Reward encourages reactive, goal-directed suppression of attention

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Abstract

2	Stimuli that signal large reward have an increased likelihood of capturing attention and
3	gaze relative to stimuli that signal small or no reward, even when capture
4	counterproductively prevents reward delivery. These findings suggest that a stimulus's
5	signalling relationship with reward (the contingency between stimulus presentation and
6	reward delivery) is a potent influence on selective attention. Recent studies have also
7	implicated a stimulus's response relationship with reward (the contingency between
8	orienting to a stimulus and reward delivery) in reducing capture by signals of reward.
9	Here we show that this response pathway modulates capture by encouraging a reactive,
10	goal-directed distractor suppression process. In a rewarded visual search task,
11	participants demonstrated an oculomotor preference away from a distractor that had a
12	negative response relationship with high reward (looking at the distractor caused reward
13	omission) and towards a distractor that had no such negative response relationship,
14	providing evidence for the role of the response relationship in suppressing capture by
15	reward-related distractors. Analysis of the temporal dynamics of eye-movements
16	suggests that this distractor suppression process operates via a reactive mechanism of
17	rapid disengagement (Experiment 1). Consistent with a goal-directed mechanism, the
18	influence of the response relationship was eliminated when reward was unavailable
19	(Experiment 2). These findings highlight the multifaceted role of stimulus-reward
20	relationships in attentional selection.

21 Keywords: Attentional capture, reward learning, distractor suppression

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Public Significance Statement:

- 24 This study highlights the complex relationship between reward and attentional selection.
- 25 Stimuli that signal rewarding outcomes come to automatically capture attention and
- gaze, even when such capture is counter to an individual's goals. However, when there
- 27 are negative reward-related consequences for attending to a stimulus, the rate of
- 28 capture can be reduced.

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attention have been labelled selection history.

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 experience-driven influences on

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One of the attentional phenomena that has been described in terms of selection history is the finding that stimuli signalling high reward have an increased likelihood of capturing attention and gaze compared to 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 to be a colour-singleton distractor. The colour of this distractor signalled the reward available for an eye-movement to the target: 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 looked at the high-reward distractor more often than the low-reward distractor, triggering the omission of more high-value rewards than lowvalue rewards. This study demonstrates that a stimulus feature's signalling relationship with reward—i.e., the rate at which that stimulus feature and reward co-occur (see Figure 1)—increases the likelihood of that feature capturing overt attention (i.e., inducing an involuntary eye-movement towards that feature), even when such capture is explicitly counterproductive. This phenomenon has been labelled value modulated attentional capture (VMAC).

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Figure 1. Schematic diagram of the signalling and response relationships in Le Pelley et al.'s (2015) VMAC task. There are two distractor-reward relationships that participants could learn in this task. The signalling relationship (shaded rectangle) is the contingency between the presence of the distractor and reward delivery: 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) is 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. Figure adapted from Pearson and Le Pelley (2020).

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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; see also Luck et al., 2020). 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 research has also been consistent with the idea that reward has a rapid influence on the visual system, with reward modulation of stimulus-driven activity being observed as early as 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 attentional bias to reward signals persists even when explicit instructions about the counterproductive consequences of orienting to the reward-signalling distractor are provided (Kim & Anderson, 2019; Pearson et al., 2015), and under conditions in which capture by physically salient stimuli can be suppressed (Kim & Anderson, 2021; Le Pelley

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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 guestion the idea that capture by reward-signalling stimuli is immune to suppression. For instance, depleting cognitive control resources by loading working memory increases the magnitude of VMAC (Watson, Pearson, Chow, et al., 2019), suggesting that goal-directed control can reduce the likelihood of (but not eliminate) 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 attending to the distractor and reward (i.e., the task described earlier in which capture by the reward-signalling distractor 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. Overall, participants 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 experience with the negative response contingency encouraged 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 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 that stimulus captures gaze, the mechanism responsible for this reduction in capture is currently unclear. The visual attention system is thought to use two distinct sets of mechanisms to suppress capture by distracting stimuli (Geng, 2014): reactive suppression involves the rapid disengagement of attention from the distractor following initial capture, but before a saccade to the distractor is initiated; whereas proactive suppression involves down-weighting the attentional priority of the distractor

prior to stimulus presentation, such that attention is never directed to it in the first place. The response relationship 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 (i.e., if the participant involuntarily attends the high-reward distractor without making an eye movement to it), 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 distractor, 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 downweighting 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).

