Value-driven interference in visual search: Attention to reward-associated distractors.

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Abstract

We used an implicit learning paradigm to examine the acquisition of color-reward associations when colors were task-irrelevant and attention to color was detrimental to performance. Our task required a manual classification response to a shape target and a correct response was rewarded with either 1 or 10 cent. The amount of reward was contingent on the color of a simultaneous color distractor and different colors were associated with low reward (always 1 Cent), partial reward (randomly either 1 or 10 Cent), and high reward (always 10 Cent). Attention to color was nonstrategic for maximizing reward because it interfered with the response to the target. We examined the potential of reward-associated colors to capture and hold overt attention automatically. Reward expectancy increased with the average amount of associated reward (low < partial < high). Reward uncertainty was highest for the partially reward distractor color (low < partial > high). Results revealed that capture frequency was linked to reward expectancy, while capture duration additionally seemed to be influenced by uncertainty, complementing previous findings of such a dissociation in appetitive and aversive learning (Koenig, Kadel, Uengoer, Schubö, & Lachnit, 2017; Koenig, Uengoer, & Lachnit, 2017).

Keywords: Associative Learning, Reward, Expectancy, Uncertainty, Attention, Eye Movements

Introduction

There now is converging empirical evidence that attention can be captured automatically by non-salient and task-irrelevant stimuli if these stimuli are associated with either reward or punishment (Anderson 2015; Anderson & Kim, 2018; Anderson, Laurent & Yantis, 2011a, 2011b; Anderson & Yantis, 2012; Gluth et al., 2020; Le Pelley et al, 2016; Rusz et al., 2020; Schmidt, Belopolsky, & Theeuwes, 2015a, 2015b; Wang, Yu, & Zhou, 2013; Wentura, Mueller, & Rothermund, 2014). Most of these experiments have concluded that the potential of an irrelevant distractor to capture attention is linked to the strength of its association with reward. In accord with this perspective, a distractor associated with a large reward typically features a higher capture probability compared with a small reward distractor (Anderson et al., 2011b; Anderson & Jantis, 2013), and a distractor frequently followed by an electric shock in the past captures attention more frequently than a distractor not associated with shock (Wang et al. 2013; Schmidt et al. 2015).

Two previous experiments have tried to disentangle the two dimensions of reward *expectancy* and *uncertainty* that might simultaneously affect the distracter value and in turn influence value-based capture. In the learning task of Koenig, Kadel, Uengoer, Schubö, & Lachnit (2017) participants acquired manual responses to different color cues, and correct responses were rewarded with either 1 or 10 Cent depending on the color. For three different colors, a correct response was followed by the higher reward on 0%, 50%, and 100% of the trials respectively, and colors were thus established as cues for low reward, partial reward, and high reward respectively. Trials of this learning task were presented randomly intermixed with a second task, in which color was introduced as an irrelevant distracter during visual search for a shape target. The authors examined the potential of color distracters to capture and hold attention in the search task depending on their acquired value from the learning task, and reported that the frequency of such attentional capture was linked to reward expectancy while capture duration was linked to uncertainty. For a similar search task after aversive conditioning, Koenig, Uengoer & Lachnit (2017) reported a similar pattern with capture frequency being exclusively linked to shock expectancy, and capture duration being additionally influenced by uncertainty.

In the experiments summarized above participants attended to the color cues in the learning task in order to gain reward or predict shock, and it could have been this selection history (Awh, Belopolsky & Theeuwes, 2012) that caused attentional capture subsequently. In contrast to this hypothesis, Le Pelley et al. (2015) demonstrated attentional capture by stimuli, that *never* were task relevant, and that *never* had to be selected. Participants were instructed to perform a saccadic eye movement to a shape singleton (diamond) as fast as possible and to ignore all simultaneous circular distracters. Participants were told that the amount of reward would be contingent on the saccadic reaction time, when it actually was contingent on the color of a simultaneous distractor. For example, selecting the shape target with an eye movement was followed by high reward in the presence of a green distractor, but the same eye movement to the shape target was followed by low reward with a red distractor. Although attentional selection of the color distractor was irrelevant for the task, the high valued distractor significantly slowed search for the shape target. In a gaze-contingent version of this paradigm, Le Pelley et al. (2015) moreover demonstrated that oculomotor capture by high value distracters occurred even when their selection was explicitly punished: If participants looked at the distractor before turning towards the target, reward was omitted on that trial (omission training). Nonetheless the authors found a higher frequency of oculomotor capture (and in turn a higher reward omission rate) by distracters that were associated with high reward.

