Reward encourages reactive, goal-directed suppression of attention

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Abstract

Stimuli that signal large reward are more likely to capture attention and gaze than stimuli that signal lesser or no reward, even when capture counterproductively prevents reward delivery. This suggests that a stimulus's *signalling relationship* with reward (the contingency between stimulus presentation and reward delivery) is a potent influence on selective attention. Recent studies have also implicated a stimulus's *response relationship* with reward (the reward-related consequences of attending to a stimulus) in reducing capture by signals of reward. Here we show that this response pathway modulates capture by encouraging a reactive, goal-directed distractor suppression process. In a rewarded visual search task, participants demonstrated an oculomotor preference away from a distractor that had a negative response relationship with high reward (looking at the distractor caused reward to be cancelled) and towards a distractor that had no such negative response relationship, providing evidence for the role of the response relationship in suppressing capture by reward-related distractors. Analysis of the temporal dynamics of eye-movements suggests that this distractor suppression process operates via a reactive mechanism of rapid disengagement (Experiment 1). Consistent with a goal-directed mechanism, the influence of the response relationship was eliminated when reward was unavailable (Experiment 2). These findings highlight the multifaceted role of learned stimulus-reward relationships in attentional selection.

Keywords: Attentional capture, reward learning, distractor suppression

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Attention refers to the set of cognitive mechanisms that enable us to selectively parse sensory information; prioritising relevant or important information to be processed further, and de-prioritising irrelevant or unimportant information to be ignored. It is well established that attention can be influenced by our goals and volitions (i.e., *goal-directed control*: we can intentionally focus our attention on a given region of space, or set of stimulus features; e.g., Folk et al., 1992; Posner et al., 1980), as well as the physical characteristics of stimuli (*stimulus-driven control*: physically salient stimuli can draw attention regardless of our goals and intentions; Itti & Koch, 2001; Theeuwes, 2010). More recently, research has demonstrated that attention is also guided by our prior experiences with stimuli in the environment (Awh et al., 2012; Failing & Theeuwes, 2018; Le Pelley et al., 2016). This third category of influences on attentional selection has been labelled *selection history*.

One of the attentional phenomena that has been described in terms of selection history is the finding that stimuli signalling high reward are more likely to capture attention and gaze than stimuli signalling lesser or no reward (for reviews, see: Anderson, 2016; Failing & Theeuwes, 2018; Le Pelley et al., 2016; Watson, Pearson, Wiers, et al., 2019). For example, in a study by Le Pelley et al. (2015) participants were tasked with shifting their gaze to a diamond-shaped target presented among circle non-targets on each trial. On most trials, one of the non-targets was rendered in a different colour from the other shapes in the display, so as to be a colour-singleton distractor. The colour of this distractor signalled the magnitude of reward that could be earned for a rapid saccade to the target on that trial: one colour signalled that a high reward was available, and another colour signalled that a low reward was available. Importantly, while the distractor signalled the magnitude of reward available, the reward for the trial was *cancelled* if gaze was detected in the vicinity of the distractor. Thus, looking at the distractor was counterproductive, particularly when it appeared in the high-reward-signalling colour (as looking at this high-reward distractor triggered the omission of relatively large reward). Nevertheless, participants came to look at the high-reward distractor more often than the low-reward distractor, triggering the omission of more high-value rewards than low-value rewards. This study demonstrates that a stimulus feature's *signalling relationship* with reward—i.e., the statistical co-occurrence of that stimulus feature and reward (see Figure 1)—increases the likelihood of that feature capturing attention and gaze, even when such capture is explicitly counterproductive. This phenomenon has been labelled *value modulated attentional capture* (VMAC).

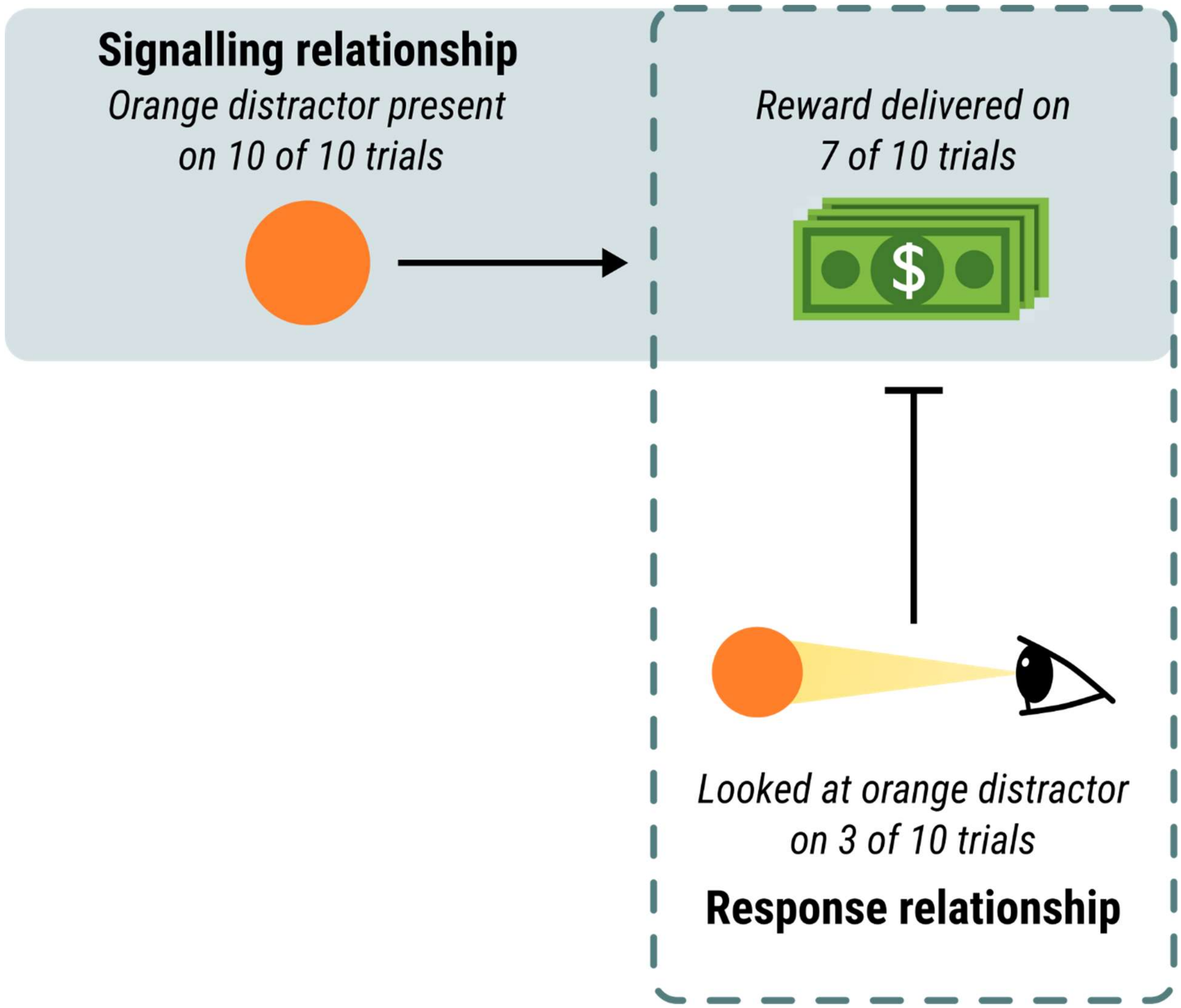

Figure 1. Schematic diagram of the signalling and response relationships in Le Pelley et al.'s (2015) value modulated attentional capture task. There are two stimulus-reward relationships that participants can learn. The signalling relationship (shown in the shaded rectangle) is the statistical co-occurrence of the distractor and reward: in the example illustrated here, reward was delivered on 7 of 10 the trials in which the orange distractor was presented. The response relationship (dashed rectangle) refers to the contingency between making an eye-movement to the distractor and reward: on the 3 trials in which the participant looked at the orange distractor, reward was omitted (indicated by the capped line).

One of the mechanisms suggested to underlie VMAC is augmentation of the reward-signalling stimulus feature's representation in early sensory processing areas, akin to increasing its physical salience (Anderson, 2019; Pearson et al., 2016). This value-boosted signal then feeds forward into a common *attentional priority map*, where it competes with other rapidly-generated priority signals corresponding to stimulus-driven inputs, as well as (slower) priority signals associated with goal-directed inputs (Awh et al., 2012; Belopolsky, 2015; Failing & Theeuwes, 2018; Pearson et al., 2016; Theeuwes, 2018). Consistent with this idea, the oculomotor bias to reward-signalling stimuli is largest among rapidly initiated saccades (Failing et al., 2015; Pearson et al., 2016), a similar pattern to that observed in capture by physically salient distractors (e.g., van Zoest et al., 2004). Electrophysiological and neuroimaging studies have also suggested that reward's influence arises early on in visual processing, with modulation being observed as early as low-level sensory cortex (Hickey et al., 2010; MacLean & Giesbrecht, 2015; Serences, 2008; Serences & Saproo, 2010; but see Tankelevitch et al., 2020). Moreover, the VMAC effect has been demonstrated to be largely immune to goal-directed attentional control, in that the overt attentional bias to signals of reward persists even when participants are explicitly instructed about the counterproductive consequences of looking at the reward-signalling distractor (Kim & Anderson, 2019; Pearson et al., 2015), and under conditions that allow capture by physically salient stimuli to be suppressed (Le Pelley et al., 2020; Pearson et al., 2020). Together, these findings suggest that signals of reward are afforded special priority within the visual system, such that they rapidly and automatically capture our attention and gaze, even when suppressing such capture would be in our best interest.