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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 (i.e., saccades that are initiated well after the presentation of the search display), with shorter-latency saccades being primarily driven by the early priority-map representation of the stimuli in the display (Godijn & Theeuwes, 2002; van Zoest et al., 2004; Wolf & Lappe, 2020). So, the reactive account predicts that slow saccades will be preferentially directed away from stimuli that have negative response contingencies, relative to stimuli without negative response contingencies. On the other hand, fast saccades should be relatively unaffected by the response pathway, such that they will be equally distributed between stimuli that equally signal reward – regardless of whether those stimuli have a negative response contingency. By contrast, if a stimulus's response relationship with reward *proactively* alters its early representation on the priority map, we should expect even the most rapidly initiated saccades to be directed away from stimuli with negative response contingencies.

Second, previous studies have shown that reactive disengagement from a distractor stimulus produces shorter fixations on the distractor following oculomotor capture. For example, fixations on a distractor are shorter when its features are never shared with a target (so these features can be reactively suppressed) compared to when

its features can sometimes be shared with the target (Geng & DiQuattro, 2010; see also Geng, 2014; 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 tasked with moving their eyes to a diamond target in an array of circles. On most trials, one or two of the circles were coloured distractors (all other shapes were grey). There were 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 reward delivery (Figure 2B).

The critical comparison came on the trials in which both distractors of a particular reward level were presented together (*high-choice* and *low-choice* trials, Figure 2C).

These choice trials represent a particularly sensitive measure of the influence of each

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distractor's response relationship on attentional selection, as the comparison between the two distractors presented on a choice trial isolates the influence of the distractors' response relationships on capture from: (1) the influence of physical salience (as the distractors are approximately isoluminant and presented equidistant from the target, they should draw attention equally on the basis of their physical salience; see Pearson et al., 2016), and (2) the influence of each distractor's signalling relationship (as the distractors are paired with reward an equal number of times due to the yoking procedure, they should draw attention equally on the basis of their signalling relationships with reward; see Pearson & Le Pelley, 2020). As a result, any difference in the rate of capture between the distractors presented on a choice trial must be a consequence of their differing response contingencies. As in previous studies of VMAC, it was expected that participants would be unable to prevent themselves from having their gaze captured by signals of high reward on choice trials. However, if the response relationship influences attentional selection, then we should expect to see this capture preferentially directed towards the safe distractor versus the omission distractor. Moreover, if any bias for the safe distractor over the omission distractor was present among the shortest-latency saccades, 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 oculomotor bias to the safe distractor was present only for longer-latency saccades, this would suggest that the

response pathway influences attentional selection by encouraging a reactive control process. 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

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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 2.3°) arranged evenly around the centre of the screen at 5.1° eccentricity. 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/m²) was lower than that of the other colours (~24.5 cd/m²). 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).

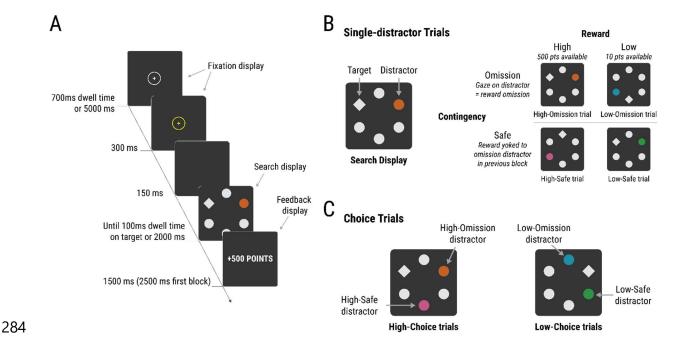


Figure 2. Trial structure of Experiments 1 and 2. (A) Each trial began with the presentation of a central fixation cross surrounded by a ring. After gaze was detected at fixation, a search display was presented, and participants were required to make aneye-movement to the grey diamond target. On single-distractor 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 making an eye-movement to the target, whereas low-reward distractors signalled that 10 points were typically available. If gaze was ever 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 distractor was positioned randomly with the constraint that it was positioned one or two positions away from the target (i.e., the angular deviation between the target and 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 instructed to move their eyes to the diamond "as quickly and directly as possible" on each trial. 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 were not provided with the specific conversion rate from points to money.

