

Reward associations and spatial probabilities produce additive effects on attentional selection

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Abstract Recent studies have shown that reward history acts as a powerful attentional bias, even overcoming top-down goals. This has led to the suggestion that rewards belong to a class of attentional cues based on selection history, which are defined by past outcomes with a stimulus feature. Selection history is thought to be separate from traditional attentional cues based on physical salience and voluntary goals, but there is relatively little understanding of how selection history operates as a mechanism of attentional selection. Critically, it has yet to be understood how multiple sources of selection history interact when presented simultaneously. For example, it may be easier to find something we like if it also appears in a predictable location. We therefore pitted spatial probabilities against reward associations and found that the two sources of information had independent and additive effects. Additionally, the strength of the two sources in biasing attentional selection could be equated. In contrast, while a nonpredictive but perceptually salient cue also exhibited independent and additive effects with reward, reward associations dominated the perceptually salient cue at all levels. Our data indicate that reward associations are part of a class of particularly potent attentional cues that guide behavior through learned expectations. However, selection history should not be thought of as a unitary concept but should be understood as a collection of

independent sources of information that bias attention in a similar fashion.

Keywords Attention · Reward · Spatial probability · Selection

Introduction

At any moment, our sensory environment contains more information than we can process. Therefore, we rely on mechanisms of attention to select and prioritize sources of information according to their importance. Importance has traditionally been defined in two ways: through an observer's voluntary goals (e.g., red things when searching for an apple to eat) or through the perceptual salience of stimuli (e.g., flashing billboard lights) (Corbetta & Shulman, 2002; Desimone & Duncan, 1995; Egeth & Yantis, 1997; Horowitz & Wolfe, 1998; Itti & Koch, 2000; Posner, 1980). However, it has recently been suggested that there is a third class of attentional cues, based on a feature's selection history (Awh, Belopolsky, & Theeuwes, 2012; Chelazzi, Perlato, Santandrea, & Della Libera, 2013). Selection history is defined by past outcomes (e.g., rewards associated with a stimulus color or the spatial probability of a target's location) and is particularly interesting as an attentional cue because it has been shown to override traditional voluntary- and salience-based attentional control (Anderson, Laurent, & Yantis, 2011b; Geng & Behrmann, 2005; Hickey & van Zoest, 2013; Jiang, Sigstad, & Swallow, 2012; Jiang, Swallow, & Sun, 2013). However, despite recent interest in the mechanisms of selection history juxtaposed against traditional top-down and bottom-up selection, it is almost entirely unknown how multiple sources of information are integrated when they occur simultaneously. In this study, we attempt to do so by examining the consequences

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of attentional capture by known reward associations when an implicit spatial probability, or sensory salience, is introduced.

Object features that have learned reward associations are assigned high attentional priority and frequently override selection based on voluntary- and salience-based cues (Anderson et al., 2011b; Della Libera & Chelazzi, 2006; Della Libera, Perlato, & Chelazzi, 2011; Hickey, Chelazzi, & Theeuwes, 2010; Kiss, Driver, & Eimer, 2009; Krebs, Boehler, Egnér, & Woldorff, 2011; Kristjánsson, Sigurjónsdóttir, & Driver, 2010; Lee & Shomstein, 2013; Peck, Jangraw, Suzuki, Efem, & Gottlieb, 2009; Raymond & O'Brien, 2009). For example, the presence of a salient distractor interferes with visual search more when it was previously associated with monetary reward, as compared with the same salient distractor without previous reward associations (Anderson, Laurent, & Yantis, 2011a). Similarly, a color oddball target will be detected more quickly when it is associated with reward (Kiss et al., 2009; Kristjánsson et al., 2010). Correspondingly, a stimulus feature (e.g., color or shape) that is perceptually nonsalient will begin to capture attention when associated with reward and will continue to capture attention even when the reward contingencies have ceased or become task irrelevant (Anderson & Yantis, 2012, 2013; Anderson et al., 2011a, 2011b; Della Libera & Chelazzi, 2009). Thus, learned reward associations appear to be consistently assigned the highest attentional priority and be difficult to extinguish. Interestingly, reward associations are often explicitly learned and reinforced across many trials, suggesting that the robustness of reward cues may be due to combined expectancies from top-down goals and historical reinforcement.

Similar to rewards, statistical regularities are a form of selection history that biases attention toward stimuli that have produced positive outcomes in the past. The positive outcomes in these studies typically involve increased efficiency and accuracy in task performance (e.g., finding a visual search target more rapidly), rather than explicit monetary reward. For example, visual search targets are found faster when their location is probabilistically higher in a specific location or a region of space or relative to a configuration of objects (Chun & Jiang, 1998; Druker & Anderson, 2010; Fecteau, Korjoukov, & Roelfsema, 2009; Geng & Behrmann, 2002, 2005; Hoffmann & Kunde, 1999; Jiang, Swallow, & Sun, 2013; Miller, 1988). Spatial probabilities are similar to reward associations in that they are learned rapidly, take a long time to extinguish after becoming task irrelevant (Geng et al., 2013; Jiang, Swallow, & Rosenbaum, 2013; Jiang, Swallow, Rosenbaum, & Herzog, 2013) and outcompete salient stimuli for attentional priority (Geng & Behrmann, 2005). However, spatial probabilities do not require explicit knowledge to learn and are often implicit even after priority is clearly established (Chun & Jiang, 1998; Druker & Anderson, 2010; Geng & Behrmann, 2002, 2005; Miller, 1988). Thus, statistical

regularities have a similar profile on attentional processing as reward associations: Both appear to involve a form of attentional control distinct from traditional voluntary- and salience-based mechanisms yet have a profound impact on information selection.