However, recent findings have called into question the idea that capture by reward-signalling stimuli is immune to suppression. For instance, the magnitude of VMAC has been shown to increase when cognitive control resources are depleted (Watson, Pearson, Chow, et al., 2019), suggesting a limited role for goal-directed control in reducing the likelihood of (but not eliminating) capture by reward signals. Moreover, a recent study by Pearson & Le Pelley (2020) suggests a role for a stimulus's *response relationship* with reward—i.e., the reward-related consequences of attending/saccading to the stimulus (Figure 1)—in modulating capture by reward-signalling stimuli. In a variant of Le Pelley et al.'s (2015) VMAC task, participants either experienced a negative response relationship between making a saccade to the distractor and reward delivery (i.e., the task described earlier in which capture by the reward-signalling distractors triggers reward omission) or they experienced no response relationship (looking at the distractors had no consequence for reward delivery). Importantly, the signalling relationship between each distractor and its associated reward was held equivalent across the two groups via a yoking procedure. Participants in both groups were more likely to look at the high-reward distractor than the low-reward distractor, replicating the finding that a stimulus's signalling relationship with reward increases its attentional priority. However, removing the negative consequences for capture resulted in more eye-movements to the high-reward distractor, but did not affect the number of eye-movements to the low-reward distractor, suggesting that participants who experienced the negative response contingency were using some form of attentional control to specifically reduce capture by the high-reward distractor. This is presumably because avoiding capture by the high-reward distractor resulted in a relatively large reward, whereas avoiding capture by the low-reward distractor resulted in a small reward. The implication is that a stimulus's response relationship with reward has a feature-specific, value-modulated influence on attentional selection that is independent of the influence of that stimulus's signalling relationship with reward.

Potential mechanisms for the influence of response relationships on attentional selection

While Pearson and Le Pelley's (2020) findings suggest that a negative response relationship between a stimulus and reward affects attentional selection by reducing the extent to which the stimulus captures gaze, the mechanism by which this occurs is currently unclear. There are thought to be two distinct sets of mechanisms that the visual attention system uses to suppress distractors (Geng, 2014): *reactive suppression*, where attention is rapidly disengaged from a distractor following initial capture, but before an eye-movement to the distractor is initiated; and *proactive suppression*, where the attentional priority of a distractor is down-weighted prior to stimulus presentation, such that attention is never directed to it in the first place. A stimulus's response relationship with reward may influence attentional selection via either of these mechanisms. That is, participants may reactively engage goal-directed control to rapidly disengage attention from a stimulus that has a negative response relationship with high reward, thereby reducing oculomotor capture by that stimulus. Alternatively (or in addition), the attentional priority of the stimulus that has a negative response relationship with high reward could be proactively down-weighted, such that the visual system treats it as though it is less salient than a reward-signalling stimulus without a negative response contingency, thus making it less likely to capture attention and gaze.

According to the reactive account, participants learn throughout the task that there are negative consequences for making a saccade to a distractor that has a negative response relationship with high reward. Consequently, if covert attention is captured by the high-reward distractor, reactive control processes are deployed to rapidly disengage attention and redirect it to the location of the next highest peak on the attentional priority map. On some trials, this disengagement will occur before the participant initiates their first saccade, and thus the reward-related distractor will not capture gaze (Theeuwes et al., 2003). On other trials, however, this disengagement will occur relatively slowly, and participants will still be attending to the reward-related distractor when they initiate their first saccade. On these trials, gaze will be captured by the reward-related distractor and a reward omission will be triggered. By contrast, if the participant is presented with a distractor that does not have a negative response relationship, there is less incentive to exercise reactive control to rapidly disengage from the distractors, and thus gaze is more likely to be captured, especially if the distractor signals high reward.

The proactive account instead suggests that the priority-map representation of a distractor that both signals and has a negative response relationship with reward is reduced, compared to a stimulus that signals reward but has no negative response relationship. Put simply, a distractor with a negative response relationship does not '*pop out*' from the display to the same extent as a distractor without a negative response relationship and is therefore less likely to capture attention and gaze. To the extent that such proactive suppression is possible, it is thought to be an automatic consequence of participants' recent experience, rather than the result of strategic goal-directed control processes (i.e., it belongs to the class of selection history effects; Gaspelin et al., 2019; Gaspelin & Luck, 2019; Wang & Theeuwes, 2018). Therefore, the proactive down-weighting of the distractor's attentional priority may be an automatic consequence of repeated experience with the negative response relationship, in the same way that repeated experience of the distractor's signalling relationship automatically leads to an increase in its attentional priority (Failing et al., 2015; Pearson et al., 2015, 2016).

The reactive and proactive accounts make different predictions regarding the time-course of attentional control. First, because reactive control processes (by definition) are initiated after the presentation of the search display, their influence should be most apparent for longer-latency saccades, with shorter-latency saccades driven by the early priority-map representation of the stimuli in the display (Godijn & Theeuwes, 2002; van Zoest et al., 2004). By contrast, if a stimulus's response relationship with reward proactively alters its early representation on the priority map, we should expect to see its influence emerging even in the most rapidly initiated saccades. Second, previous studies have shown that reactive disengagement from a distractor stimulus produces shorter fixations on the distractor following oculomotor capture (Geng & DiQuattro, 2010; Godijn & Theeuwes, 2002). Thus, if the response pathway affects attentional selection by encouraging reactive control, we should expect to see shorter fixations following saccades to stimuli with negative response contingencies than following saccades to stimuli without negative response contingencies. The current study tested these ideas.

Experiment 1

Participants were trained with four different distractor colours: two signalled high reward, and two signalled low reward (with yoking ensuring that both colours of each type had an equivalent signalling relationship with their respective reward level). Within each reward-level pair, one of the distractors was an '*omission*' distractor, and the other was a *'safe'* distractor. The omission distractor had a negative response relationship with reward, in that making a saccade to it caused the omission of reward. By contrast, the safe distractor had no negative response relationship with reward, as making a saccade to it had no consequence for the delivery of reward. The critical comparison came from trials in which both of these distractors were presented together (*choice trials*). As in previous studies of VMAC, it was expected that participants would be unable to prevent themselves from having their gaze captured by stimuli that signalled high reward. However, if a stimulus's response relationship with reward also influences attentional selection, then we should expect to see this capture preferentially directed towards the safe distractor versus the omission distractor. If an oculomotor preference for the safe distractor was apparent for the most rapidly initiated saccades, then this would suggest that the response pathway influences attentional selection by proactively down-weighting the attentional priority of the reward-related stimulus. On the other hand, if the effect were present only for longer-latency saccades, this would suggest that the response pathway influences attentional selection by encouraging reactive control processes. Furthermore, if the response pathway encourages reactive control, the duration of fixations on omission distractors should be shorter than those on safe distractors.

Method

Participants

This study was approved by the UNSW Sydney Human Research Ethics Advisory Panel (Psychology). Previous studies of value-modulated attentional capture have demonstrated medium to very large effect sizes (d_z = 0.54-2.2; Failing et al., 2015; Le Pelley et al., 2015; Pearson et al., 2015, 2016). A power analysis conducted with G*Power (Faul et al., 2007) indicated that a sample size of 40 participants would provide adequate power (power ~.87) to detect a medium effect size (d_z = 0.5). We therefore tested 40 UNSW Sydney students (21 females, age M = 22.9 years, SD = 6.65 years) who participated for course credit. All participants received a performance-dependent monetary bonus (M = 9.28 AUD, SD = 2.47 AUD).

Apparatus

Participants were tested using a Tobii TX-300 eye-tracker, mounted on a 23-in. monitor (1920 × 1080 resolution, 60 Hz monitor refresh rate, 300 Hz eye-tracker sampling rate). A chin rest was used to position the participant’s head 60 cm from the screen. For gaze-contingent calculations, gaze data were down-sampled to 100 Hz. Stimulus presentation was controlled by MATLAB using Psychophysics Toolbox extensions (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997). Raw data and analysis scripts for all experiments reported here are available via the Open Science Framework at https://osf.io/43ygk/.

Stimuli

Each trial consisted of a fixation display, search display, and feedback display (Figure 2A). Screen background was black. The fixation display comprised a white cross (0.5° visual angle), inside of a white circle (diameter 3.0°) in the centre of the screen. The search display consisted of five filled circle non-targets and a filled diamond target (all shapes subtended 1.6°). The diamond target and three of the non-target circles were always grey (CIE *x*, *y* chromaticity coordinates of .327/.400). Depending on the trial type (see Design), the remaining two circles were either rendered in orange, blue, pink, or green so as to be a coloured distractor (CIE *x*, *y*, chromaticity coordinates, orange: .492/.445, blue: .192/.216, pink: .407/.336, green: .302/.538), or rendered in the same shade of grey as the other shapes. The luminance of grey (~8.3 cd/m^2) was lower than that of the other colours (~24.5 cd/m^2). The feedback display showed the points earned on the current trial. If response time (RT) exceeded 1000 ms, the message "+0 points. Too slow" was presented. If the participant looked at one of the coloured distractors before moving their eyes to the target, the feedback "You looked at the [COLOUR] distractor" was presented alongside the reward feedback.