Each trial began with the presentation of a fixation display. Gaze location was shown on the screen as a yellow dot. Once 700 ms of gaze time was recorded within the circle around the fixation cross, or after 5000 ms, the cross and the circle turned yellow and the gaze location marker disappeared. The screen blanked after 300 ms, and after a 150 ms delay was followed by the presentation of the search display. The search display remained on screen until the participant moved their eyes to the target, or the trial timed out (2000 ms timeout limit). The feedback display was then presented for 1500 ms (2500 ms in the first block). Participants took a short break after every 4 blocks. The inter-trial interval was 700 ms.

Data Analysis

Primary analyses for both single-distractor and choice trials were conducted on the percentage of trials in which gaze was recorded within the distractor ROI(s). As in previously reported analysis protocols (Le Pelley et al., 2015; Pearson et al., 2015, 2016; Watson, Pearson, & Le Pelley, 2020), data from the first two trials, and the first two trials after each break were discarded to minimise the potential for artefacts as a result of

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participants (re)engaging with the task. Timeouts (1.8% of all trials) were also discarded. Data from one participant were discarded due to the mean proportion of valid gaze samples during each trial falling below 50%. Valid gaze data were registered on an average of 97.3% (SD = 7.2%) of samples, suggesting high fidelity of gaze data among the remaining participants.

For analyses of the time course of oculomotor capture and fixation duration, saccades were identified from the raw gaze data (300 Hz sample rate) using a velocitythreshold identification algorithm (Salvucci & Goldberg, 2000). Gaps in the raw gaze data shorter than 75 ms were first interpolated using linear interpolation. The gaze data were then smoothed using a five-point moving average filter. Saccade latency was measured as the duration from search display onset to the point at which eyemovement velocity exceeded 40° visual angle per second and remained above this threshold for a period of at least 10ms. The angular deviation between the saccade endpoint and the centre of each stimulus location was calculated, and the saccade was classified as going in the direction of a stimulus if the deviation was less than 30°. 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. Additional trial exclusions for these analyses were: trials in which saccade latency was <80 ms (7.2% of all trials), trials containing gaps in the gaze data which were too large to be interpolated and/or in which there was insufficient gaze data to detect a saccade (1.1% of trials), and trials in

which no gaze was recorded within 100 pixels (5.1°) of the fixation point during the first 80 ms of the trial (4.2% of trials). Data from two participants were excluded from the saccade latency and fixation duration 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 trials¹.

Statistical analyses were conducted using R (Version 4.0.3; R Core Team, 2020). The afex package (Singmann et al., 2018) was used to calculate ANOVAs. Greenhouse-Geisser corrections to degrees of freedom are reported where appropriate. When 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)

¹ Across both Experiments 1 and 2, restricting all analyses to the subset of participants who met criteria for inclusion in the fixation duration analysis did not change the pattern of significant results.

Results

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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, $F(1, \frac{1}{2})$ 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, $\eta_p^2 = .050$.

