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Visual Cognition

Publication details, including instructions for authors and subscription information:

<http://www.tandfonline.com/loi/pvis20>

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Published online: 28 Nov 2014.

To cite this article: Berno Bucker, Artem V. Belopolsky & Jan Theeuwes (2014): Distractors that signal reward attract the eyes, *Visual Cognition*, DOI: [10.1080/13506285.2014.980483](https://doi.org/10.1080/13506285.2014.980483)

To link to this article: <http://dx.doi.org/10.1080/13506285.2014.980483>

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Distractors that signal reward attract the eyes

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(Received 28 May 2014; accepted 20 October 2014)

Salient stimuli and stimuli associated with reward have the ability to attract both attention and the eyes. The current study exploited the effects of reward on the well-known global effect in which two objects appear simultaneously in close spatial proximity. Participants always made saccades to a predefined target, while the colour of a nearby distractor signalled the reward available (high/low) for that trial. Unlike previous reward studies, in the current study these distractors never served as targets. We show that participants made fast saccades towards the target. However, saccades landed significantly closer to the high compared to the low reward signalling distractor. This reward effect was already present in the first block and remained stable throughout the experiment. Instead of landing exactly in between the two stimuli (i.e., the classic global effect), the fastest eye movements landed closer towards the reward signalling distractor. Results of a control experiment, in which no distractor-reward contingencies were present, confirmed that the observed effects were driven by reward and not by physical salience. Furthermore, there were trial-by-trial reward priming effects in which saccades landed significantly closer to the high instead of the low reward signalling distractor when the same distractor was presented on two consecutive trials. Together the results imply that a reward signalling stimulus that was never part of the task set has an automatic effect on the oculomotor system.

Keywords: Reward; Attention; Eye movements; Priming; Global effect.

Visual selective attention is crucial in order to function and survive in our visually rich world. While sampling information from the visual environment, selective attention determines which parts of the visual scene are prioritized for further processing and which parts are ignored. Typically, visual attention is categorized into goal-directed (top-down) attention and stimulus-driven (bottom-up) attention

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This research was supported by an ERC advanced grant [ERC-2012-AdG-323413] to Jan Theeuwes.

(Chelazzi et al., 2013; Corbetta & Schulman, 2002; Desimone & Duncan, 1995; Itti & Koch, 2001; Theeuwes, 2010). Top-down attention is driven by endogenous factors and is completely under volitional control. Bottom-up attention is driven by exogenous factors and is determined by the feature properties present in the environment. An observer can voluntarily choose what to select from the environment according to specific goals and priorities, while physically salient stimuli may automatically attract the observer's attention in a passive way. In addition to goal-directed and stimulus-driven attention, a recent body of literature suggests that attention can be influenced by the value coupled to reward predicting stimuli (see Anderson, 2013; Chelazzi et al., 2013 for reviews). Since the bottom-up and top-down dichotomy fails to explain a growing number of reported selection biases due to reward value, it has been proposed that "reward history" is integrated with task-goals and physical salience to shape an integrated priority map (Awh, Belopolsky, & Theeuwes, 2012).

While it was already recognized that the knowledge of reward availability works as an incentive to enhance voluntary attentional processes resulting in fast and accurate responses (e.g., Bucker & Theeuwes, 2014; Engelmann, Damaraju, Padmala, & Pessoa, 2009; Small et al., 2005), recent evidence suggests that reward can automatically influence visual attention beyond and sometimes even against the strategic control of goal-directed attention (see Chelazzi et al., 2013, for a review). Several recent studies have shown that a stimulus that has been previously associated with high monetary reward captures attention (Anderson, Laurent, & Yantis, 2011a, 2011b; Della Libera & Chelazzi, 2009; Failing & Theeuwes, 2014) and the eyes (Anderson & Yantis, 2012; Theeuwes & Belopolsky, 2012) more strongly than that same stimulus when previously associated with low monetary reward. Typically these studies include an initial training phase, in which participants actively search for a stimulus that is either associated with high or low reward. In a subsequent test-phase, when the reward association is no longer in place and the previously trained stimulus is no longer the target (but a distractor instead), the previously high rewarded stimulus captures attention and the eyes more strongly than the low rewarded stimulus.

For example, experiments of Anderson, Laurent, and Yantis (2011a, 2011b) contained a training- and test-phase. In the training-phase, observers actively searched for either one of two specifically coloured target circles amongst differently coloured distractor circles and reported the orientation of a bar within the target circle. One of the target colours was associated with a high chance (80%) of obtaining a high reward and a low chance (20%) of obtaining a low reward. For the other colour, the colour-reward contingencies were reversed. Immediately after the training-phase, there was a test-phase in which no rewards were provided. Observers were asked to search for a uniquely shaped target amongst differently shaped and coloured distractors. Crucially, one of the distractors was presented in the colour that was associated with high or low reward value as was learned during

the initial training-phase. Although participants were informed that colour was task-irrelevant and had to be ignored, the results showed that reaction times were slower if a stimulus previously associated with high reward was present relative to a stimulus associated with low reward. The authors conclude that the value that was associated with a specific stimulus feature during training biased attention towards that feature, even in a different task context, in which it was non-salient, task-irrelevant and non-rewarded.