In the current experiment, colors in were associated with different reward expectancies and uncertainties, however in contrast to Koenig et al. (2017) colors never had to be attended in order to earn reward. Participants again were required to find a shape target as quickly as possible and to suppress the selection of a simultaneous color distractor. Participants performed a manual response to indicate the line orientation within the target but in contrast to unrewarded search trials of previous experiments (Koenig et al. 2017; Anderson, 2011a, 2011b) a correct manual response was rewarded. The amount of reward depended on the color of the simultaneous distractor. One color indicated the availability of high reward whereas another color indicated the availability of low reward, as in the experiments of Le Pelley et al. (2015). In extension of previous experiments, a third color indicated random payment of either high or low reward. Importantly attention to color always was nonstrategic for maximizing reward because it never instructed which button to press, or marked the location of a behaviorally relevant stimulus. With this design the maximum profit could have been generated by disregarding any color stimulus during the entire experimental session and solely focusing on the shape target instead.

Method

Participants

Thirty-six students of the University of Marburg participated in the experiment and received either course credit or payment. All participants had normal or corrected-to-normal vision. Twenty-eight subjects were female and eight were male. Their age ranged from 21 to 36.

Apparatus

Testing took place in a sound-attenuated, dimmed room. Monocular eye movements were recorded using an infrared video-based eye tracker (Eyelink 2000, SR-Research, Mississauga, ON, Canada) that sampled gaze position and pupil size at a frequency of 1000Hz. Sampling of the left versus right eye was counterbalanced across participants. The eye tracker restrained the participants head via chin and forehead rests and was table-mounted in front of a 22”-CRT monitor (Iiyama, Vision Master Pro514) yielding an eye-to-screen-distance of 78 cm. The eye tracker was calibrated with a 9-point grid of calibration targets. For each participant, the calibration procedure was repeated until subsequent validation confirmed a maximal calibration error < 0.5°. Stimulus delivery was controlled by Presentation® software (Version 16.1, www.neurobs.com).

All stimuli were presented on a dark gray (L* = 36) background. The search array displayed in every trial of our experiment consisted of six, circularly arranged stimuli, that were placed at a distance of 100 mm (7.34 degrees of visual angle; dva) to the center of the computer screen as shown in Figure 2. In 75% of the trials the search array consisted of four gray annuli, one colored distracter annulus, and a gray shape target (diamond). In the remaining 25% of the trials the display showed five gray annuli plus the shape target (no distracter baseline). Annuli and target were 31 mm and 35 mm in height respectively, and were drawn with a line width of 4 mm (0.29 dva). The three distractor colors red, green and blue, were chosen to be equidistant in CIE L*a*b* color space. They were matched for lightness (L* = 65) and chroma (C* = 40), with hues of h° = 30, 150, and 270 respectively. Gray shapes were rendered with the same lightness (L* = 65), but no chroma (C* = 0).

Stimuli and procedure

Stimuli were identical with stimuli from the search trials of Koenig et al. (2017). Three colors, red, green, and blue, served as distractor stimuli. After responding to the line orientation within the target, feedback about the amount of reward was visually presented at the center of the computer screen and also read by a computer-generated voice (“Correct, 10 Cent”, “Correct, 1 Cent”, “Incorrect, 0 Cent”).