Despite strong evidence that both reward associations and spatial probabilities act as attentional cues, there is little information about how the two types of information should interact to control attention. For example, if all sources of information impact attentional control through a single mechanism, having multiple such sources should produce interactive effects on behavior. However, if the effect of reward associations and spatial probabilities originate from independent sources that contribute to attentional control at different stages of processing, we might expect additive effects (Sternberg, 1967, 1969). An additive profile would be particularly interesting because it would suggest that selection history includes distinct sources of information that operate on attentional selection at multiple stages of processing and yet produce similar consequences on attentional selection. This type of reasoning has been used extensively to characterize the relationship between voluntary and salience-based attentional control (Chica, Bartolomeo, & Lupiáñez, 2013; Jonides, 1981; Müller & Rabbitt, 1989; Pinto, van der Leij, Sligte, Lamme, & Scholte, 2013) and is important for situating reward associations and spatial probabilities within the taxonomy of attentional control mechanisms.

There are reasons to think that reward associations and spatial probabilities could be additive or to think that they would interact. Predictions for additivity come from evidence that the two types of information have separate neural sources (Knutson & Cooper, 2005; Krebs et al., 2011; Leathers & Olson, 2012). Although information from these neural sources might converge (e.g., sum in a shared priority map), the impact could also be at different stages of processing, since the reward association is based on one feature (i.e., color) and the target probability on another (i.e., spatial location). On the other hand, rewards and spatial probabilities have similar profiles on behavior (see above) and are often combined into a single quantity, called *expected value* (EV), in the decision-making literature (Dorris & Glimcher, 2004; Platt & Glimcher, 1999; Sugrue, 2004; Sugrue, Corrado, & Newsome, 2005; see also Raymond & O'Brien, 2009, for studies using EV in the attention literature). EV is calculated by the multiplication of reward quantity and probability of reinforcement (Arnauld & Nicole, 1662/1996; Pascal, 1670/1966; for a review, see Glimcher, 2003). If attentional priority in our study relies on a similar mechanism as described within the decision-making literature, the data should be predicted by the multiplication of the known reward value and the strength of the spatial probability. In contrast, an additive profile would suggest that reward value and target spatial probability are independent sources of information that guide attention in our study.

To anticipate our results, we found that the effect of attentional capture by a reward-associated stimulus was additive with facilitation from spatial probabilities, across varying strengths of probabilistic evidence. We then investigated whether a similar profile of additivity would be found when reward associations were combined with a physically salient but uninformative spatial cue (Egeth & Yantis, 1997; Müller & Rabbitt, 1989; Posner, 1980); we again found that the relationship was additive, with rewards always having a larger effect on performance. Together, the results provide novel evidence that reward associations and spatial cues produce additive effects on attention, irrespective of whether the source of the spatial cue lies in implicitly learned probabilities or exogenous cuing.

Experiment 1

The purpose of Experiment 1 was to test whether two sources of information, in the form of target spatial probabilities and a learned association between target color and monetary reward, would have an interactive or additive effect on attentional control. To do this, we kept the reward associations constant and varied the strength of the target spatial probability over time (Fig. 1a, b). If the two sources of information interact, the magnitude of attentional facilitation for the rewarded feature should change as the strength of the probability increases. However, if the effects are independent, the effect of reward should be constant over changing spatial probability.

Method

Participants

Twenty-one participants were recruited from the University of California, Davis. All had normal or corrected-to-normal vision. Participants received partial course credit and monetary payout based on task performance (mean = \$11.25). Informed consent was obtained in accordance with the University of California, Davis Institutional Review Board. Data from 5 individuals were excluded due to incomplete data sets (e.g., due to time constraints), and data from 4 individuals were excluded due to poor central fixation (e.g., due to multiple recalibrations during a block or excessive difficulty initiating a trial by holding central fixation), resulting in analysis of data from 12 participants (7 males; mean age = 21.08 years; age range = 18–27; 12 right-handed). One subject refused the monetary payout at the end of the study but was not excluded.

Apparatus

An Intel® Core™ i7 equipped with Presentation software (Version 14.9; <http://neurobs.com>) was used to present the

stimuli on a Dell 2408WFP monitor. The participants viewed the monitor from a distance of ~60 cm in a dimly lit room. Responses were entered using a standard 101-key US layout keyboard. Eye position data for each participant was collected using an EyeLink1000 version 4.56 (SR Research, Canada; sampling rate = 500 Hz).

Stimuli

The general sequence of events for the target discrimination task is shown in Fig. 1a. Cue stimuli were colored circles (orange, 25.9 cd/m²; or green, 25.7 cd/m²; 1.62° × 1.62° visual angle) presented centrally in the baseline or bilaterally in the target discrimination task (each 5.30° visual angle from the center of the screen; see Fig. 1a). Targets were a single black dot (0.38° × 0.38°) added above or below the horizontal meridian of the cue circle. In the target discrimination task, the center-to-center vertical distance of the target dot from fixation was 5.09° of visual angle. Distractors were identical to targets, but the dot was to the left or right of the vertical meridian (i.e., a 90° rotation of the target). The feedback display consisted of white text (“+0.04” or “+0.00”) presented 1.05° above a central fixation cross and informed participants of the reward earned on that trial.