Design

The location of the target was determined randomly on each trial. A small circular region of interest (ROI) with diameter 3.5° was defined around the target, with a larger ROI (diameter 5.1°) defined around each coloured distractor. A response was registered after the participant accumulated 100 ms of gaze dwell time within the target ROI. Responses with RTs slower than 1000 ms were not rewarded. The distractors were categorised on two different dimensions: *reward* (high/low) and *contingency* (omission/safe; see Figure 2B).

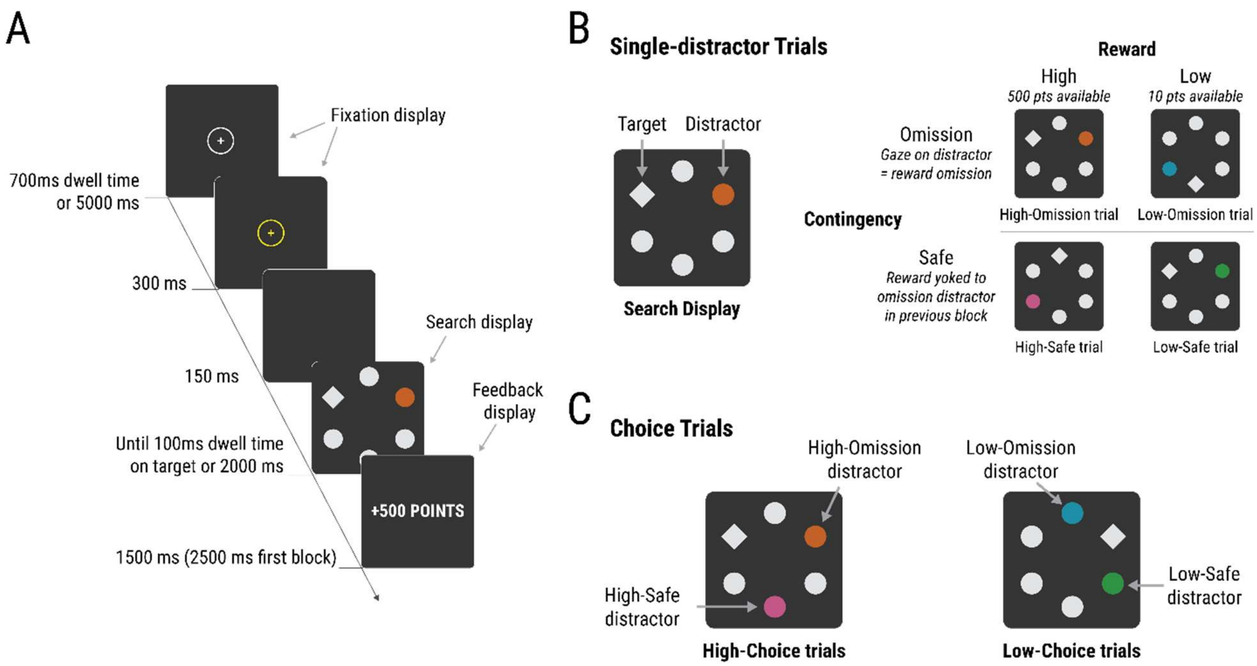

Figure 2. Trial structure of Experiments 1 and 2. (A) Each trial began with the presentation of a central fixation cross. A search display then appeared, and participants were required to make a rapid saccade to the grey diamond target. On single-distractor trials (B) there was one coloured distractor present in the search display. Each distractor was categorised on two dimensions: reward (high/low) and contingency (omission/safe). High-reward distractors signalled that 500 points were available for a rapid saccade to the target; low-reward distractors signalled that 10 points were available. If participants looked at the omission distractor before the target, the reward for the trial was cancelled, whereas looking at the safe distractor had no effect on reward delivery (reward was yoked to the omission distractor of equivalent reward level). On choice trials (C), both distractors of a given reward-level appeared in the same search display. In Experiment 1, looking at the omission distractor on choice trials triggered the omission of reward, whereas looking at the safe distractor did not affect reward delivery. In Experiment 2, no reward was available on choice trials.

High-reward distractors signalled that 500 points were typically available for a rapid eye-movement to the target, whereas low-reward distractors signalled that 10 points were typically available. If gaze was detected on the ROI surrounding an omission distractor, the reward for the trial was cancelled (i.e., a reward omission was triggered), whereas gaze on the ROI surrounding a safe distractor did not trigger a reward omission. Thus, there were four different types of distractor, with each corresponding to a different combination of reward level and contingency*: high-omission, high-safe, low-omission*, and *low-safe*. Each distractor type was rendered in a different colour (from the set: orange, blue, pink, and green), with the assignment of colours counterbalanced across participants.

Each trial was either a *single-distractor* trial, a *choice* trial, or a *distractor-absent* trial. On single-distractor trials, there was one colour singleton distractor present in the search display (Figure 2B). The reward available for a rapid saccade to the target was determined by the type of distractor that was present (500 points for high-reward distractors, 10 points for low-reward distractors). If the distractor was an omission distractor, then the reward for the trial was omitted if participants looked at the distractor. If the distractor was a safe distractor, then the reward for the trial was randomly determined based on the omission rate for trials containing the omission distractor of equivalent reward level in the previous block of trials (i.e., if the participant triggered reward omissions on 4 of 10 high-omission trials in block *b*, reward would randomly be omitted on 4 of 10 high-safe trials in block *b* + 1). The only exception was during the first block of training, in which an omission could never be triggered on single-distractor trials containing the 'safe' distractor, as there was no previous block of trials to determine the appropriate omission rate. Yoking the omission rate for the 'safe' distractor to the omission rate of the corresponding 'omission' distractor in this way ensured that each distractor had an approximately equivalent signalling relationship with reward (i.e., each distractor was paired with reward approximately the same number of times, such that the cumulative expected values for the safe and omission distractors of a particular reward level were similar), while removing the negative response relationship from the safe distractor.

On choice trials, both the omission and safe distractors for a particular reward level were present in the same search display. Thus, there were two different types of choice trial: high-choice, and low-choice (Figure 2C). The reward available for an accurate eye-movement to the target corresponded to the reward level of the distractors present in the display (i.e., 500 points on high-choice trials, and 10 points on low-choice trials). If gaze was detected in the ROI surrounding the omission distractor, the reward for the trial was cancelled. However, if gaze was detected in the ROI surrounding the safe distractor, the reward for the trial remained available.

On distractor-absent trials, all non-target shapes were rendered in grey, and no reward was available. One of the non-target circles was chosen to act as a 'distractor' location: trials in which gaze fell on the ROI surrounding this ‘distractor’ location were recorded as a baseline measure of eye-movements to physically non-salient non-targets.

The experiment comprised 50 blocks of 16 trials each, for a total of 800 trials. Each block consisted of 4 single-distractor trials (1 with each distractor type: high-omission, high-safe, low-omission, low-safe), 8 choice trials (4 with distractors from each reward level: high-choice, low-choice) and 4 distractor-absent trials. On single-distractor trials, the location of the distractor was random with the constraint that it was never positioned directly opposite the target but was either one or two positions away (i.e., the polar angle between the target and the distractor was either 60° or 120°). On choice-trials, one distractor was positioned with the same constraints as above, and the second distractor was positioned so as to be the same distance from the target (i.e., if the first distractor was 60° from the target in the clockwise direction, the second distractor would be 60° from the target in the anticlockwise direction). On distractor-absent trials, the grey circle that was selected to act as a ’distractor’ location was chosen following the same constraints as on single-distractor trials.

Procedure

Participants were told that their task was to move their eyes to the diamond target “as quickly and directly as possible”. Participants were also given instructions about the reward level and contingency of each distractor type: that is, they were told which colours signalled high and low reward for a rapid saccade to the target, and the consequences of looking at each type of distractor before making a saccade to the target (i.e., whether it would cause reward omission or not). Participants were told that they could earn between 7 and 15 AUD for good performance, but no specific information about the conversion rate from points to money was provided. Each trial began with the presentation of the fixation display. Participants’ gaze location was superimposed over the display as a small yellow dot. Once 700 ms of gaze time had accumulated within the circle surrounding the fixation cross, or after 5000 ms, the cross and the circle turned yellow and the dot marking gaze location disappeared. After 300 ms the screen blanked, and after a 150 ms delay the search display appeared and remained on screen until a response was recorded, or the trial timed out after 2000 ms. The feedback display then appeared and remained on screen for 2500 ms during the first block, and 1500 ms in all subsequent blocks. The inter-trial interval was 700 ms. Participants took a short break after every 4 blocks.

Data Analysis

In line with previous analysis protocols (Le Pelley et al., 2015; Pearson et al., 2015, 2016), data from the first two trials, and the first two trials after each break were discarded. Timeouts (1.8% of all trials) were also discarded. Data from one participant were discarded because the mean proportion of valid gaze samples during each trial was less than 50%. For the remaining participants, valid gaze data were registered on an average of 97.3% (SD = 7.2%) of samples, suggesting high fidelity of gaze data.