Participants read instructions, gave informed consent, and performed eight practice search trials (with no color distractor) to ensure that instruction were understood. The eye tracker then was calibrated as described above. Participants then performed 192 search trials, that are illustrated in Figure 1. Trials began with a 2-sec gray fixation cross, that instructed participants to stop blinking and pay attention. The subsequent 2-sec search display presented a diamond-shaped target stimulus embedded among five circular distractor stimuli. Participants were instructed to find and fixate on the shape target as quickly as possible, and were required to identify the line orientation in the target by pressing a right versus left mouse button with their right hand. In 25% of the trials all circular distracters were gray (baseline condition), in 75% of the trials one of the distracters was rendered either red, green, or blue. All stimuli were matched for lightness ($L^* = 65$) in CIE L^*a^*b space. Colors were defined with hues of $h° = 30$, 150, and 270 respectively, and the same chroma ($C^* = 40$). All stimuli were presented on a dark gray ($L^* = 36$) background.

Participants were instructed that their manual response to the target would be rewarded with either 1 cent or 10 cent in each trial depending on the reaction time. In reality however, the amount of reward did not depend on the reaction time but was contingent on the color of the distractor stimulus. In the context of the first distractor color, a correct response was always rewarded with 1 cent. The same amount was paid in the no-distractor baseline condition, In the context of the second color, a correct response was randomly rewarded with either 1 cent or 10 cent. At last, with the third color present as a distracter, a correct response always was rewarded with 10 cent. Contingencies between the colors and high reward (10 cent) thus were 0%, 50%, and 100% respectively, and established the distracter colors as cues for low reward (L), partial reinforcement (P), and high reward (H). Each color, L, P, and H was presented in 48 trials. With the additional 48 no-distracter baseline trials (N), the experiment consisted of 192 trials. Trials types were presented intermixed, in a separate pseudo-random sequence for each participant. With the restriction that the same condition did not occur more than three time in a row. The sequence was constructed from eight successive blocks of 24 trials, with 6 trials per condition N, L, P, and H. In each block each color was presented once at each of the six spatial positions in the search array, and the partially reinforced color had the same frequency of 1 cent and 10 cent reinforcements.

Dependent variables

Our dependent variables were selected to provide measures of how visual search for the shape target (diamond shape) was slowed by the acquired value of the color distractor. Attentional engagement with the shape target was indicated by our participants manual response to the orientation of the line embedded with this diamond shape. We analyzed the *accuracy* and the *latency* of this manual response as done by previous studies (Anderson et al, 2011a, 2011b). However, in our experiment we used such a small size of the embedded line, that line identification was only possible foveally, and participants thus were required to fixate on the shape target before they could emit a correct response. The time the eyes arrived at the shape target in a given trial, thus was (a) dependent on whether the color distractor was strong enough to attract the first fixation and (b) dependent on how long participants dwelt on the distractor if they fixated it first. From this perspective we computed two measures of *capture frequency* (frequency of trials with first fixations on the distractor) and *capture duration* (duration of the distractor fixation in capture trials) to yield oculomotor measures of attentional capture and attentional holding respectively (Koster, Krombez, Van Damme, Verschuere, & De Houwer, 2004).

Data Analysis

The analysis included valid trials only. A trial was scored valid if participants fixated on the central fixation cross when the search display appeared and moved their eyes to the shape target within the two seconds of search array presentation (with the possibility of an intervening distracter fixation). Also, a trial was excluded if the search interval included any signal loss (mostly due to blinks) that could have masked a relevant fixation. With these criteria, about 95% of the search trials were regarded as valid and taken into account for further analysis.

Custom MATLAB (The MathWorks, Inc., 2012) software was used for the parametrization of eye movement traces (Koenig, 2010). Fixations were detected using a velocity-based algorithm with a threshold of 30°/sec.

