task-irrelevant peripheral locations, we presented them centrally – in the form of a colored ring closely surrounding the RSVP stream of letters.If the reward value associated with the colored ring causes interference in the RSVP task, then that would indicate that our paradigm is indeed capable of revealing value-driven capture when the valuable colors are located in task-relevant locations.

Methods, results, and discussion

To reach the same projected sample size as in Experiment 1, data were collected from 66 undergraduate students. Fifty-five of them were included in the analyses using the same data-cleaning criteria as in Experiments 1–3. The value training phase was identical to that from Experiment 3. The RSVP test phase was the same as in Experiment 3, except that the four peripheral flankers were replaced with a centrally presented (distractor) ring (2.5 cm diameter, 2 mm outline thickness) surrounding the letter stream as shown in Fig. 8, with the ring presented equally often in the previously rewarded or previously non-rewarded color. The onset timing of the ring was the same as that of the flankers in Experiments 1–3: on one-half of the trials it was synchronized with the letter two frames preceding the target letter, and on the other half of the trials it was synchronized with the target letter.

The same data-cleaning method as in Experiments 1–3 was used, which resulted in 4.11% of the total trials removed from the training phase data and 3.34% from the test phase data. The RT results from the training phase are shown in Fig. 9 (left panel). The training phase showed a significant learning effect: The rewarded color received significantly faster responses (636 ms) than the non-rewarded color (655 ms), $t(54) = 3.290$, $p < .01$, $d = .444$. Accuracy during training was consistent with the RTs. Rewarded color (89.3%) led to slightly but not significantly higher accuracy than non-rewarded color (88.8%), $t(54) = .694$, $p = .490$, $d = .094$.

Accuracy results from the RSVP test phase are shown in Fig. 9 (right panel). An ANOVA revealed neither a main effect of distractor color nor of ring-target lag, for distractor

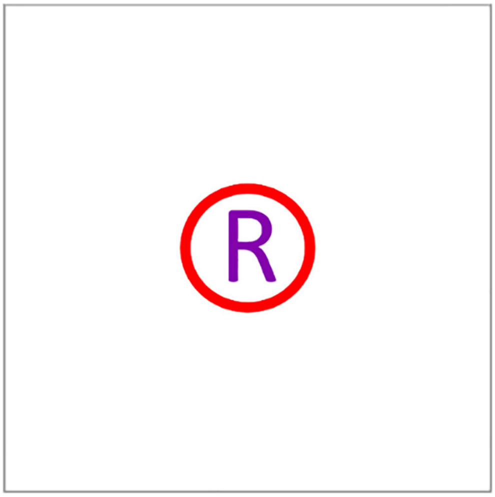

Fig. 8 Depiction of one frame of the RSVP task from Experiment 4: One letter of the stream surrounded by the central distractor ring. Elements are drawn to scale

color: $F(1, 54) = .072$, $p = .790$, $\eta^2_p = .001$; for lag: $F(1, 54) = 1.789$, $p = .187$, $\eta^2_p = .032$. Crucially, there was a significant interaction between the two factors, $F(1, 54) = 4.200$, $p = .045$, $\eta^2_p = .072$. Post hoc t-tests showed that a previously rewarded color ring significantly impaired accuracy in the 2-item lag condition (66.1%) compared to the no-lag condition (71.5%), $t\,(54) = 2.441$, $p = .018$, $d = .329$, but there was no effect of lag for the previously non-rewarded color ring (Lag 2: 68.8%; Lag 0: 68.0%), $t\,(54) = .327$, $p = .745$, $d = .044$. RTs in the RSVP task revealed no main effects for distractor color or lag (for distractor color: $F(1, 54) = 1.073$, $p = .305$, $\eta^2_p = .019$; for lag: $F(1, 54) = .069$, $p = .794$, $\eta^2_p = .001$), and no interaction between the two factors, $F(1, 54) = .104$, $p = .748$, $\eta^2_p = .002$.

To compare the distractive effect of rewarded colors presented at either task-relevant or task-irrelevant locations, we conducted a three-way mixed ANOVA on the RSVP task accuracy comparing Experiments 3 and 4 [within-subject factors: distractor color (previously rewarded or previously non-rewarded), lag (0 or 2); between-subject factor: experiment (Experiment 3 or Experiment 4)]. The analysis revealed no main effect of distractor color, $F(1, 83) = 1.096$, $p = .298$, $\eta^2_p = .013$, but a significant main effect of lag, $F(1, 83) = 4.652$, $p = .034$, $\eta^2_p = .053$, with overall performance poorer at lag 2. None of the two-way interactions between distractor color and lag, between distractor color and experiment, or between lag and experiment were significant, Fs < 1. But importantly, the three-way interaction between distractor color, lag, and experiment was significant, $F(1, 83) = 5.082$, $p = .027$, $\eta^2_p = .058$. The results confirm that previously rewarded colors captured attention in an RSVP task when presented at task relevant locations (Experiment 4), but not when presented at task irrelevant locations (Experiment 3).