Saccades were identified from the raw gaze data (300 Hz sample rate) using a velocity-threshold identification algorithm (Salvucci & Goldberg, 2000) with a threshold of 40° visual angle per second. Saccade latency was measured as the duration from search display onset to the point at which eye-movement velocity exceeded the threshold. To determine the direction of the first saccade on each trial, the angular deviation between the saccade endpoint and each stimulus location was calculated, and a saccade was classified as going in the direction of a stimulus if the angular deviation was less than 30° from the centre of that stimulus. For analysis of fixation duration, the first fixation was defined as the period in which velocity was less than 40°/s following the first saccade. In line with previous protocols (Pearson et al., 2016), we excluded all trials containing anticipatory saccades (saccade latency <80 ms; 7.2% of all trials), trials in which no gaze was recorded within 100 pixels (5.1°) of the fixation point within the first 80 ms (4.2% of trials), and trials in which there was insufficient gaze data to detect a saccade (1.1% of trials). Data from two participants were excluded from the saccade analyses due to having >50% of trials discarded according to these criteria. Data from two additional participants were excluded from the fixation duration analysis as they never made a saccade to one of the distractor types on either high-choice or low-choice trials.

Statistical analyses were conducted in R (Version 3.5.1; R Core Team, 2018) with the afex package (Singmann et al., 2018) used to calculate ANOVAs. Greenhouse-Geisser corrections to degrees of freedom are reported where appropriate. In cases where a conclusion is drawn on the basis of a null effect, we report the Bayes factor that corresponds to a Bayesian *t*-test using the default JZS prior (Rouder et al., 2009), conducted using the BayesFactor package (Morey & Rouder, 2018). Bayes factors are interpreted in line with the guidelines suggested by Jeffreys (1961; Lee & Wagenmakers, 2014)

Results

Single-distractor trials

Figure 3A shows the percentage of single-distractor trials on which participants looked at the colour singleton distractor (or the designated 'distractor' location), across single-distractor and distractor-absent trials. Planned paired-samples *t*-tests confirmed that the colour-singleton distractors captured overt attention, with participants more likely to look at the distractor location on all trial types that featured a colour-singleton distractor than on distractor-absent trials (all p < .001, d_z > 1.27). More importantly, ANOVA analysis of data from single-distractor trials with factors of reward (high-reward vs low-reward) and contingency (omission vs safe) revealed a main effect of reward, $F(1, 38) = 15.0$, $p < .001$, $\eta_p^2 = .283$, with participants more likely to look at high-reward distractors than low-reward distractors—i.e., there was a significant VMAC effect on single-distractor trials. While Figure 2A suggests a trend towards participants looking at the distractor more often on high-safe trials than high-omission trials, contingency did not exert a significant main effect, $F(1, 38) = 0.73$, $p = .398$, $\eta_p^2 = .019$, or interact with reward, $F(1, 38) = 2.01$, $p = .164$, $\eta_p^2 = .050$.

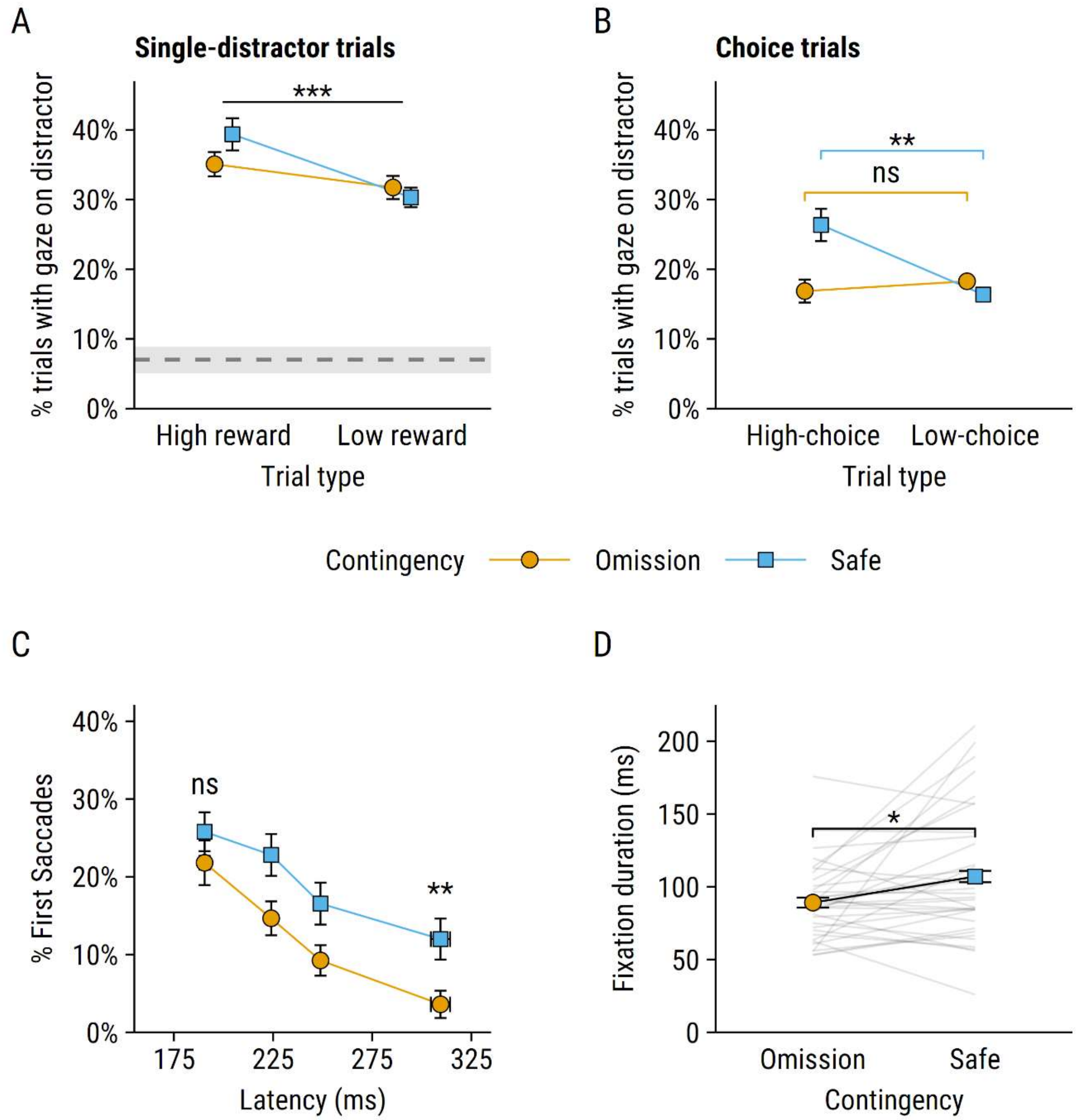

Figure 3. Results of Experiment 1. (A) Percentage of trials with gaze on the distractor location on single-distractor trials. Dashed line represents baseline performance on distractor-absent trials. (B) Percentage of trials with gaze on each distractor type on choice trials. (C) Percentage of first saccades in the direction of each type of distractor (omission and safe) as a function of saccade latency on high-choice trials. (D) Fixation duration following first saccades to the omission and safe distractor on high-choice trials. Faint grey lines show individual participant performance. Error bars and shaded areas in all figures represent within-subjects SEM (Morey, 2008). * $p < .05$, ** $p < .01$, *** $p < .001$, ns = non-significant.

Choice trials

Figure 3B shows the percentage of trials on which participants looked at each distractor type on high-choice and low-choice trials. ANOVA analysis of these data revealed a significant main effect of reward (high-reward vs low-reward), $F(1, 38) = 14.45$, $p < .001$, $\eta_p^2 = .275$, as well as a significant main effect of contingency (omission vs safe), $F(1, 38) = 4.40$, $p = .043$, $\eta_p^2 = .104$. Critically, there was also a significant reward × contingency interaction, $F(1, 38) = 6.62$, $p = .014$, $\eta_p^2 = .148$. Follow-up paired-samples *t*-tests revealed that participants were significantly more likely to look at the safe distractor on high-choice trials than low-choice trials, $t(38) = 3.36$, $p = .002$, $d_z = 0.53$. That is, there was a significant VMAC effect on choice-trials when comparing gaze on the safe distractors. By contrast, there was no significant difference between high-choice and low-choice trials in the rate of capture by the omission distractor, $t(38) = 0.75$, $p = .45$, $d_z = .12$, with a corresponding Bayes Factor of $BF_{01} = 4.45$, indicating moderate support for the null hypothesis. Recall that greater capture by a high-omission distractor than a low-omission distractor is the typical VMAC result (e.g., Le Pelley et al., 2015). However, the current findings show that when participants were given the option to direct their gaze to a ‘safe’ distractor without a negative response contingency, there was no difference in the rate of capture by the two omission distractors. Thus, while participants were more likely to look at a reward-associated distractor on high-choice trials than low-choice trials, they were able to preferentially direct their gaze towards the high-safe distractor (for which looking had no negative consequence) over the high-omission distractor (for which looking resulted in the omission of reward).

Orthogonal *t*-tests were conducted to investigate whether there was a significant effect of distractor type (omission vs safe) within each type of trial (high- and low-choice) separately. On high-choice trials, participants were significantly more likely to look at the safe distractor than the omission distractor, $t(38) = 2.46$, $p = .018$, $d_z = 0.39$. That is, the response relationship of high-reward distractors exerted a significant influence on performance on choice trials. By contrast, on low-choice trials there was no significant difference in the percentage of trials with gaze on the omission and safe distractors, $t(38) = 1.57$, $p = .126$, $d_z = 0.25$. For this latter contrast, the corresponding Bayes factor of $BF_{01} = 1.89$ indicated only anecdotal support for the null hypothesis; notably, however, Figure 3B shows that the numerical trend was that participants were *less* likely to look at the safe distractor than the omission distractor on low-choice trials. If the analysis is restricted to investigating whether participants were more likely to look at the safe distractor than the omission distractor (as would be predicted if the low-omission distractor's response relationship was influencing attention), the corresponding one-tailed Bayes factor was $BF_{01} = 13.76$, indicating strong support for the hypothesis that participants were no more likely to look at the safe distractor than the omission distractor on low-choice trials.