Analyses of variance (ANOVA) were computed from (generalized) linear-mixed models (Bates, Meachler, Bolker, and Walker, 2015), that at least included random intercepts within participants to account for the repeated measures structure of the data. More complex random-effect structures (allowing for random variation of distracter type and block within participant) were included if supported by likelihood-ratio model comparison. All statistical analyses were conducted using the R language and environment for statistical computing (R Core Team, 2021). *F*- and *t*-statistics were computed from approximate degrees of freedom using the method of Kenward and Roger (1997; Halekoh and Hojsgaard, 2014).

Results

Manual response. In the current experiment participants earned reward for a correct manual response to the line orientation within the shape target while an additional color singleton competed for attentional selection and was correlated with reward. Figure 2a depicts the accuracy of the manual choice response. Fitting a generalized-linear-mixed model with logit link function revealed that the frequency of a correct manual response did not differ when the diamond target was accompanied by no distractor (baseline) or a distractor associated with low, partial or high reward, $\chi^2(3) = 2.636$, $p = .451$. Across participants and experimental conditions accuracy was high and ranged from 88% to 100% ($M = 94.37$, $SD = 3.10$). With each correct response earning a monetary reward of either 1 or 10 Cent average rewards in the low, partial and high reward condition were 0.951 Cent, 5.168 Cent and 9.421 Cent respectively indicating the intended increase in *reward expectancy* across experimental conditions. In contrast standard deviations were 0.216 Cent, 4.556 Cent and 2.335 Cent, indicating that *reward uncertainty* was highest in the partially rewarded condition.

Figure 2b depicts the latency of correct manual responses. An ANOVA revealed a significant effect of reward, $F(2,72) = 25.837$, $p < .001$, $\eta^2_p = .425$. Response latency was higher when the target was accompanied by a high reward distractor than by a low reward distractor, $t(105) = -3.175$, $p = .010$, or by a partial reward distractor $t(105) = -2.556$, $p = .057$, while there was no difference between the partial and low reward condition, $t(105) = -0.620$, $p = .925$. The latency in all distractor conditions exceeded the latency in the no-distractor baseline condition (all $p < .001$).

Continuous fixation probability and total dwell time. Figure 3 depicts continuous fixation probability over the 2-sec search screen presenting target and distractor simultaneously. The probability of fixating the diamond target (solid gray line) increased after the search display appeared but after participants emitted their manual response (see Figure 2b) they disengaged from the target to fixate on the center of the screen at the end of the 2-sec interval in anticipation of the reward feedback presented at the center of the screen (dashed gray line). Importantly, the color distractor (solid blue line) also captured attention early after onset of the search screen and fixation probability seem to increase with the amount of expected reward. For statistical analysis we computed the mean distractor fixation probability over the entire 2-sec search interval and multiplied by 2000ms to yield the total dwell time on the distractor (blue shaded area) which was about 37ms, 41ms, and 54ms for the low, partial and high reward distractor respectively (pooled $SE = 7.95$), $F(2,62) = 7.273$, $p = .002$, $\eta^2_p = .172$. The high reward distractor attracted more attention than both the partial reward distractor, $t(70) = -2.798$, $p = .018$, and the low reward distractor, $t(70) = -3.644$, $p = .002$, which did not differ from each other, $t(70) = -0.845$, $p = .676$. For interpreting total dwell times please keep in mind that short distractor fixations (with an average duration of about 44ms) result because they are confounded with distractor fixation probability (scoring a dwell of zero for trials without a distractor fixation).