Design and procedure

During the baseline task, participants were acquainted with the task and the color–reward pairings. Each trial was initiated only if 100 ms of continuous central fixation was detected. Each trial began with a single centrally presented fixation cue (“+”) for a randomly jittered duration from 350 to 450 ms, after which the target appeared for 200 ms. Participants made the forced choice target identification by pressing the k (“above”) or m (“below”) keys with their right middle and index fingers, respectively. Response times (RTs) were measured from the onset of the target display. Responses were followed by a feedback screen for 1,000 ms that indicated the amount of reward gained (i.e., reward = \$0.04; no reward = \$0.00). The intertrial interval lasted 800–1,200 ms. Each color was presented in a pseudorandom fashion. The color–reward pairings were randomly assigned and counterbalanced across participants. The baseline task consisted of 144 trials, and participants were given a break every 72 trials. Knowledge of the color–reward contingencies was verbally assessed at the beginning and end of the baseline task.

The target discrimination task was identical, except that the cue and target screens were composed of one orange and one green circle presented bilaterally. The target was randomly assigned to either the left or the right circle, and a distractor was in the opposite location. The target (above, below) and distractor (left, right) locations were randomly assigned on each trial. Additionally, a parametric manipulation of target

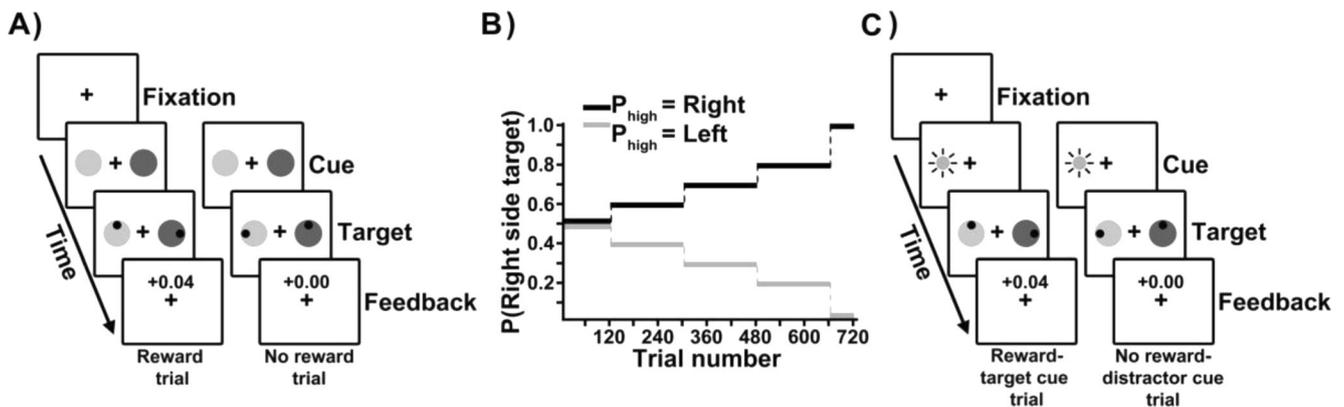


Fig. 1 **a** Illustration of the trial procedure for the target discrimination tasks for Experiment 1. Cue circles are shown in light gray and dark gray to illustrate rewarded and nonrewarded cue colors, respectively, which were green and orange in the actual paradigm. **b** Parametric manipulation of spatial probability in Experiment 1. Participants were assigned to one of two target side high-probability groups, right or left. Staircase shown

above indicates the flow of the task through blocks where the target becomes increasingly likely to fall to one side. **c** Illustration of the basic trial procedure for the target discrimination task for Experiment 2. Note the main difference is the substitution of the cue screen from Experiment 1 with a cue screen that includes a salient flash at one side of the screen

spatial probability was introduced in the discrimination task (Fig. 1b). The experiment consisted of five blocks where the spatial probability of the target at the *high-probability* location was: .5, .6, .7, .8, and 1.0. The target appeared in the opposite *low-probability* location on the remaining proportion of trials. Note that the “high-” and “low-”probability locations in the .5 block were defined on the basis of their status in later blocks. No information about the block structure was given to participants. The high-probability location (left, right) was counterbalanced between participants. There were 720 total trials in the target discrimination task, with a break every 60 trials. There were 120, 180, 180, 180, and 60 trials in each of the probability blocks, respectively, to maximize sampling of low-spatial-probability trials.

Within each probability block, the design was given by the factorial crossing of two target features: reward (\$0.04 or present, \$0.00 or absent) and spatial probability (high, low). This resulted in two conditions where the factors were congruent and two where they were incongruent. In the congruent conditions, the target had the rewarded color and was in the high-probability location or had the nonrewarded color and was in the low-probability location ($R_{\text{present}}P_{\text{high}}$, $R_{\text{absent}}P_{\text{low}}$). In the incongruent conditions, the target either had the rewarded color and occurred in the low-probability location or had the nonrewarded color and appeared in the high-probability location ($R_{\text{present}}P_{\text{low}}$, $R_{\text{absent}}P_{\text{high}}$). Importantly, the locations of the reward-present and reward-absent colors were randomly assigned on each trial, and this assignment was orthogonal to the location of the target. Thus, the cue circle color did not predict the location of the target.

Participants were told that responses must be made within 1,000 ms to be deemed correct. Correct responses within 1,000 ms to targets in the rewarded color were followed with reward feedback (\$0.04). All responses to nonrewarded

targets were followed with a reward-absent feedback display (\$0.00). Incorrect or slow responses to rewarded targets were also followed with a reward-absent feedback display. During the breaks, participants were informed of the amount of money earned during the previous block of trials, as well as the total amount earned. Participants were rewarded on a 1.5:1 scale (i.e., \$1.50 in the task equaled an actual payout of \$1.00).

All participants were given written and oral descriptions of the tasks. Participants were instructed that no rewards would be given for responses that were too slow and that they should try to respond as quickly and accurately as possible. Each participant was tested individually over the course of a single 1.5-h session.