Time-course of oculomotor capture

Reactive processes take time to implement, and thus should primarily affect longer-latency saccades (Geng, 2014). By contrast, shorter-latency saccades are primarily driven by the early representation of stimuli on the priority map (Godijn & Theeuwes, 2002; van Zoest et al., 2004). Therefore, if participants are using reactive processes to preferentially direct their gaze to the safe distractor over the omission distractor on high-choice trials, we should expect to see this preference emerge as saccade latency increases. Alternately, if the oculomotor preference for safe distractors is driven by proactive down-weighting of the attentional priority of the high-omission distractor as a consequence of training with a negative response contingency, we would expect to observe the effect among the most rapidly initiated saccades. In order to investigate the time-course of the overt attentional preference for the safe distractor on high-choice trials, we analysed the percentage of first saccades going towards the omission and safe distractors using the Vincentizing procedure (Ratcliff, 1979). We calculated mean saccade latency and the percentage of first saccades going towards each distractor for each quartile of the individual saccade latency distributions. As the overall analysis of choice trials suggested an oculomotor preference for the safe distractor on high-choice trials only, we restricted the time-course analysis to high-choice trials (see Figure 3C). However, for completeness we report a similar time-course analysis of low-choice trials in Supplementary Materials.

ANOVA with factors of contingency (omission vs safe) and quartile (1-4) revealed a significant main effect of quartile, $F(2.32, 83.37) = 49.38$, $p < .001$, $\eta_p^2 = .578$, with fewer saccades being directed towards either distractor as saccade latency increased. There was also a significant main effect of contingency, $F(1, 36) = 4.46$, $p = .042$, $\eta_p^2 = .110$, with saccades more often directed to the safe distractor than the omission distractor, averaged across saccade latency quartile. The quartile × contingency interaction was non-significant, $F(2.15, 77.26) = 0.77$, $p = .474$, $\eta_p^2 = .021$. However, as we were specifically interested in whether the oculomotor preference for the safe distractor was present among participants' fastest eye-movements, or otherwise emerged as saccade latency increased, paired-samples *t*-tests were used to compare the percentage of first saccades directed to the high-omission and high-safe distractor for the fastest and slowest quartiles of saccades. There was a non-significant difference in the proportion of fastest-quartile saccades directed to the omission versus safe distractor, $t(36) = 0.91$, $p = .37$, $d_z = 0.15$, with a corresponding Bayes factor of $BF_{01} = 3.86$ indicating moderate support for the null hypothesis that participants were equally likely to direct their fastest saccades towards either distractor. Given that we are specifically interested in whether participants were less likely to direct their gaze to the omission distractor than the safe distractor on choice trials, a one-tailed Bayesian *t*-test may be considered more appropriate; this analysis also indicated that the evidence was in favour of the null hypothesis of no difference between the two distractor types, $BF_{01} = 2.39$. By contrast, for the slowest quartile of saccades, participants were significantly less likely to direct their gaze towards the high-omission distractor compared to the high-safe distractor, t(36) = 2.87, p = .007, d_z = 0.47, suggesting that the oculomotor preference for the safe distractor on high-choice trials emerged with increased saccade latency.

Fixation duration

Figure 3D shows the average fixation duration for the first fixation after a saccade to the omission and safe distractors on high-choice trials. Participants' first fixations were significantly shorter following a first saccade to the omission distractor than the safe distractor, $t(34)$ = 2.68, p = .011, d_z = 0.45, suggesting that participants were faster to disengage from the omission distractor on high choice trials. By contrast, on low-choice trials fixation durations were not significantly different following saccades to the omission distractor relative to the safe distractor (see Supplementary Materials).

Discussion

In Experiment 1, participants were more likely to have their gaze captured by a physically salient distractor that signalled high reward, than an equivalent distractor that signalled low reward. That is, participants demonstrated a VMAC effect. Importantly, however, while participants were seemingly unable to prevent themselves from having their gaze captured by distractors that signalled high reward, they were able to preferentially direct their gaze to a 'safe' distractor for which capture had no negative consequences, over a distractor for which capture resulted in the omission of reward, when both options were available to them. Notably, participants did not show such a preference when low reward was at stake. This suggests that participants specifically learned to direct their gaze to the high-safe distractor over the high-omission distractor, presumably because looking at the high-omission distractor resulted in the omission of a high-value reward, whereas looking at the low-omission distractor resulted in the omission of only a low-value reward. Thus, these results add to recent findings (Pearson & Le Pelley, 2020) in indicating that attentional selection is influenced by a stimulus's *response relationship* with reward as well as its *signalling relationship* with reward.

While participants were generally more likely to look at a safe distractor than an omission distractor on high-choice trials, no significant preference was observed among the most rapidly initiated saccades, with a Bayesian analysis suggesting moderate support for the null hypothesis of no preference. This suggests that the shortest-latency saccades did not show sensitivity to the stimulus's response relationship with reward. On the other hand, the longest-latency saccades did demonstrate a significant preference for the safe distractor over the omission distractor, suggesting that the oculomotor preference for the distractor without a negative response relationship emerges as saccade latency increases. The implication is that the response pathway may influence attentional selection by encouraging reactive control processes, rather than by proactively changing the stimulus's attentional priority (which has previously been demonstrated to be the mechanism through which the *signalling* pathway influences attentional selection; see Failing et al., 2015; Pearson et al., 2016). Further support for this reactive account comes from the analysis of fixation duration on choice trials. Participants had shorter fixations (i.e., were faster to move their eyes away) following saccades to the omission distractor than to the safe distractor on high-choice trials. This suggests that, following capture of attention, participants used reactive control processes to rapidly disengage their attention from the high-omission distractor (Geng, 2014; Geng & DiQuattro, 2010; Godijn & Theeuwes, 2002; Watson et al., 2020).

However, some aspects of the data from Experiment 1 warrant further consideration. When averaged across saccade latency, saccades were more likely to go towards the safe distractor than the omission distractor on high-choice trials. A planned comparison found that this preference was significant in the slowest quartile of saccades, but no significant difference for the fastest quartile of saccades, in line with the idea that the preference for the safe distractor emerged for longer-latency saccades. Notably, however, the interaction between distractor contingency and saccade latency quartile was non-significant—that is, participants' oculomotor preference for the high-safe distractor over the high-omission distractor did not significantly vary across saccade latency. These somewhat inconsistent findings make it difficult to tease apart the reactive and proactive accounts of the response pathway's influence on attentional selection: the result of the planned contrasts suggest that response contingencies do not influence the fastest saccades, in line with an account based on reactive processes;

whereas the non-significant interaction suggests that the effect of response contingencies on selection may not depend on saccade latency, and thus may (at least partially) involve a proactive change in the early priority-map representation of the distractor.

Notwithstanding the above, the fact that we did not observe a preference for the safe distractor over the omission distractor among the fastest saccades is consistent with a relatively slow, reactive influence of the response relationship on attentional selection. This leads to the question of how that influence is mediated. One possibility is that the reactive influence of the response relationship is a goal-directed effect that is under participants' volitional control. Indeed, directing gaze to the safe distractor on high-choice trials was in line with participants' goal of maximising reward. Recall that the most effective behaviour in this task is to avoid all coloured distractors entirely—they are never the target of participants' search and avoiding them would result in delivery of reward on every trial. If, however, participants are sometimes unable to prevent themselves from looking at a high-reward distractor, then the 'next-best' option is that they would preferentially direct their gaze to the safe distractor rather than the omission distractor, since this is a better option in terms of their overall goal of maximising reward. Alternatively, the reactive suppression of the high-omission distractor could be triggered (or enhanced) as an automatic consequence of participants' recent experience with that distractor (i.e., the suppression process can be driven by selection-history). In

Experiment 1, repeated training with the response relationship of the high-omission distractor may have automatically enhanced reactive suppression of that high-omission distractor through a process of instrumental learning. According to this account, repeatedly experiencing a stimulus's signalling relationship with reward automatically increases its attentional priority, whereas repeatedly experiencing a stimulus's response relationship with reward automatically improves reactive disengagement from that stimulus.

In summary, it is possible that the influence of the response contingency on oculomotor behaviour observed in Experiment 1 reflects either goal-directed control, or a more automatic consequence of training via repeated exposure to the different response contingencies (i.e., an effect of selection history). Experiment 2 attempted to discriminate between these alternative interpretations. The influence of selection history on attention is known to persist even when the consequences are counter to the participant's current goals (Awh et al., 2012; Failing & Theeuwes, 2018; Theeuwes, 2018). Thus, if the oculomotor preference for the safe distractor over the omission distractor on high-choice trials were an automatic consequence of training with the response contingencies (a selection history effect), then this bias should persist even when there is no goal-directed benefit to looking at the safe distractor over the omission distractor on choice trials. By contrast, if the preference for the high-safe distractor reflected strategic control of attention (a goal-directed effort to prevent reward omission), then this bias should disappear if we were to remove the benefit to selecting the safe distractor over the omission distractor. Experiment 2 tested this idea.