Capture frequency. To further analyze the frequency of attentional capture by the color distractor, for each trial we computed whether the first peripheral fixation after onset of the search display was on the diamond target, the color distractor or one of the remaining gray distractors. We fitted a generalized-mixed-model to the frequency of distractor fixations. The model included the factor reward (low, partial, high) and the onset latency of the fixation as a continuous predictor and revealed effects of reward, $\chi^2(2) = 30.571$, $p < .001$, and latency, $\chi^2(1) = 55.038$, $p < .001$, with no interaction, $\chi^2(2) = 2.050$, $p = .358$. Figure 4a depicts the main effect of reward which induced capture frequencies of 13.4%, 14.2% and 20.4% for a low, partial and high reward distractor respectively. Pairwise comparisons revealed that the high reward distractor induced a higher frequency of first fixations than both, the partial reward distractor, $OR = .648$, $z = -3.138$, $p = .005$, as well as the low reward distractor , $OR = .604$, $z = -3.231$, $p = .003$, while the latter two did not differ from each other, $OR = .933$, $z = -0.444$, $p = .897$. The main effect of fixation latency was due to the fact that first fixations on the distractor occurred earlier within trial, M = 280ms, SE = 11.9, than first fixations on the target, M = 364ms, SE = 16.5 as shown in Figure 4b. A linear-mixed model with latency as the dependent variable and fixation target (shape target, color distractor) and reward (low, partial, high) as independent variables revealed a main effect of fixation target, $F(1,21) = 83.537$, $p < .001$, but no effect of reward and no interaction, both $F < 1$.

Capture duration. If the first fixation in a trial was on the color distractor, participants had to disengage from the distractor and move their eyes to the diamond shape in order to identify the line orientation in the target. Our analysis revealed that this duration of attentional capture by the color distractor was modulated by reward (low, partial, high) as well as the error of the fixation (distance to distractor). Figure 5a shows fixation error as the scatter of fixation positions around the actual distractor positions. Figure 5b shows how this fixation error (ranging from 0 to 40mm for distractor fixations) and the distractor color (associated with low, partial or high reward) affected the duration of the distractor fixation. A mixed model with factor reward (low, partial, high) and fixation error revealed effects of reward , $F(2,164) = 4.515$, $p = .012$, error, $F(1,979) = 44.524$, $p < .001$, and a Reward X Error interaction, $F(2,692) = 4.931$, $p = .007$. For fixations far away from the distractor (error = 40mm) a low reward distractor induced a longer fixation duration than both, the partial reward distractor, $t(466) = 2.420$, $p = .042$, and the high reward distractor, $t(423) = 2.308$, $p = .055$, while the latter two did not differ from each other, $t(591) = -0.307$, $p = .949$. However, the reverse pattern emerged for fixations on the distractor (error = 0) where a low reward distractor induced shorter durations than both, the partial reward distractor, $t(112) = -2.402$, $p = .046$, and the high reward distractor, $t(125) = -2.637$, $p = .025$, while the latter two did not differ from each other, $t(149) = -0.021$, $p = .999$.

Discussion

In the current experiment our participants task was to find and fixate on a diamond shape singleton as quickly as possible. The diamond shape was the designated target by instruction but additionally fixating on the diamond shape also was essential to identify a high acuity feature which indicated which button to press in order to earn reward. While the most rational strategy under these task requirements would be to dismiss any distracting information as much as possible an additional color single that occurred in 75% of the search trials captured the first fixation in about 16% of the distractor trials on average. This attentional capture was likely caused by the bottom-up salience of the color singleton at some baseline level but also was caused by the fact that the distractor color indicated the amount and uncertainty of reward and thus was endowed with motivational and informational value. Results revealed that attentional capture was more pronounced for a distractor color that was associated with high reward (always

10 Cent) than the distractor color associated with partial reward (randomly 1 or 10 Cent) or low reward (always 1 Cent). Observing such an effect of reward in the current design suggest that the acquisition and attentional expression of learned color-reward associations was automatic to a large extent because several competing explanations can be ruled out. First of all, there was no previous selection history (Awh et al., 2012; Failing & Theeuwes, 2018; Meyer et al., 2020; Theeuwes & Failing, 2020) for color because the search task was the primary (and only) task during which color never had to be selected in order to retrieve and maximize reward. Furthermore, capture by reward could not have been caused by a task switching effect such as possibly found in Koenig et al. (2017). This experiment featured two different trials types, learning trials and search trials, that required different task sets. In learning trials, attention to color was necessary to choose a correct manual response and earn reward. In contrast, attention to color was counterproductive for the fast detection of the shape target in search trials. Trial types were presented randomly intermixed and we observed that reward expectancy and uncertainty associated with different colors in learning trials transferred to search trials and increased the frequency and duration of attentional capture when colors were introduced as task irrelevant distracters. The origin of this bias remained somewhat unclear because the effect to some extent could also have resulted from a failure to switch task sets. In contrast, the current results provide further evidence for reward learning as an incidental process as well as the automatic attentional expression of such learned reward associations.