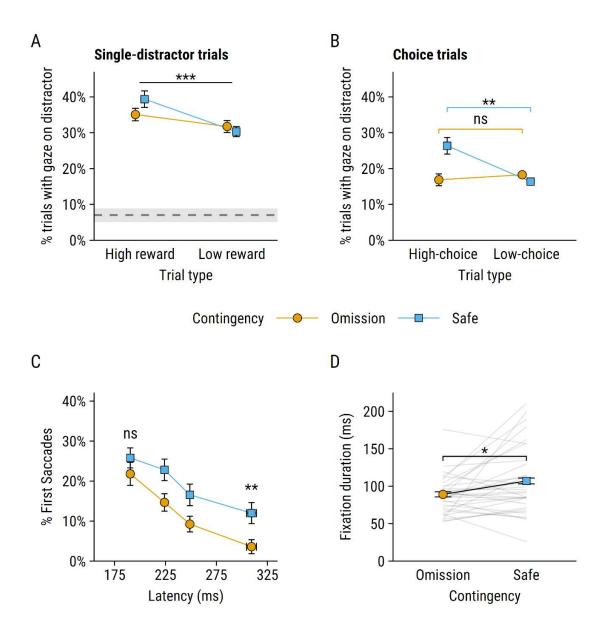


Figure 3. Results of Experiment 1. (A) Percentage of trials with gaze on the distractor location on single-distractor trials. Dashed line represents baseline performance on distractor-absent trials. (B) Percentage of trials with gaze on each distractor type on choice trials. (C) Percentage of first saccades 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

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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 \times contingency interaction, F(1, 38) = 6.62, p = .014, $\eta_p^2 = .148$. Follow-up paired-samples ttests 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 BF₀₁ = 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

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high-safe distractor (for which looking had no negative consequence) over the highomission 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 lowchoice) 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 lowomission distractor's response relationship was influencing attention), the corresponding one-tailed Bayes factor was $BF_{0+} = 13.76$, 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

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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. To investigate the timecourse 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 as a function of saccade latency (Pearson et al., 2016; Ratcliff, 1979). For each quartile of each participant's individual saccade latency distribution, we calculated the percentage of first saccades going towards each distractor and mean saccade latency. 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 highchoice trials (see Figure 3C). However, for completeness we report a similar time-course

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analysis of low-choice trials, as well as presenting the full distribution of saccade direction for each trial type and distractor location, 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 BF₀₁ = 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, $BF_{0+} = 2.39$. 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 demonstrated a VMAC effect. That is, they were more likely to have their overt attention captured by a salient distractor that signalled high reward, than an equivalent distractor that signalled low reward. Importantly, however, while participants were seemingly unable to prevent capture 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 triggered the omission of a high-value reward, whereas looking at the low-omission distractor triggered 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, Pearson, Theeuwes, et al., 2020).

However, not all of the findings in Experiment 1 were consistent with the idea that a stimulus's response relationship with reward affects suppression of attention through a reactive mechanism. First, while there was a significant interaction between distractor reward level and contingency on choice trials, the equivalent interaction on single-distractor trials was non-significant. However, previous research *has* found a significantly reduced VMAC effect for "omission" distractors relative to "safe" distractors on single-distractor trials (Pearson & Le Pelley, 2020). The failure of the interaction to reach significance for single-distractor trials in Experiment 1 may reflect a lack of power for the analysis of these data. As choice trials represent a particularly sensitive measure of the influence of the response pathway on selection, Experiment 1 was designed such

that the majority of the trials (400 out of 600) were choice trials. This means that participants experienced only 200 single-distractor trials (50 with each distractor type) over the course of the experiment. By contrast, in Pearson and Le Pelley's (2020) study, participants experienced four times as many single-distractor trials (200 with each distractor type). The reduced number of single-distractor trials in the current Experiment 1 may have reduced the sensitivity to detect the influence of the response contingency on single-distractor trials. Nevertheless, putting the issue of power aside, the null result of the reward × contingency interaction on single-distractor trials does raise the possibility that a stimulus's response with relationship with reward might be more effective at resolving competition between salient stimuli than at preventing capture by salient stimuli altogether. We return to this possibility in the General Discussion.

Second, 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 bias was significant in the slowest quartile of saccades, but was not significant for the fastest quartile of saccades, in line with the idea that the preference for the safe distractor emerged for longer-latency saccades. 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

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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. One possibility is that the non-significant interaction here may be the result of insufficient statistical power to detect the emergence of the bias for the safe distractor over the omission distractor with increasing saccade latencies. Notably, Experiment 1 was powered based on the effect size that has been observed for the standard VMAC effect (i.e., the difference in the proportion of trials with gaze on the high- and low-reward distractors), not the change in the bias for the safe distractor over the omission distractor as a function of saccade latency. An alternative possibility is that the response pathway may influence selection via a particularly fast reactive suppression process that is enacted prior to (at least a subset of) participants' most rapidly generated saccades. Estimates of the speed of distractor rejection are highly varied and task dependent. On the high end, estimates from attentional dwell paradigms suggest that it takes 150-300 ms to shift attention away from a non-target item (Theeuwes et al., 2004). On the low end, estimates from difficult visual search paradigms suggest that non-target items can be rejected in 25-75 ms (Wolfe, 1998). This wide range of estimates raises the possibility