Experiment 2

In Experiment 2, reward was made unavailable on choice trials. As a result, there was no longer any goal-directed benefit to directing gaze to the safe distractor over the omission distractor on these trials. If the preference for the high-safe distractor over the high-omission distractor on the choice trials of Experiment 1 was a consequence of volitional goal-directed control, we should not expect to see any preference for the high-safe distractor on choice trials in Experiment 2. By contrast, if the preference for the safe distractor over the omission distractor was an automatic consequence of training with the different response relationships on the single distractor trials, we should expect this preference to persist on choice trials of Experiment 2, even though now there was no advantage to be gained by this pattern (since rewards were never available on choice trials).

To give participants sufficient opportunity to experience the signalling and response relationships before expressing this learning on choice trials, in Experiment 2 we split the task into two phases. In the first phase, participants were trained primarily with single-distractor trials (that were rewarded as in Experiment 1). In the second phase, participants were primarily presented with unrewarded choice trials.

Method

Participants

A power analysis conducted with G*Power indicated that a sample size of 56 participants would provide adequate power (power ~.85) to reliably detect the critical reward × contingency interaction on choice trials with an equivalent effect size to that observed in Experiment 1 (d_z = 0.41). Therefore, 56 UNSW Sydney students (39 females, age *M* = 22.2 years, *SD* = 3.05 years) participated in Experiment 2 in exchange for course credit. All participants received a monetary bonus that was dependent on their performance (*M* = 11.80 AUD, *SD* = 1.72 AUD).

Apparatus, stimuli and design

The apparatus and stimuli were identical to those of Experiment 1. All details of the trial types were as for Experiment 1, with two exceptions: (1) there was no reward available on choice trials, so there was no advantage to directing gaze to the safe distractor over the omission distractor on these trials; and (2) there were no distractor-absent trials.

Experiment 2 consisted of two phases. In the first phase, participants experienced primarily single-distractor trials, whereas in the second phase, participants experienced primarily choice trials. Phase 1 comprised 14 blocks of 36 trials. Each block of phase 1 consisted of 32 single-distractor trials (8 with each distractor type: high-omission, high-safe, low-omission, low-safe) and 4 choice trials (2 high-choice, 2 low-choice). Phase 2 comprised 10 blocks of 36 trials, with each block consisting of 8 single-distractor trials (2 with each distractor type) and 28 choice trials (14 high-choice, 14 low-choice). Splitting the task into these two phases allowed participants sufficient opportunity to experience the different signalling and response relationships of each distractor during the first phase, before seeing how these relationships affected performance on choice-trials in the second phase. All other aspects of the design were as for Experiment 1.

Procedure

The general procedure was the same as in Experiment 1. The only difference was that, in Experiment 2, participants were explicitly informed that there would be no reward available on choice trials but were instructed that they should “still try and move (their) eyes to the diamond as quickly and accurately as possible”.

Data Analysis

Data from one participant were discarded due to equipment failure part-way through the experiment. For remaining data, the same analysis protocol was used as in Experiment 1. Trials that timed out with no response (2.2% of trials) were discarded. For the analysis of saccade latency and time-course of oculomotor capture, 6.4% of trials were discarded due to anticipatory saccades, 5.7% of trials were discarded due to no valid gaze samples being recorded within 5.1° of the fixation point in the 80 ms after display onset, and 2.5% of trials were discarded due to insufficient gaze data to detect a saccade.

Results

Single-distractor trials

Figure 4A shows the percentage of single-distractor trials on which the participant looked at the colour-singleton distractor across all single-distractor trial types, averaged across both phases. ANOVA revealed a significant main effect of reward, $F(1, 54) = 13.36$, $p < .001$, $\eta_p^2 = .198$, with participants more likely to look at a high-reward distractor than a low-reward distractor. Contingency did not exert a significant main effect, $F(1, 54) = 0.12$, $p = .729$, $\eta_p^2 = .002$, or interact with reward, $F(1, 54) = 0.15$, $p = .704$, $\eta_p^2 = .003$.

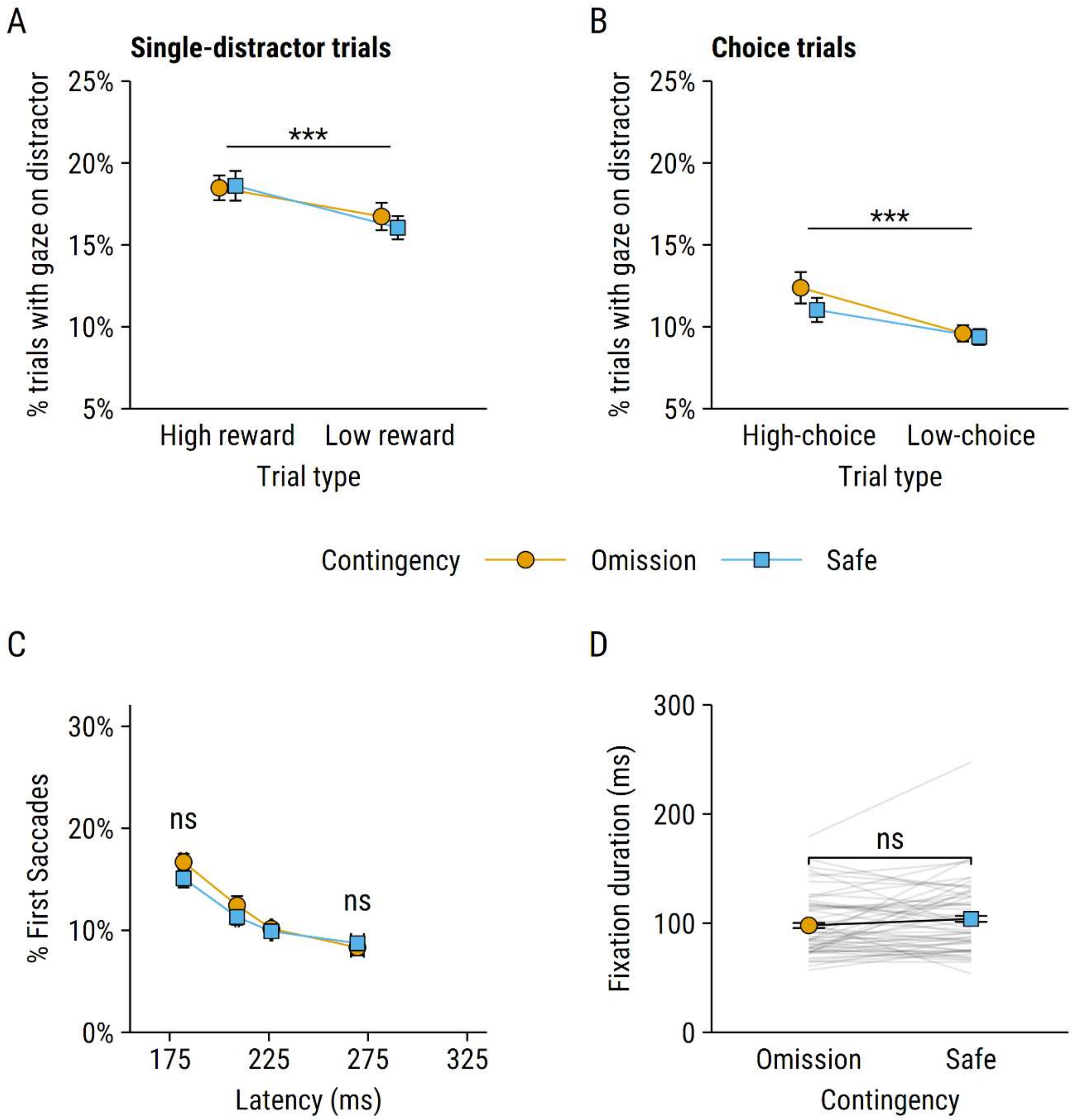

Figure 4. Results of Experiment 2. (A) Percentage of trials with gaze on the distractor location on single-distractor trials. (B) Percentage of trials with gaze on each distractor type on choice trials. (C) Percentage of first saccades in the direction of each type of distractor (omission and safe) as a function of saccade latency on high-choice trials. (D) Fixation duration following first saccades to the omission and safe distractor on high-choice trials. Faint grey lines show individual participant performance. *** p < .001, ns = non-significant.

Choice trials

Figure 4B shows the percentage of trials on which participants looked at each type of distractor on high-choice and low-choice trials, averaged across both phases. ANOVA with factors of reward (high-reward vs low-reward), and contingency (omission vs safe) indicated a significant main effect of reward, $F(1, 54) = 17.75$, $p < .001$, $\eta_p^2 = .247$, with participants more likely to look at distractors on high-choice trials than low-choice trials. The main effect of contingency was non-significant, $F(1, 54) = 1.05$, $p = .311$, $\eta_p^2 = .019$. Critically, the reward × contingency interaction was also non-significant, $F(1, 54) = 0.31$, $p = .583$, $\eta_p^2 = .583$. In Experiment 1, participants demonstrated a VMAC effect on choice trials when considering the high- and low-safe distractors, but no VMAC effect for the high- and low-omission distractors. In order to quantify the support for this pattern of results in Experiment 2, a one-tailed Bayesian t-test was conducted, which indicated moderate support for the null hypothesis of no difference in the size of the VMAC effect between the two distractor types, $BF_{01} = 9.93$. Similarly, in Experiment 1, participants were significantly more likely to look at the high-safe distractor than the high-omission distractor on high-choice trials. By contrast, in Experiment 2 a one-tailed Bayesian t-test indicated strong support for the null hypothesis of no difference in the rate of oculomotor capture by the two distractor types, $BF_{01} = 11.69$.