Participants were asked three questions at the end of the experiment to assess their knowledge of the implicit spatial probability manipulation. The questions were the following: (1) Did you notice anything about the task? (2) Did you notice anything about where the targets fell? and (3) If you had to guess, which side do you think the target would fall on a given trial?

Analysis

Only correct answers with RTs less than two *SDs* above or below the individual’s condition mean were included for analysis. We included correct trials where the participants responded too slowly (i.e., $RT > 1,000$ ms) and were thus given no-reward feedback regardless of cue circle color–reward pairing. Our rationale for keeping these trials in was that, at the time of the buttonpress, the participants did not know with absolute certainty whether their response was too slow to receive a reward and we are interested in the effects of reward on attentional selection, not on feedback processing. Trials where participants did not hold central fixation were also

excluded (average number of trials excluded was less than 3 % in each experiment).

Results

Baseline task

There was no effect of reward on RT ($\$0.04$, $M = 473.89$ ms; $\$0.00$, $M = 455.60$ ms), $t(11) = 0.90$, $p = .39$, or accuracy ($\$0.04$, $M = .99$; $\$0.00$, $M = .99$), $t(11) = 0.29$, $p = .77$. Perceptual processing of the rewarded and nonrewarded stimuli was similar when the stimuli were centrally presented on their own and there was no competition for attention.

Target discrimination task

Additive versus multiplicative effects of reward and spatial probability To understand the effects of reward and spatial probability on attentional selection, RT and accuracy data from the target discrimination task were entered into random-effects ANOVAs with the factors reward (present, absent), spatial probability (high, low), and block (.5, .6, .7, .8). Data from the 1.0 block were excluded from the analysis because it lacked low-probability targets. The spatial probabilities for targets in the .5 block were assigned on the basis of future probability (i.e., high or low in the uneven probability blocks).

Significant main effects from the RT analysis were observed for reward, $F(1, 11) = 36.65$, $p < .0001$, spatial probability, $F(1, 11) = 21.64$, $p < .001$, and block, $F(3, 33) = 7.22$, $p < .001$. RTs were shorter to rewarded than to nonrewarded targets and to high- than to low-probability targets, and RTs became shorter as the task progressed [i.e., a pairwise t -test showed that RTs were significantly different in the .5 vs. .8 block overall: $t(11) = 6.20$, $p < .0001$]. There was also a significant two-way interaction between probability and block, $F(3, 33) = 23.90$, $p < .0001$, indicating that RTs decreased as the strength of the spatial probability cue increased over the course of the task (Fig. 2a, b).

In contrast, neither of the interactions involving reward value and probability or reward value and block was significant. The two-way interaction between reward and block was not significant, $F(3, 33) = 1.61$, $p = .21$; the difference in RTs to high- versus low-rewarded targets was constant across blocks even though the spatial probability changed (Fig. 2a, c). The two-way interaction between reward and probability, $F(1, 11) = 1.41$, $p = .26$, was also not significant, demonstrating that the attentional benefit associated with the high-probability location did not change as a function of the target's reward value, and the benefit associated with the rewarded color was also unaffected by the target's location. Finally, the three-way interaction between reward, probability, and block also was not

significant, $F(3, 33) = 1.61$, $p = .21$. These results were consistent with an additive effects profile and indicated that reward and probability did not interact: The effect of reward was constant and provided an additional RT advantage for every level of probability, even as the strength of the spatial probability increased (Fig. 2c). Conversely, the RT difference between targets in the low- and high-probability locations increased as the strength of the probability increased, but this was not affected by reward value.

Accuracy was high during the target discrimination task ($M = .93$), and there were no significant main effects for reward, $F(1, 11) = 1.02$, $p = .33$, or spatial probability, $F(1, 11) = 0.38$, $p = .55$. There was a significant main effect of block, $F(3, 33) = 3.56$, $p < .05$, that showed higher accuracy as the task progressed (accuracy in .5 block, $M = .90$; .8 block, $M = .95$). However, none of the pairwise comparisons survived Bonferroni correction for six comparisons, all $t_s(11) < 2.3$, all $p_s > .25$. There were no significant two-way interactions, all $F_s(3, 33) < 1.2$, all $p_s > .35$, but there was a significant three-way interaction between reward, probability, and block, $F(3, 33) = 3.87$, $p = .018$. This result was driven by lower accuracy in the $R_{\text{absent}}P_{\text{low}}$ condition ($M = .90$), as compared with the other three conditions ($R_{\text{absent}}P_{\text{high}}$, $M = .94$; $R_{\text{present}}P_{\text{high}}$, $M = .95$; $R_{\text{present}}P_{\text{low}}$, $M = .96$) in the .7 block, but this effect did not survive Bonferroni correction for four comparisons.

Competition between incongruent conditions In the previous analysis, we found that the overall effect of probability and reward on attention were additive (i.e., they did not interact). However, in order to better understand how competition between these two sources of information might resolve when they are in conflict, we conducted an additional analysis that included only the conditions where spatial probability and reward were incongruent (i.e., $R_{\text{absent}}P_{\text{high}}$, $R_{\text{present}}P_{\text{low}}$). On these trials, information from the spatial probability and the reward association favored opposite locations. Because the effect of reward was fixed over blocks (see above) but the effect of spatial probability increased over blocks, we wished to determine when the strength of the high-spatial-probability target (with no reward) would produce similar RTs to low-spatial-probability targets (with reward).