The results of Experiment 4 show significant value-driven attentional capture in the RSVP task when the previously rewarded color appeared at a task-relevant location. This demonstrates that value associations learned in a visual search training phase can transfer to, and affect, identification of target letters in an RSVP task, further supporting our conclusion that the inability to find capture in Experiments 1–3 occurred because the distracting flankers there were presented in task-irrelevant locations.

General discussion

The reward history associated with a stimulus can serve as a powerful source of attentional bias in addition to other influences from bottom-up and top-down sources. However, no study to date has provided a rigorous examination of how a stimulus' spatial relevance to the task could moderate the strength of the effect. We showed here in three experiments that a value-associated stimulus was unable to capture attention when presented in a peripheral location irrelevant to the

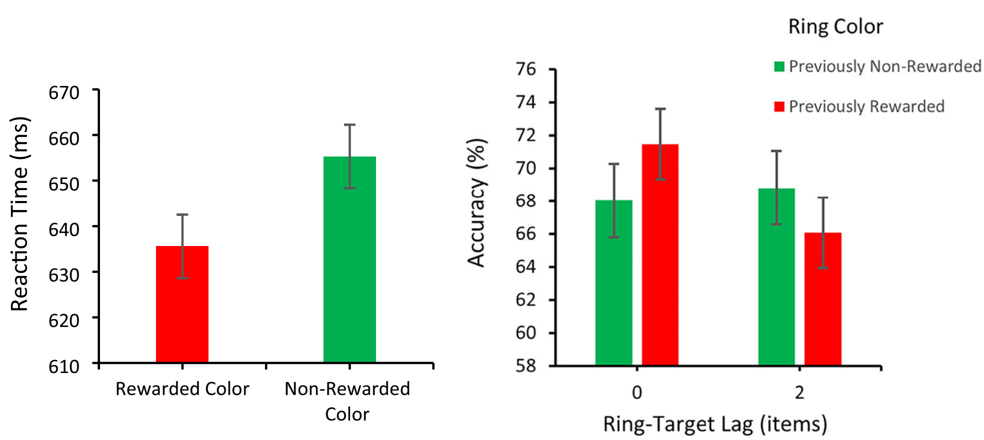

Fig. 9 Mean reaction time in the training phase (**left panel**) and mean accuracy in the test phase (**right panel**) from Experiment 4. Here the flanker was presented as a central ring closely surrounding the target letters in the RSVP task. Error bars indicate within-subject standard errors

participant's task, while a goal-relevant color in the same location did indeed capture attention. The results suggest that a previously rewarded stimulus only receives preferential selection when presented at a task-relevant location, differentiating value-driven capture from other forms of attentional prioritization.

Experiment 1 compared peripheral distractors that were either associated with reward, or that matched the task-relevant search goal. While the latter effectively attracted attention (as inferred from an impairment in identification of the central target letter), the former did not. Experiment 2 replicated those results and also included an additional condition in which the distractor matched the non-rewarded color that participants had also searched for during training. Neither the rewarded nor non-rewarded colors impaired performance on the central task, ruling out the possibility that the absence of the non-rewarded color in the test phase of Experiment 1 had prevented an effect of the reward-associated color. Experiment 3 replicated the findings from Experiment 2 and also provided evidence of the strength of the value training throughout the final test phase. Finally, Experiment 4 confirmed that the RSVP task used in the present experiments can induce value-driven attentional capture when the rewarded stimulus is presented at a task-relevant location.

Comparison to earlier studies

The present study differs in important ways from the few previous examinations of value-driven attention at task-irrelevant locations. In particular, by always presenting the target in the central letter stream in the RSVP task, the present experiments fully eliminated spatial uncertainty in attentional orienting. This offers some advantages over previous studies that manipulated top-down orienting but did not spatially segregate the distractor from the target (MacLean et al., 2016; Wang et al., 2015). And while those studies found that reward value continued to influence attention, we found an absence of value-driven capture. In addition, we showed here that the peripheral flanker that we used was indeed capable of capturing attention when its color matched the top-down goal (but not when it matched the previously valuable color). This eliminates a concern regarding the MacLean and Giesbrecht (2015a, 2015b) studies that the absence of an effect of value there might have stemmed from the rewarded stimuli being entirely perceptually excluded from the search.