Time-course of oculomotor capture

To assess the time-course of oculomotor capture on choice trials, we again analysed the proportion of first saccades going towards the omission and safe distractors on high-choice trials as a function of their saccade latency (see Figure 4C). Data were analysed using ANOVA with factors distractor contingency (omission vs safe) and latency quartile (1–4). This revealed a main effect of quartile, $F(2.76, 149.08) = 50.97$, $p < .001$, $\eta_p^2 = .486$, with participants less likely to saccade towards distractors as saccade latency increased. Distractor contingency did not exert a significant main effect, $F(1, 54) = 0.48$, $p = .491$, $\eta_p^2 = .009$, or significantly interact with quartile, $F(2.67, 144.08) = 1.09$, $p = .350$, $\eta_p^2 = .020$. Planned *t*-tests were used to investigate whether participants preferentially directed their most rapidly initiated saccades, or their slowest saccades, towards either the safe or omission distractor on high-choice trials. These analyses indicated that both the fastest and the slowest quartiles of saccades were equivalently likely to be directed toward either type of distractor: fastest quartile, $t(54) = 1.17$, $p = .247$, $d_z = 0.16$, $BF_{01} = 3.56$ (one-tailed: $BF_{01} = 13.81$); slowest quartile, $t(54) = 0.59$, $p = .560$, $d_z = 0.08$, $BF_{01} = 5.77$ (one-tailed: $BF_{01} = 4.03$).

Fixation duration

Figure 4D shows average fixation durations following saccades to the omission and safe distractors on high-choice trials. There was no significant difference in the duration of fixations following a saccade to the omission distractor versus the safe distractor, $t(54) = 1.66$, $p = .103$, $d_z = 0.22$. However, the corresponding Bayes factor of $BF_{01} = 1.89$ suggested only anecdotal evidence in support of the null hypothesis. Similarly, on low-choice trials fixation durations were not significantly different following saccades to the omission distractor versus the safe distractor (see Supplementary Materials).

Discussion

In Experiment 2, participants once again demonstrated a significant VMAC effect: they were more likely to look at distractors that signalled high reward than those that signalled low reward across both single-distractor and choice trials. However, when there was no goal-directed benefit to looking at the safe distractor on choice trials (as there was no reward available on these trials), participants were equally likely to look at the omission distractor as the safe distractor, and this pattern did not vary across saccade latencies. This suggests that the oculomotor preference for the safe distractor seen on high-choice trials in Experiment 1 was driven by goal-directed attentional control processes, rather than being an automatic consequence of repeated experience with the different response contingencies associated with safe and omission distractors (i.e., selection history).

General Discussion

The current study investigated the extent to which a stimulus's response relationship with reward influences attentional selection. Across two experiments, participants completed a visual search task that featured four different distractor stimuli. Two of these distractors signalled availability of high reward for a rapid saccade to the target, and two signalled low reward. Within each reward-level set, the ‘omission’ distractor had a negative response relationship with reward (making a saccade to this distractor resulted in the omission of reward), whereas the ‘safe’ distractor had no response relationship with reward (making a saccade to this distractor had no consequence for reward delivery). In both experiments, participants were more likely to look at distractors signalling high reward than distractors signalling low-reward, even though looking at the distractors was counterproductive to participants’ task of moving their eyes to the target—i.e., they demonstrated a VMAC effect. However, while participants were seemingly unable to prevent their gaze from being captured by signals of high reward, Experiment 1 demonstrated that participants could preferentially direct this capture to the safe distractor rather than the omission distractor when high reward was at stake and both distractors appeared in the search display. This finding adds to recent research in suggesting that attentional selection is influenced by both a stimulus’s signalling relationship with reward, as well as its response relationship with reward (Pearson & Le Pelley, 2020).

What is the mechanism for the response pathway's influence on attentional selection?

Reactive versus proactive?

There are thought to be two different sets of mechanisms that the visual attention system can use to suppress distracting information (Geng, 2014). The attentional priority of a distractor can be proactively suppressed (e.g., Gaspelin & Luck, 2018a; Wang & Theeuwes, 2018), such that it is treated as less 'salient' from the moment that it is presented to the observer, and is therefore less likely to capture attention and gaze. Alternately, a distractor can be reactively suppressed (e.g., Geng & DiQuattro, 2010), such that attention is rapidly disengaged from the distractor following initial capture, and redirected to another stimulus in the display. The analysis of the time-course of capture in Experiment 1 suggests that a stimulus's response relationship with reward influences attentional selection through a reactive mechanism. While, participants' slowest saccades were more likely to be directed to a high-reward distractor that had no negative consequences for capture than a high-reward distractor for which there were negative consequences for capture, this preference was not present among participants' most rapidly initiated saccades. The finding that the fastest saccades were equally distributed between the reward-signalling distractors, regardless of their response contingency, suggests that the response pathway's influence on attentional selection takes time to be implemented and thus must rely on a reactive process. Further evidence suggestive of a reactive process comes from analyses of the duration of fixations following capture by each of the distractors: participants spent less time fixating on the high-reward distractor that had negative consequences for capture (the ‘high-omission’ distractor) than the distractor that had no negative consequences for capture (the ‘high-safe’ distractor). The implication is that covert attention is initially captured by the reward-related distractors on the basis of their signalling relationship with reward (in addition to their physical salience), and then attention is rapidly disengaged from the omission distractor based on its response relationship with reward. On trials where this disengagement occurs before a saccade is initiated to the omission distractor, the saccade can be redirected to another stimulus in the search display (e.g., the safe distractor or the target) and thus the omission distractor will not capture gaze. When the disengagement instead occurs after a saccade is initiated to the omission distractor, gaze is captured by the omission distractor, but the eyes do not linger on it for long, as the rapid disengagement of attention allows a second saccade to another stimulus to be produced quickly (cf. Geng & DiQuattro, 2010; Godijn & Theeuwes, 2002).

It is instructive to consider how this framework tallies with the findings of Pearson and Le Pelley (2020), which suggested that participants who experienced the response contingency between making a saccade to the distractor and the omission of reward could exert partial—but not total—control over the VMAC effect. To briefly recap those findings, participants who experienced the omission contingency showed less capture by the high-reward distractor than those who did not experience the omission contingency. However, both groups of participants demonstrated a significant VMAC effect overall (i.e., they were more likely to look at the high-reward distractor than the low-reward distractor). By contrast, on choice trials of the current Experiment 1, the ‘standard’ VMAC effect was eliminated—i.e., there was no difference in the rate of capture by the high-omission and low-omission distractors when participants were given the opportunity to look at a ‘safe’ distractor. This raises the question: how does the presence of a safe distractor allow participants to completely overcome the standard VMAC effect? One possibility is that reactive suppression processes are more effective at resolving competition between two salient stimuli than they are at preventing capture by salient stimuli altogether (cf. Godijn & Theeuwes, 2002). For instance, on high-choice trials of Experiment 1, participants were presented with two physically-salient, reward-signalling distractors that would rapidly generate large peaks of activity on the priority map (Figure 5A). In addition, the target would gradually generate a peak of activity as (slow) goal-directed inputs to the priority map are incorporated. Covert attention will initially be drawn towards the highest peak of activity, but if this peak is associated with the omission distractor, reactive suppression processes are activated and attention is rapidly disengaged—effectively inhibiting the priority signal of the omission distractor while leaving that of the safe distractor unaffected. After the omission distractor’s priority signal decreases a small amount, the safe distractor’s priority signal becomes the largest peak on the priority map, and thus any saccades that are initiated will likely be directed towards the safe distractor. By contrast, when the omission distractor is the only physically-salient, reward-related stimulus in the display (such as on high-omission single-distractor trials; Figure 5B), there are only two peaks of activity on the priority map: a rapidly-generated peak corresponding to the distractor, and a slowly-generated peak corresponding to the target. Even as reactive suppression begins to reduce the priority signal associated with the distractor, it will remain the largest peak of activity on the priority map until eventually it is overtaken by the slow goal-directed activity associated with the target. Thus, even after suppression of the individually presented distractor has begun, it may continue to capture gaze. According to this account, then, while reactive suppression processes can somewhat reduce capture by a reward-signalling distractor that has negative consequences for capture (as was the case in Pearson & Le Pelley, 2020) these processes are considerably more effective in directing capture towards another reward-signalling (salient) stimulus that has no negative consequences for capture.