To do this, we conducted post hoc paired t -tests of RTs in the two incongruent conditions over each block. RT differences were significant in the .5, $t(11) = 4.15$, $p = .002$, and .6, $t(11) = 4.02$, $p = .002$, blocks, but not in the .7, $t(11) = 1.68$, $p = .12$, and .8, $t(15) = 0.12$, $p = .86$ blocks (the comparisons in the .5 and .6 blocks were significant with Bonferroni correction for four comparisons). These data suggest that the strength of the spatial probability in biasing attention to the more likely location "caught up" with that of the reward association when it was approximately 70 %–80 % predictive in this study. Note that the advantage of reward did not change over blocks (compare dotted lines in Fig. 2a), but

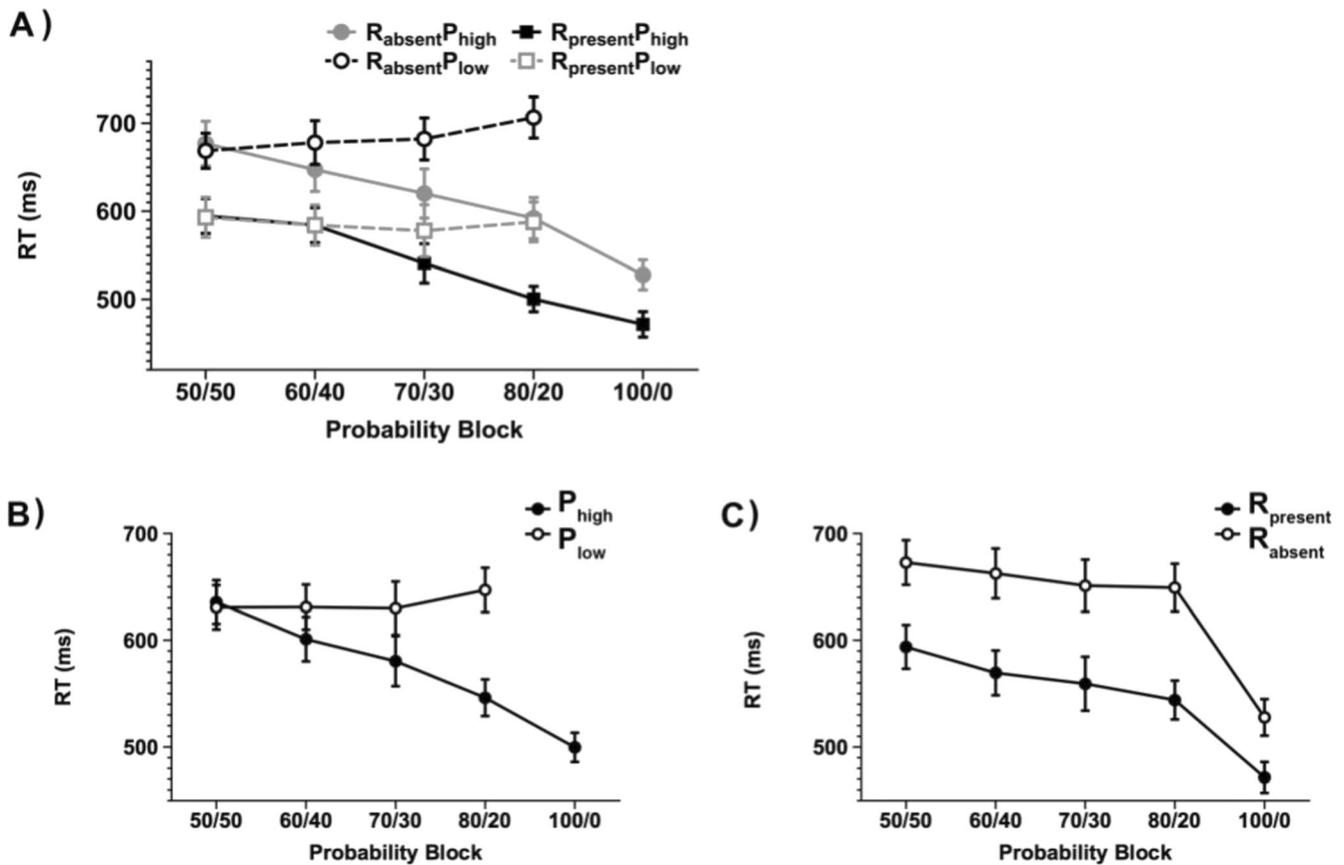


Fig. 2 Interaction between reward, spatial probability, and block from the target discrimination task in Experiment 1. **a** The gray lines are data from the incongruent conditions of interest. In the early blocks, shorter response times (RTs) are seen for the $R_{\text{present}}P_{\text{low}}$ condition (open squares), but as the strength of probability increases in the $R_{\text{absent}}P_{\text{high}}$ condition (closed circles), RTs become shorter and a point of subjective equality is reached between blocks .7 and .8. The black lines are data from congruent trials, where the shortest RTs occur in the $R_{\text{present}}P_{\text{high}}$

condition (closed squares) and the longest RTs in the $R_{\text{absent}}P_{\text{low}}$ condition (open circles). Panels b and c illustrate two-way interactions present within the larger three-way interaction from panel a. **b** An increase in the strength of the probability manipulation (closed circles) resulted in shorter RTs. There was no effect of a decrease in the strength of the probability manipulation (open circles) on RTs. **c** There was a constant effect of rewarded (closed circles) and nonrewarded (open circles) targets across the probability blocks. Error bars are *SEMs*

there was an increase in attentional facilitation for the high-probability location as the strength of that information increased over blocks (see solid lines in Fig. 2a). This result highlights the fact that the attentional bias to the rewarded feature did not change as a function of the spatial probability even when they were in competition with each other; in contrast, there was an independent increase in attentional bias toward the high-probability location commensurate with the strength of that cue.