The frequency of first distractor fixations as described above resulted from the attentional selection of a peripheral color singleton over a competing shape singleton. Participants fixated centrally when the search display appeared and then shifted their gaze to the distractor. In these capture trials we additionally analyzed the duration of distractor fixations before participants eventually shifted their gaze to the designated target. Our results revealed that this *capture duration* was modulated by reward as well but the effect was less clear at first glance and modulated by the position error of the first fixation which – after shifting gaze from the central fixation cross to the periphery - could land either *on* the distractor or - with some residual error - only *near* the distractor. In the former case we observed that disengagement from the distractor was prolonged for both partial reward and high reward cues. In the latter case we observed a reverse effect with shorter fixations for partial and high reward cues. We interpret the former case as a direct effect of stimulus value with longer dwell time on high-valued distractors that - once fixated - hamper attentional disengagement (Watson et al., 2020). We interpret the latter effect to be caused by the possibility that high-valued stimuli might specifically shorten fixations that exhibit some residual position error because subsequent shifts of gaze that are required to further correct positional error are executed with higher priority (i. e. faster) for high-valued stimuli. In any case, our results revealed that the partially rewarded, uncertain distractor exhibited a stronger effect on capture duration (observed effect: high = partial > low) than on capture frequency (observed effect: high> partial = low). This replicates previous reports of a such a dissociation between the two measures (Koenig, Kadel et al., 2017; Koenig Uengoer et al., 2017) and further suggests that the prediction error observed after an uncertain cue for reward might increase attention to the cue for future learning (Torrents-Rodas et al., 2021a, 2021b) as posited by attentional learning theories (Gottlieb, 2012; Le Pelley, 2004; Le Pelley et al., 2016; Pearce and Hall, 1980; Pearce & Mackintosh, 2010). However, we currently cannot provide a sound explanation why an acquired value of reward uncertainty would effect capture frequency and duration differently. We have speculated previously that reward expectancy could be represented more strongly early within trial (start of distractor fixations) than reward uncertainty (end of distractor fixations) but our analysis of continuous fixation probability over the course of the search trial (see Figure 3) did not support such an interpretation. Further research is needed to address the dissociation between measures.

In summary our experiment provided further evidence for the role of reward expectancy and uncertainty in shaping overt attention. Particularly, effects of attentional capture observed in the current design again suggest a rather automatic process that shifts gaze to a reward-associated stimulus even if this stimulus is task-irrelevant and any attention to the stimulus is detrimental to the task.