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that participants may have started to reactively suppress the omission distractor prior to the initiation of even their earliest saccades, resulting in an oculomotor bias to the safe distractor over the omission distractor across the entire saccade latency distribution that is nonetheless the consequence of a reactive distractor-suppression process.

Notwithstanding the above, the fact that a Bayesian analysis suggested moderate evidence of no bias towards the safe distractor over the omission distractor among the fastest quartile of 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 \sim .85) to reliably detect the critical reward \times 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 the time course of oculomotor capture and fixation duration, 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. Data from four participants were excluded from the fixation duration analysis

as they did not make a saccade to one of the distractor types on either high-choice or low-choice trials.

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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, $\eta_p^2 = .003$.

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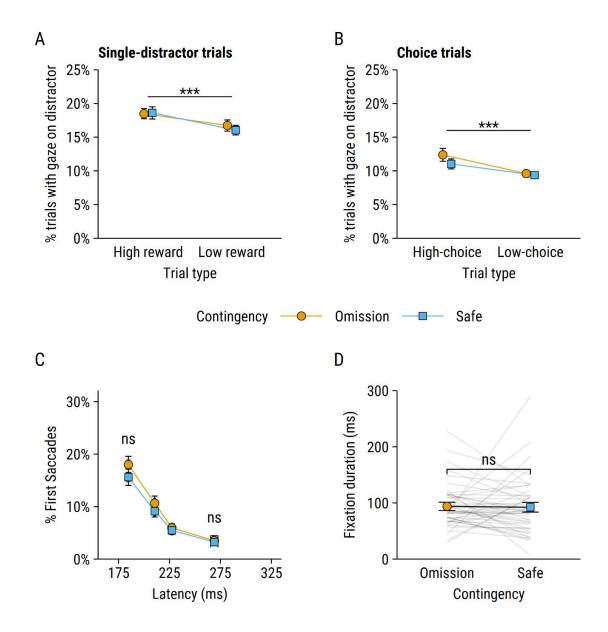


Figure 4. Results of Experiment 2. (A) Percentage of trials with gaze on the distractor location on single-distractor trials. (B) Percentage of trials with gaze on each distractor type on choice trials. (C) Percentage of first saccades in the direction of each type of distractor (omission and safe) as 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. Note the different scales on the y-axes compared to Figure 3. Faint grey lines show individual participant performance. *** p < .001, ns = non-significant.

Choice trials

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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, η_p^2 = .019. Critically, the reward × contingency interaction was also non-significant, F(1,54) = 0.31, p = .583, η_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, $BF_{0+} = 11.69$.

Time-course of oculomotor capture

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758 To assess the time-course of oculomotor capture on choice trials, we again 759 analysed the proportion of first saccades going towards the omission and safe 760 distractors on high-choice trials as a function of their saccade latency (see Figure 4C). 761 Data were analysed using ANOVA with factors distractor contingency (omission vs safe) 762 and latency quartile (1-4). This revealed a main effect of quartile, F(1.97, 106.26) = 107.1, p < .001, $\eta_p^2 = .665$, with participants less likely to saccade towards distractors as saccade 763 latency increased. Distractor contingency did not exert a significant main effect, F(1, 54)764 = 0.64, p = .426, η_p^2 = .012, or significantly interact with quartile, F(2.05, 110.82) = 0.56, p765 = .577, η_p^2 = .010. Planned t-tests were used to investigate whether participants 766 767 preferentially directed their most rapidly initiated saccades, or their slowest saccades, 768 towards either the safe or omission distractor on high-choice trials. These analyses 769 indicated that both the fastest and the slowest quartiles of saccades were equivalently 770 likely to be directed toward either type of distractor: fastest quartile, t(54) = 0.91, p 771 = .366, d_z = 0.12, BF₀₁ = 4.59 (one-tailed: BF₀₊ = 12.15); slowest quartile, t(54) = 0.45, p772 = .652, d_z = 0.06, BF₀₁ = 6.16 (one-tailed: BF₀₊ = 9.34).