Intertrial priming Our manipulation of spatial probability involved increasing the frequency of targets in a particular spatial location. Repetitions of target features (e.g., spatial location, color, shape, etc.) are also known to facilitate performance (Kristjánsson & Campana, 2010). Facilitation from repetition priming can interact with probability manipulations in two ways. First, the size of repetition priming may accumulate with the number of consecutive repetitions, resulting in greater priming with an increasing number of targets in the

same place (Maljkovic & Nakayama, 1994). Second, even if the size of repetition priming remains fixed for any pair of trials, the number of such repetitions in the high-probability location would increase with probability. Both of these possibilities predict an increasing repetition benefit with increasing probability.

To examine the contribution of repetition priming to our spatial probability manipulation, we examined RTs as a function of repetition priming (no-rep, rep) in two ways. First, we compared RTs for high-probability targets as a function of block. The data were entered into a random-effects ANOVA with the factors repetition (yes, no) and spatial probability (.5, .6, .7, .8). If the effect of spatial probability interacts with repetition priming, we would expect greater facilitation for repetitions in blocks with more frequent repetitions (i.e., .7 and .8, as compared with .5 and .6). There were main effects of both repetition, $F(1, 11) = 33.06, p = .001$, and spatial probability, $F(3, 33) = 16.66, p < .001$, which indicated a larger

decrease in RTs for repeated, as compared with nonrepeated, targets and an overall speeding in RTs as the strength of probability increased. Importantly, there was no interaction between repetition and spatial probability, $F(3, 33) = 0.908$, $p = .45$.

For the second analysis, we conducted another repeated measures ANOVA with factors of repetition (no-rep, rep) and probability (low, high). If repetition priming accounted entirely for the RT benefit to high-probability targets, we would have expected a greater difference between repetition and no-repetition trials in the high-probability location, as compared with the low-probability location. However, in contrast, the significant interaction was actually driven by a larger repetition priming effect in the low-probability location, as compared with the high, $F(1, 11) = 14.13$, $p < .005$. There was also again significant main effects of repetition and probability, $F(1, 11) = 49.5$, $p < .001$, and $F(1, 11) = 16.53$, $p < .005$, respectively.

Thus, while it is clear that intertrial priming improved behavioral performance (Kristjánsson & Campana, 2010) and that learning of probabilities may well involve mechanisms of repetition priming, the magnitude of priming in the high-probability location did not depend upon the advantage conferred by repetition priming alone. Thus, it is unlikely that priming alone could be the sole source of behavioral facilitation for high-probability targets across blocks, even though spatial probability and priming are both important forms of information that work together to shape selection history and attentional selection.

Postexperiment interview During our postexperiment interview, which immediately followed the 1.0/0 block when targets occurred only at the high-probability side, only 1 participant successfully guessed that the targets were progressively more likely to fall at one location. Participants were at chance in identifying the likely target side on a hypothetical upcoming trial (left or right; 6 of 12 participants were correct) further supporting the finding that implicit spatial probability information modulates behavior even in the absence of explicit knowledge.

Experiment 2

The results from Experiment 1 suggested that spatial probabilities had an independent effect on attentional selection from that of reward associations. Moreover, in the .7 block, RTs in the two incongruent conditions (i.e., where probability and reward biased attention to opposite locations) were equivalent, suggesting that the two sources of information exerted an equally strong bias on attentional selection. In Experiment 2, we used a task-irrelevant spatial cue to better understand how spatial

cuing interacts with reward processing when the spatial cue was perceptually salient but nonpredictive. We expected that rewards and the exogenous spatial cue would produce additive effects similar to those in Experiment 1 but that the strength of the spatial cue might not reach that of the rewarded feature because, unlike spatial probabilities, the cue here provided no task-relevant information.

Method

Participants

Eighteen participants were recruited from the University of California, Davis. All had normal or corrected-to-normal vision. Participants received partial course credit and monetary payout based on performance (mean = \$8.80). None had participated in the previous experiment. Informed consent was obtained from participants in accordance with the local Institutional Review Board. Data from 3 individuals were incomplete, and 3 individuals were unable to maintain central fixation, resulting in analysis of data from 12 participants (5 males; mean age = 20.5 years; age range = 18–23; 11 right-handed).

Design and procedure

The baseline task was identical to that in the previous experiment, with the exception that an exogenous cue was presented 50, 100, or 150 ms prior to the central stimulus, meaning that the cue screen of Experiment 1 was replaced with a salient cue. There were a total of 120 trials, with breaks every 60 trials. The target discrimination task was also identical to that in the previous experiment but now included a parametric manipulation of perceptual salience, instead of a parametric manipulation of spatial probability. The task consisted of 480 trials, with breaks every 60 trials (Fig. 1c). On each trial, a perceptually salient flash (i.e., a standard exogenous cue) lasting 50 ms validly or invalidly cued the target by 50, 100, or 150 ms. The location of the exogenous cue at either location was randomly determined on each trial. The exogenous cue was a grayscale colored circle ($1.05^\circ \times 1.05^\circ$) presented 5.30° from central fixation and had one of four luminance (i.e., saliency) values that spanned black (i.e., absent) to white: high (250.33 cd/m^2), medium (57.93 cd/m^2), low (4.19 cd/m^2), or absent. Brighter objects have been shown to be more perceptually salient and produce stronger attentional capture (Wright & Richard, 2003), and we hypothesized that there may be increasing attentional capture with the brighter cue; however, since the cue occurred on an otherwise black screen, it may also have maximal capture at the lowest value.