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Figures

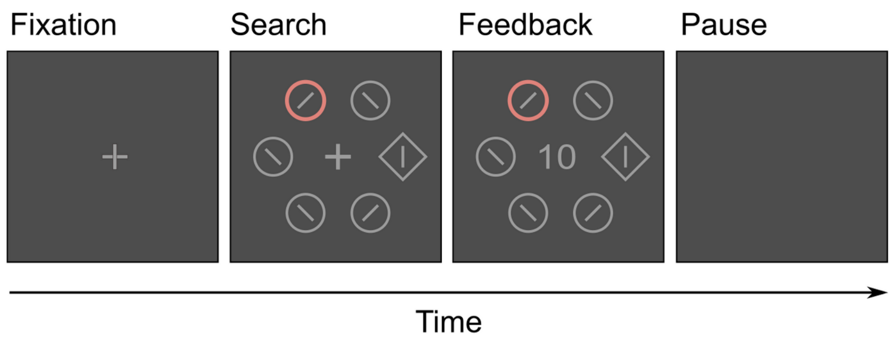


Figure 1. Trials started with a fixation cross. A subsequent search display contained a diamond shape singleton which was the designated target and contained a line orientation that instructed a manual choice response. In 75% of the trials the search screen presented an additional color singleton as a distractor. In 25% of the trials the distractor was omitted to provide a baseline. Three distractor colors were associated with low reward (always 1 Cent), partial reward (randomly either 1 Cent or 10 Cent), and high reward (always 10 Cent) presented on the subsequent feedback screen.

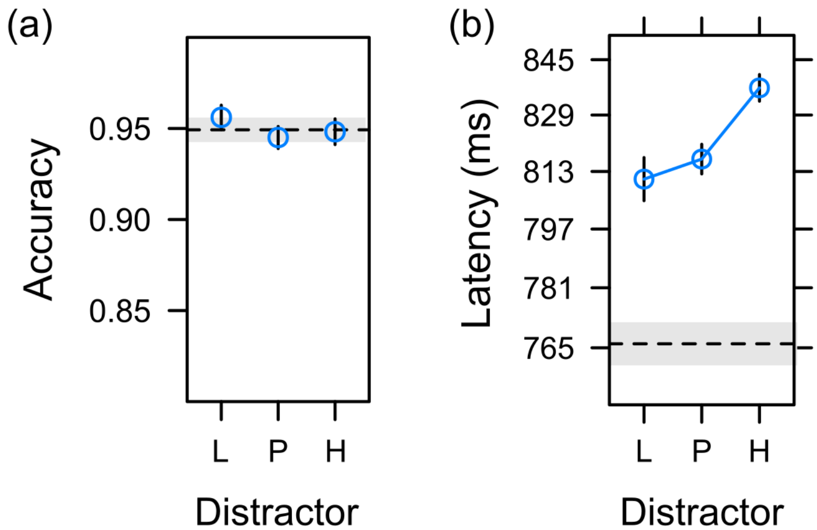


Figure 2. Accuracy (a) and Latency (b) of the manual response that classified the line orientation in the diamond shape target. Response latency increases with the amount of associated reward (Low, Partial, High). Dashed horizontal lines depict the no-distractor baseline condition. Error bars and bands depict the standard error of the mean.