Fixation duration

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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(50) = 0.20, p = .840, $d_z = 0.03$. The corresponding Bayes factor of BF₀₁ = 6.43 suggested moderate 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 again demonstrated a significant VMAC effect overall: 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).

Notably, we once again did not observe a significant interaction between distractor contingency and reward on single-distractor trials (in contrast to previous findings; Pearson & Le Pelley, 2020), despite there being a goal-directed benefit to suppressing capture on these trials and an increased number of single-distractor trials in

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Experiment 2 compared to Experiment 1. However, while there were relatively more single-distractor trials in Experiment 2, this number was still fewer than in the previously published study (132 trials with each distractor type in Experiment 2 versus 200 trials with each distractor type in Pearson & Le Pelley, 2020). As a result, the sensitivity to detect an influence of the response relationship on capture remained lower in the current study. Moreover, some of the single-distractor trials were presented in the second phase of the experiment, when most trials were unrewarded choice trials (in which suppressing capture by the omission distractors was of no benefit). If participants use goal-directed control processes to reduce capture by distractors that have negative response relationships with reward, we might expect that they would be less likely to engage these processes during phase 2: because the vast majority of trials are choice trials, there is only a large goal-directed benefit to avoiding capture on the ~5% of trials in which the high-omission distractor is presented alone, and participants had no way of knowing ahead of time which trials these would be. This may have resulted in participants being less motivated to suppress capture by the high-omission distractor in phase two, thereby reducing the likelihood that we would detect an interaction between distractor contingency and reward on single-distractor trials when the data were collapsed across both phases of the experiment.

It is also noteworthy that the proportion of trials with gaze on any distractor was substantially reduced in Experiment 2, relative to Experiment 1. For example, while on

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average participants looked at the distractor on ~35% of high-omission single-distractor trials in Experiment 1 (Figure 3A), they looked at the distractor on only ~18% of highomission single-distractor trials in Experiment 2 (Figure 4A). One interpretation of this difference between experiments is that (because of the unavailability of reward on choice trials) the signalling relationship between each distractor and its associated reward was substantially reduced in Experiment 2. Returning to the example of the highomission distractor, reward was available on 100% of the trials in which this distractor was presented in Experiment 1 (provided the participant did not look at the highomission distractor before fixating the target). By contrast, in Experiment 2, reward was available on only 44% of the trials in which the high-omission distractor was presented (i.e., the high-omission single-distractor trials, with the remaining 56% being highchoice trials in which reward was unavailable). This difference in the overall rate of reward availability means that the signalling relationship between each distractor and its associated reward was substantially reduced in Experiment 2 versus Experiment 1. As a result, we would expect the attentional priority of the distractors to be lower. Critically, however, while the overall strength of the signalling relationships was lower in Experiment 2, the difference in the signalling relationships between the high- and lowreward distractors were maintained. That is, while the high-omission distractor signalled that high reward was available on 44% of the trials in which it was presented, the lowomission distractor similarly signalled that low reward was available on 44% of the trials

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in which it was presented. So, the difference in the attentional priority of the two distractor types should be maintained; this is reflected in the significant VMAC effect observed across both single-distractor and choice trials.

General Discussion

The current study investigated the role that a stimulus's response relationship with reward plays in selective attention. 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 (shifting gaze to this distractor resulted in reward omission), whereas the 'safe' distractor had no response relationship with reward (shifting gaze to this distractor did not affect 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 relationship's influence on attentional selection?

Reactive versus proactive?