Results

Baseline task

RT and accuracy data from the baseline task were entered into random-effects ANOVAs with factors of reward (present, absent) and cue saliency (absent, low, medium, high). A significant effect was observed for cue saliency, $F(3, 33) = 4.80$, $p = .007$. Pairwise comparisons showed that participants were faster to respond to targets preceded by the low and high exogenous cues, as compared with the absent or medium cues, all $t(11) > 4.23$, all $ps < .002$, with Bonferroni correction for six comparisons; all other comparisons, $t(11) < 2.20$, all $ps > .3$. Consistent with the baseline data in the first experiment, there were no significant effects of reward ($\$0.04$, $M = 563.77$ ms; $\$0.00$, $M = 579.84$ ms), $F(1, 11) = 3.21$, $p = .10$, or the interaction between reward and cue saliency, $F(3, 33) = 2.40$, $p = .09$.

Accuracy was high, and there was no main effect reward ($\$0.04$, $M = .991$; $\$0.00$, $M = .984$), $F(1, 11) = 0.68$, $p = .43$, nor a main effect of saliency, $F(3, 33) = 0.81$, $p = .50$, nor an interaction between reward and cue saliency, $F(3, 33) = .26$, $p = .85$.

Target discrimination task

Similar to Experiment 1, RT and accuracy data were entered into separate random-effects ANOVAs with factors of reward (present, absent), cued object (target, distractor), and cue saliency (low, medium, high). Significant main effects were observed for reward, $F(1, 11) = 39.56$, $p < .0001$, and cued object, $F(1, 11) = 14.78$, $p = .003$ (Fig. 3). The main effects were expected and showed shorter RTs to the rewarded target, as compared with the nonrewarded targets, and shorter RTs when the target was the cued object. There was no significant main effect of cue saliency, $F(2, 22) = 1.85$, $p = .18$, suggesting that even the dimmest exogenous cue was maximally effective in capturing attention. This was likely due to the exogenous cue occurring on an otherwise black screen with only a fixation cross.

The only interaction that was even marginally significant was between reward and cue saliency, $F(2, 22) = 4.38$, $p = .06$. The interaction was due to a slightly larger saliency effect in the rewarded, as compared with the nonrewarded, targets, but only at the highest cue saliency (i.e., white); the effect size of this marginal interaction was small and nonspecific to the location of the cue (preceding the target or distractor) and, therefore, likely to be due to an overall alerting effect than to attentional selection. Additional pairwise comparisons demonstrated that RTs were significantly shorter to rewarded than to nonrewarded targets across all cue saliency levels, all $t(11) > 4.33$, all $ps < .004$, with Bonferroni correction for three comparisons. None of the other interactions were significant, all $Fs < 1.26$, $p > .30$. In particular, there were not

interactions that involved the location of the exogenous cue and the reward-associated target. This suggests, as in Experiment 1, that the spatial cue and the reward cue did not interact.

Next, as in Experiment 1, we conducted an additional ANOVA on just the two incongruent conditions ($R_{\text{present}}C_{\text{distractor}}$, $R_{\text{absent}}C_{\text{target}}$) and cue saliency (low, medium, high) in order to identify the relative strength of each cue when in competition with the other. There was no significant interaction, $F(2, 22) = 0.26$, $p = .77$: In contrast to the results from Experiment 1, there was no point at which performance based on the salient cue was equal with performance on rewarded targets (see Fig. 3). RTs were always shorter to rewarded targets, irrespective of cue saliency, suggesting that the reward association always dominated attentional priority when the spatial cue was uninformative.

Consistent with the RT data, there was a significant effect of reward on accuracy, $F(1, 11) = 8.18$, $p = .016$. Participants had higher accuracy on rewarded ($M = .98$) than on nonrewarded ($M = .96$) targets. There were no other significant effects in accuracy, all $Fs < 1.77$, all $ps > .21$. Together, the results suggest that the effects of reward and an exogenous spatial cue were additive and independent but that the exogenous spatial cue was weaker than reward.

Discussion

The purpose of these experiments was to understand how attentional priority is set when multiple sources of information are present. In these experiments, we compared learned reward associations and spatial probabilities as classes of

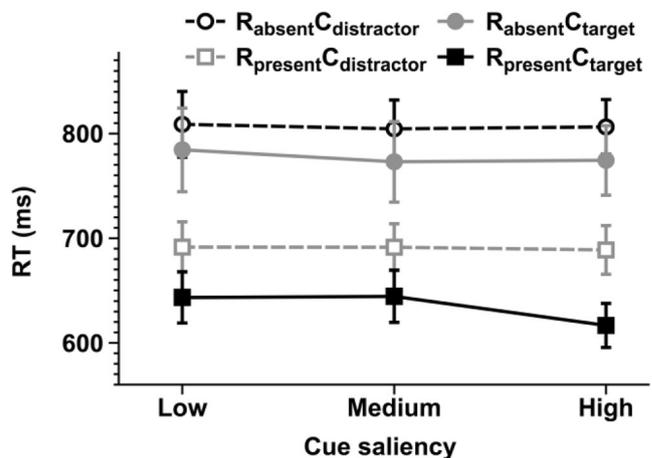


Fig. 3 Interaction between reward, cue saliency, and cued object from the target discrimination task in Experiment 2. The black lines are data from congruent trials in which response times (RTs) in the $R_{\text{present}}C_{\text{target}}$ condition (closed squares) produced shorter RTs than in the $R_{\text{absent}}C_{\text{distractor}}$ condition (open circles). The gray lines are data from incongruent trials and reflect a similar pattern as for the congruent trials, with shorter RTs in the $R_{\text{present}}C_{\text{distractor}}$ (open squares) condition and longer RTs in the $R_{\text{absent}}C_{\text{target}}$ (closed circles) condition. Note that unlike in Experiment 2, the incongruent conditions do not reach a point of equality. Error bars are SEMs

attentional cues because the properties through which they guide attention differ from traditional top-down and bottom-up cues. While the reward values were known (e.g., through training in the baseline task) and the spatial probabilities were implicit, the representation of both types of information for guiding attention was reinforced through selection history (Awh et al., 2012). In particular, we were interested in determining whether two sources of selection history would produce multiplicative or additive effects on attentional selection and whether the strength of the two sources could be equated.