One potential concern is that the present study might have failed to detect an effect of value because the RSVP task was highly attentionally demanding, which might have left little free resources for processing the value association of the peripheral stimuli. If this is true, the absence of value-driven attentional capture could be attributed to the demands of the primary task rather than to the distractor's task-irrelevant location. However, the significant effect of the top-down stimulus found in our experiments suggests that there were adequate resources available for processing features of the peripheral stimuli. In addition, Experiment 4 demonstrated significant value-driven capture when the rewarded stimulus was presented in a location adjacent to the central letter stream in an RSVP task similar to that of Experiments 1–3. Those results rule out the possibility that some unknown factor of the RSVP task prevented value-driven capture, further supporting the conclusion that the absence of capture was due to spatial task-irrelevance.

It is also worth noting that our conclusions may be qualified somewhat by the inherent ambiguity associated with null results. In particular, while it seems clear that value did not capture attention in the present experiments, it remains possible that more refined techniques in the future may indeed reveal effects of value even in task-irrelevant locations. Nevertheless, it is clear that the effects of value in such locations, if any, are substantially weaker than effects of top-down-goal relevance.

Relation between value-driven attention and top-down attention

Reward history has been thought to guide attention independently of top-down goals. Several studies provided aversive consequences for attending to rewarded stimuli, and still observed value-driven attentional capture under a conflicting goal to ignore them (le Pelley et al., 2015; Pearson et al., 2015, 2016). Other studies demonstrated different time courses for value-driven and goal-driven attention (Hickey & van Zoest, 2012). These findings suggest a distinction between value-driven and top-down attentional control – one source of bias functions independently of the another.

However, the findings of the present study that the effect of reward is contingent on spatial task relevance suggest that value-driven influences may not be fully independent of volitional control. Similar to preferential selection of task-relevant visual features, spatial selection of locations that contain potential target stimuli is also top-down in nature. The present study presented the previously rewarded stimuli at a peripheral location at a distance away from the central target location, excluding any intentional effort in selecting the location. An absence of distractive effect at that location reveals a key limitation of reward-based visual guidance: Rewarded stimuli do not bias attention automatically but require the observer's active selection of the stimulus location. This refines our understanding of the relation between value-driven and top-down attentional control, suggesting that while the effect of reward may counteract top-down featural selection, it is actually contingent upon top-down spatial selection of the rewarded stimuli.

Implications for effects of selection history

Our results may also have implications for the attentional prioritization of features of previously selected targets. Such *selection history* effects reveal that even in the absence of reward, selected targets from past episodes that are neither salient nor related to top-down goals can create lingering attentional biases (Kyllingsbæk et al., 2001, 2014; Lin et al., 2016; Qu et al., 2017; Shiffrin & Schneider, 1977). The value-associated color in all of our experiments, and the non-rewarded color in Experiments 2–4 might have been expected to attract attention simply by virtue of the fact that they had been repeatedly selected in the earlier training phase. We did find limited support for such an effect based on the Bayesian analyses in Experiments 2 and 3, but the impact of selection history was clearly very weak compared to the effects of the goal-relevant color. More work will be necessary to confirm the findings, but the very limited effects of selection history that were observed suggest that even though value-driven attention and selection history are believed to develop through different learning mechanisms (Anderson, 2014; Anderson et al., 2017; Anderson & Britton, 2019; H. Kim & Anderson, 2019), the two influences may share the property of being ineffective when stimuli appear in task-irrelevant peripheral locations.

Relation to effects of stimulus-driven capture

Several previous studies have shown that salient stimuli may sometimes fail to capture attention (or may only weakly capture attention) when presented at task-irrelevant locations (e.g., Yantis & Jonides, 1990; but see Christ & Abrams, 2006), while goal-matching stimuli continue to robustly capture attention even when in task-irrelevant locations (e.g., Du & Abrams, 2008; Folk et al., 2002; Huang et al., 2016). In light of that, our results may reveal some similarities between capture by salient stimuli and capture by valuable stimuli because effects of both types of stimuli can be modulated by spatial task relevance, and in that sense, our conclusions may not apply uniquely to the attentional effects of value.

Conclusion

The present study shows that previously rewarded stimuli fail to attract attention when presented at a task-irrelevant peripheral location while goal-matching stimuli in the same location do capture attention. The results reveal a new way in which top-down goals (spatial expectations, in this case) can influence value-driven attentional capture, showing a fundamental way in which the effects of stimulus value on attention are distinct from other top-down influences and placing important constraints on models of attentional selection. Given that multiple attentional influences are often in play during many demanding real-world activities, more work on the interactive effects of such influences may lead to a better understanding of the underlying attentional mechanisms.

Data availability The data and materials for all experiments are available via the Open Science Framework and can be accessed at https://osf.io/xpm4v/. None of the experiments was preregistered.

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