The visual attention system is thought to use two sets of mechanisms 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 the response relationship influences suppression 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

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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 based on 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 those who experienced the response

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relationship between making an eye-movement 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 were trained with the omission contingency showed reduced 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, rewardsignalling 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

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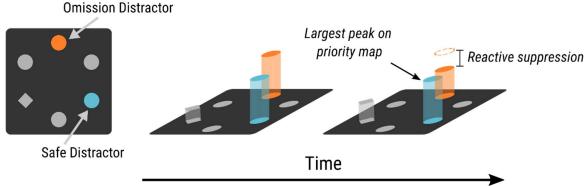
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rapidly disengaged—effectively inhibiting the priority signal of the omission distractor while leaving that of the safe distractor unaffected. After the omission distractor's priority signal decreases a small amount, the safe distractor's priority 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. This may explain why, despite observing a numerical trend towards a reduced VMAC effect on single-distractor trials of Experiment 1 and 2 (see Figures 3A and 4A), we did not observe a significant interaction between reward and contingency on these trials. According to the account outlined here, 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

937 negative consequences for capture (as was the case on choice trials in the current 938 experiments).

A High-choice trials



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High-omission single distractor trials

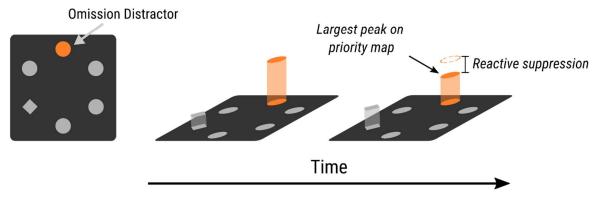


Figure 5. Images on the left show example search displays on high-choice trials and high-omission single-distractor trials; images on the right show proposed activity on the attentional priority map over time, with height indicating the magnitude of the attentional priority signal for each stimulus in 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?

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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 goaldirected 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.

Suppression versus enhancement?

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Up to this point we have described the influence of the response pathway on attentional selection in terms of suppression of the attentional priority of stimuli that have a negative response relationship with reward. However, another possible explanation for the pattern of results that we observed on high-choice trials of Experiment 1 is that participants may have strategically selected the high-safe distractor, thereby enhancing its attentional priority. Even though attending to either distractor was never the explicit goal of the task, and participants were instructed to move their eyes to the target 'as quickly and accurately as possible', it is difficult to rule out the possibility that participants may have adopted a strategy of volitionally directing their attention to the safe distractor, as it was the 'next-best' saccade destination after the target. While the finding of shorter fixations on the high-omission distractor compared to the highsafe distractor (see Figure 3D) is consistent with reactive suppression of the highomission distractor (Geng, 2014; Geng & DiQuattro, 2010), this pattern may also be consistent with strategic selection of the high-safe distractor (Theeuwes et al., 2004; cf. Godijn & Theeuwes, 2002). It is important to note that, regardless of whether the response pathway influences attentional selection via reactive suppression or strategic

enhancement (or some combination of the two), the results of the current study suggest that the response pathway's influence is relatively slow and under strategic control. Future research could explore the contribution of a distractor's response relationship with reward to suppression and enhancement using electrophysiological measures of attention derived from event-related potentials, such as the N2pc component (which is thought to be related to stimulus selection/enhancement; Eimer, 1996; Luck & Hillyard, 1994; Zivony et al., 2018) and the P_D component (which is thought to be related to stimulus suppression; Gaspar & McDonald, 2014; Gaspelin & Luck, 2018b; Hickey et al., 2009).

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-singleton target in order to earn reward, and 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

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33rd percentile of response times in the previous block of trials) that participants needed to beat in order to receive reward². Thus, the "reward" distractor had a positive signalling relationship with reward (reward was delivered only 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 1000 ms; Grégoire et al., 2020, Experiment 3) participants demonstrated the classic VMAC effect: increased capture by the rewardsignalling distractor relative to the neutral distractor.

² 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.

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

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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. The extent to which a stimulus co-occurs with a rewarding outcome (i.e., its *signalling relationship* with reward) induces a proactive increase in its attentional priority, such that a stimulus that signals large reward rapidly and automatically captures attention and gaze as though its physical salience has been augmented. By contrast, negative reward-related consequences for making an attentional orienting response to a stimulus (i.e., a negative *response relationship* with reward) triggers a reactive, goal-directed control processes of rapid disengagement from that stimulus, thereby reducing the extent to which it captures gaze.

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