In Experiment 1, we held reward information constant and parametrically increased the spatial probability of the target across blocks. The two sources of information were congruent on some trials, such that the target was both in the rewarded color and the high-probability location (or the reverse), and incongruent on other trials, producing potential competition between the two sources of information. This design allowed us to determine whether the relationship between these two sources of information was multiplicative or additive. Additionally, we increased the probability of the target across blocks in order to look for a point of subjective equality at which the strength of the probability cue was equivalent to that of reward, as determined for our particular study.

Interestingly, for any given spatial probability, there was a constant additional advantage for targets that were in the reward-associated color. This result suggested that there are independent attentional priority signals assigned to each type of information. Even at the highest spatial probability level where all targets fell at one location, there was still an advantage for reward-associated, as compared with non-rewarded, targets, and the magnitude of this advantage was the same as for all other spatial probability ratios. This finding was surprising given their similar profiles on behavior and the frequent combination of probability and reward value (i.e., the metric of expected value; EV) in the decision-making literature (e.g., Platt & Glimcher, 1999). However, such a model would have predicted data that are qualitatively dissimilar to our findings. Specifically, the pattern would have shown an interaction such that the nonrewarded targets (i.e., reward magnitude = 0; $R_{\text{absent}P_{\text{low}}}$ or $R_{\text{absent}P_{\text{high}}}$) would be given zero attentional weight and would, therefore, not be prioritized according to the probabilistic evidence in favor of it (i.e., a flat line), resulting in equally long RTs in each condition. Thus, while it may be that spatial probability and reward are combined into a single metric for the purposes of decision making, it appears that the two sources of information are kept separate in attentional selection and produce additive effects on behavior. There are other metrics that combine probabilities and reward value (e.g., utility; Bernoulli, 1954 [1738]; von Neumann & Morgenstern, 1944), but it is unclear whether those models could be used to fit our present data.

Additionally, in Experiment 1, we found a clear convergence of RTs in the two incongruent conditions: There was an

advantage for the $R_{\text{present}P_{\text{low}}}$ targets over the $R_{\text{absent}P_{\text{high}}}$ targets when the spatial probability was weak (.5, .6), but this advantage for reward was eliminated in the .7 block. Although the exact point of equality is likely dependent on the specific reward values and probability strengths used in this experiment, the data demonstrate that spatial probabilities can produce an equivalent bias on spatial attention as rewards, when it provides sufficient information. This finding stands in contrast to much of the existing literature on rewards in attention where rewards have been found to override other attentional cues (Anderson et al., 2011a, 2011b; Hickey & van Zoest, 2013; Krebs et al., 2011). This suggests that one reason rewards may produce such strong attentional capture may be that they carry information predictive of a positive outcome. When another source of predictive information is introduced, it can be assigned an equivalent priority.

It is often wondered whether performance benefits from probabilistic information based on frequencies can be fully explained by repetition priming (Kristjánsson & Campana, 2010; Maljkovic & Nakayama, 1994). Although probabilistic expectations may arise from mechanisms that compute repetition, local priming, while certainly important, could not fully explain the pattern of results in this study (see also Druker & Anderson, 2010; Geng & Behrmann, 2005; Jiang, Swallow, & Rosenbaum, 2013; Walthew & Gilchrist, 2006). Together, the additive effect between reward and spatial probability combined with the point of equality in attentional priority indicate that both sources of information provide independent attentional biases that vary in strength and can converge in priority.

In Experiment 2, the spatial probability was replaced by an exogenous spatial cue. Although the exogenous cue captured spatial attention, it was not predictive and, therefore, was devoid of any selection history. Similar to Experiment 1, the spatial cue and rewards again produced additive effects: Rewarded targets had shorter RTs irrespective of the exogenous cue validity. However, unlike Experiment 1, there was never a point of convergence where the exogenous cue produced equally strong attentional priority as the rewarded stimulus. Instead, rewards always dominated attentional priority such that the rewarded target produced shorter RTs than did unrewarded targets at all levels of exogenous cue saliency. These results are consistent with previous findings that reward associations are a powerful attentional bias that supersede voluntary goals (Anderson et al., 2011b; Peck et al., 2009) and modulates physical salience (Kiss et al., 2009). To our knowledge, this is the first study that completely separated the effect of exogenous salience from that of reward associations. Previous studies investigating the two yoked salience and reward associations together through the hue of stimuli associated or previously associated with reward (Anderson et al., 2011b; Hickey et al., 2010; Hickey & van Zoest, 2012; Kiss et al., 2009). Furthermore, within the context of Experiment 1, the data suggest that spatial cuing driven by saliency was

overall weaker than its informationally rich probabilistic counterpart; there was no point of equality between reward and spatial probability, as there was in Experiment 1.

Conclusions

In conclusion, we have provided evidence that reward associations and spatial probability have independent and additive effects on attentional selection. Moreover, the strength of priority assigned to each of the sources could be equated, suggesting that the strength of attentional bias from these sources of information can be comparable. In contrast, while salient but nonpredictive spatial cues and reward associations exhibited independent effects on attention, reward always dominated. Thus, reward associations and spatial probabilities appear to be particularly powerful classes of attentional cues that are heavily prioritized over other traditional voluntary- and salience-based cues, perhaps because both carry information that is motivationally relevant and continuously reinforced during attentional selection. Future research will be necessary to more fully characterize the mechanisms by which multiple informational sources affect attentional priority and behavior.

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