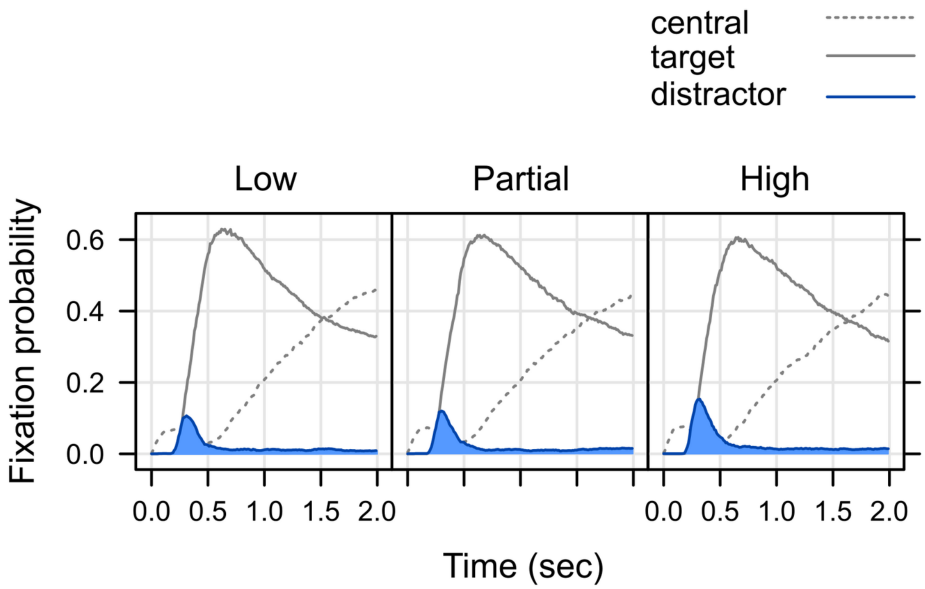
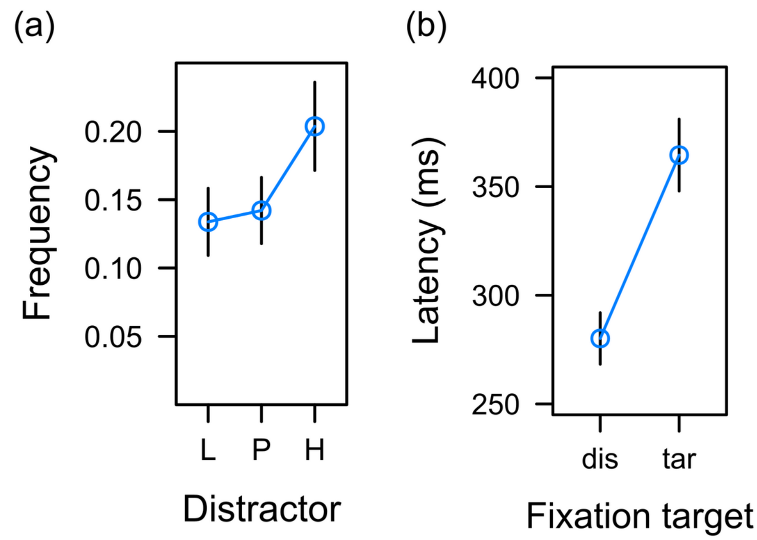


Figure 3. Continuous fixation probability over the time course of the search display. Fixations were on the shape target (solid gray line) the color distractor (solid blue line), or the center of the screen (dashed line) in anticipation of the reward display. The blue shaded area corresponds to total dwell time on the color distractor.



454 **Figure 4.** (a) Frequency of first fixations on the color distractor increases with the amount of associated reward. (b) Distractor fixations have shorter latency than target fixations.

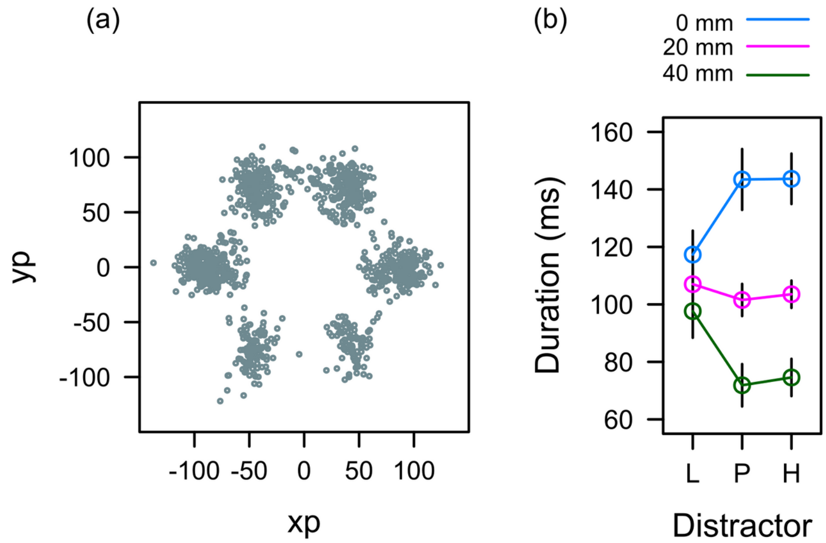


Figure 5. (a) Scatter of first fixations on the color distractor. Horizontal (xp) and vertical (yp) ey position is given in millimeter. (b) The duration of first fixations on the color distractor is modulated by fixation error and the associated reward (low, partial, high).