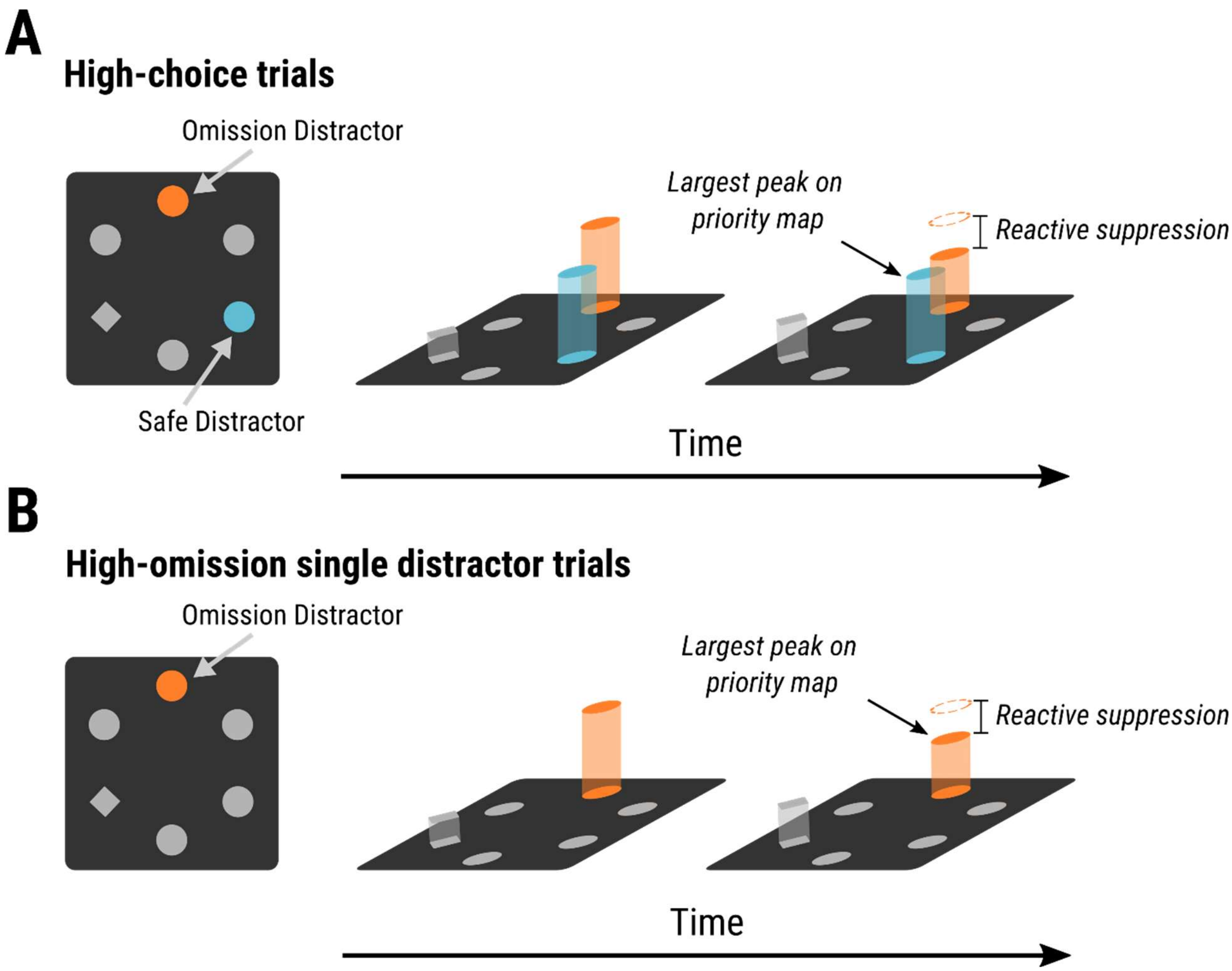

Figure 5. Images on the left show example search displays on high-choice trials and high-omission single-distractor trials; images on the right show proposed activity on the attentional priority map over time, with height indicating the magnitude of the attentional priority signal for each stimulus in the search display. (A) On high-choice trials, the activity map initially has two large peaks of activity corresponding to each of the coloured distractors, and a smaller peak associated with the target that grows as top-down influences are slowly incorporated. As time passes, participants begin to reactively suppress the omission distractor, such that the peak of activity associated with the safe distractor quickly becomes the largest peak and is therefore more likely to capture attention and gaze. (B) On high-omission single-distractor trials, there is a large peak of activity associated with the distractor and a smaller peak associated with the target. As participants begin to reactively suppress the omission distractor, its associated priority signal remains the largest peak on the priority map, and thus continues to capture attention and gaze.

Goal-directed control versus selection history?

Experiment 2 demonstrated that the reactive suppression of the high-omission distractor in Experiment 1 was a consequence of strategic goal-directed control, rather than an automatic consequence of repeated training with the response contingencies (i.e., a consequence of selection history). When there was no strategic advantage to looking at the safe distractor over the omission distractor on choice trials (as reward was unavailable), participants were still more likely to look at the distractors that signalled high-reward than the distractors that signalled low-reward, suggesting that repeated experience of a stimulus's signalling relationship with reward induces an oculomotor bias that persists even when that distractor does not currently signal reward (Mine & Saiki, 2015; Watson, Pearson, Most, et al., 2019). However, gaze was equally likely to be directed to the omission distractor as the safe distractor on these trials, indicating that the influence of the stimulus's response relationship with reward does not persist when it does not align with participants' goals, and therefore must primarily rely on goal-directed attentional control processes. Taken together then, these results suggest that a stimulus's signalling relationship with reward influences attention through selection history—in that repeatedly experiencing pairings of a distractor of a particular colour and a reward of a particular magnitude produces a long-lasting attentional and oculomotor bias that persists even when orienting to the reward-signalling stimulus is counterproductive—whereas a stimulus's response relationship with reward influences attention through encouraging strategic goal-directed control—promoting reactive suppression of stimuli that have been experienced as having large negative consequences for capture, but only when those consequences are currently active.

Motivated suppression of value-modulated attentional capture and the relative strength of signalling and response relationships with reward

A recent study by Grégoire, Britton, and Anderson (2020) examined whether reward-related attentional biases could be suppressed when participants were sufficiently motivated to avoid capture. In a similar gaze-contingent visual search task to that reported here, participants made a saccade to a shape-defined target on each trial in order to earn reward, and the identity of a colour-singleton distractor in the search display signalled the magnitude of reward that was available: a “reward” distractor signalled that reward was available, and a “neutral” distractor signalled that no reward was available. In their Experiment 1 and 2, participants were encouraged to move their eyes to the target as quickly and accurately as possible by implementing a strict response time threshold (the 33rd percentile of response times in the previous block of trials) that participants needed to beat in order to receive reward[1]. Thus, the “reward” distractor had a positive signalling relationship with reward (reward was delivered only

[1] As reward was available only on trials featuring the “reward” distractor, responding faster than the response time threshold had no consequence on trials with a “neutral” distractor.

when the “reward” distractor was present) and a negative response relationship with reward (orienting attention to the “reward” distractor would presumably prevent the participant from responding to the target faster than the response time threshold). In a subsequent “test phase”, where reward was no longer available and thus there was no goal-directed benefit to making a rapid saccade to the target, capture by the reward-signalling distractor (as measured by response times to the target and the rate of erroneous saccades to the distractor) was *reduced* relative to the neutral distractor. Notably, this pattern of results is the opposite of the standard VMAC effect (as observed in the current study and, e.g., Anderson et al., 2011; Le Pelley et al., 2015). By contrast, when the response time threshold was relaxed (such that reward was delivered on every trial in which a response was made within 2000 ms; Grégoire et al., 2020, Experiment 3) participants demonstrated the classic VMAC effect: increased capture by the reward-signalling distractor relative to the neutral distractor.

Grégoire et al.’s results suggest that there are some circumstances in which (1) a stimulus’s response relationship with reward can be the primary driver of behaviour, such that capture by a distractor that has both a positive signalling and a negative response relationship with reward is *reduced* relative to a distractor that has no relationship with reward, and (2) a stimulus’s response relationship with reward can influence attentional selection even when such selection is no longer in line with current goals. At first glance these findings do not fit neatly with those of the current study, or our previous study investigating the role of a stimulus's response contingency in attentional capture (Pearson & Le Pelley, 2020), which suggest that a stimulus's signalling relationship with reward has a larger influence on selection than its response relationship, and that the response relationship reduces capture by encouraging goal-directed suppression.

One factor that may underlie these discrepant findings is the *relative strength* of the signalling and response relationships in the two studies. In the current study, reward was omitted—due to gaze on the distractor—on around 20-35% of trials (see Figures 2A-B and 3A-B), such that participants could learn about the signalling relationship between each distractor and its associated reward on the majority (~65-80%) of trials in which reward was delivered. By contrast, in Grégoire et al.'s (2020) experiments, participants could learn about the "reward" distractor's signalling relationship only on the 33% of trials in which the participant responded faster than the response time threshold. On the other hand, while Grégoire et al.'s participants could learn about the reward-related consequences of attending to the distractor on the majority of trials in which their attention was captured by the distractor (because the strict response time threshold ensured that even covert attentional capture was likely to result in reward omission), those in the current study could learn about the response relationship between each distractor and its associated reward only on the 20-35% of trials in which covert attention was captured by the distractor, *and* they failed to reactively suppress their attention to distractor before initiating a saccade towards it. As a result, participants in the current study may have primarily learned each distractor's signalling relationship with reward (relative to the response relationships). Over the course of training, these signalling relationships are strengthened through a process of Pavlovian conditioning (Bucker & Theeuwes, 2017; Le Pelley et al., 2015; Mine & Saiki, 2018), such that the attentional priority of the high-reward distractor is enhanced and persists even when reward is no longer available (Watson, Pearson, Most, et al., 2019). However, Grégoire et al.'s design may have emphasised learning of each distractor's response relationship with reward (relative to the signalling relationships), with the response relationships strengthening through a process of instrumental conditioning, such that suppression of the reward-signalling distractor persists when reward is no longer available. It remains a question for future research to investigate whether and how the relative strength of signalling and response contingencies influence attentional selection.

Conclusion

The current results suggest that the relationship between reward and attentional selection is complex. A stimulus's signalling relationship with reward induces a powerful, proactive increase in its attentional priority, such that it comes to rapidly capture attention and gaze as though it has become more physically salient to the observer. By contrast, a stimulus's response relationship with reward can reduce the extent to which that stimulus captures gaze by encouraging reactive goal-directed control to rapidly disengage from stimuli that have negative consequences for capture.

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