In addition to reward-based capture of covert attention, several studies have investigated whether stimuli also capture the eyes as a consequence of previous stimulus-reward associations. Emphasizing the importance of eye movement measures as direct evidence for salience-based attentional capture by learned reward value, Theeuwes and Belopolsky (2012) used a reward variant of the oculomotor capture paradigm of Theeuwes et al. (1998). Similar to Anderson, Laurent, and Yantis (2011a) there was a training-phase in which one stimulus orientation was associated with high reward and another with low reward. During the subsequent test-phase, these stimuli served as distractors while observers searched for a colour singleton. The results showed that saccades were directed more often towards the stimulus that was previously associated with high reward compared to the stimulus that was associated with low reward. For the first time, this study showed that even when a stimulus no longer predicts reward, the learned value increases oculomotor capture beyond oculomotor capture that is driven by physical salience alone. Using the same experimental design, with a training- and testing-phase, Anderson and Yantis (2012) came to a similar conclusion when they showed oculomotor capture by previously rewarded stimuli during unconstrained viewing when neither eye movements nor fixations were required.

It is important to note that in all of the above mentioned experiments the reward-associated distractors that captured attention were always actively searched for during earlier trials. During the initial training-phase, the stimulus-reward association was established by reinforcing repeated goal-directed behaviour towards rewarded targets. Therefore, the reward effects that are described in these studies might have depended on prior search for reward associated stimuli. Even though these studies are assumed to provide evidence for automatic reward effects of task-irrelevant distractors, it is clear that the effect may not be as automatic as assumed as these distractors were targets during an initial training-phase. This raises the possibility that automatic capture by highly rewarding stimuli in these types of paradigms is necessarily dependent on being task relevant and highly rewarded during an earlier training-phase.

A very recent study by Le Pelley, Pearson, Griffiths, and Beesley (in press) addressed the question whether stimuli that had never been actively searched could nevertheless induce reward driven attentional capture. As in the previously described reward studies, the additional singleton paradigm was used. Participants searched for a diamond-shaped target among circles and made a response

depending on the orientation of a line segment within the diamond. All stimuli were presented in grey, but on some trials one of the non-target circles (i.e., the distractor) was coloured. The distractor colour predicted the reward magnitude (high or low) available on that trial, but obtaining the reward depended on responding to the line segment within the diamond-shaped target and not to the distractor. Furthermore, responses to the target had to be faster than a certain reaction time threshold, so that attending to the distractor hindered performance. Nevertheless the results show that reaction times on trials in which a high-value distractor was present were higher than on trials in which a low-value distractor was present, with the consequence that participants were more likely to miss the high compared with the low reward. Although participants were never instructed to search for the distractors before, the simple correlation of the distractor stimuli with reward was sufficient for attentional capture to occur.

To investigate whether the reward signalling distractors also captured the eyes, a follow-up eye tracking experiment was conducted. In this experiment, participants had to make an eye movement towards a filled grey diamond-shaped target amongst grey distractor circles. Again, on some trials one of the non-target circles was coloured to signal the reward available on that trial (high or low). When responses were slower than 600 ms and if any gaze fell inside a predefined area surrounding the distractor before a response to the target was registered, no reward was delivered. In accordance with the behavioural results of the first experiment, saccades were slower in high versus low reward distractor trials and more rewards were missed in high versus low reward distractor trials, indicating that high value distractors produced greater oculomotor capture than low value distractors. Therefore, the authors conclude that reward associated distractors can capture attention and the eyes, even if this is counterproductive.

The current study expands on this latter finding and investigates whether the eyes are automatically drawn by reward signalling distractors that never served as targets. While Le Pelley and colleagues made use of a visual search task with multiple distractors and a 600 ms response window to obtain reward, we investigated very fast eye movements in the context of the global effect paradigm (Coren & Hoenig, 1972; Findlay, 1982; see Van der Stigchel & Nijboer, 2011, for a review). The notion underlying the global effect is that eye movements typically land on the centre of gravity within the visual field, which is assumed to reflect the relative salience of elements present in the visual field. The global effect is observed when participants initiate an eye movement towards two stimuli presented simultaneously in close spatial proximity. Instead of moving to one of the two objects, typically the initial saccade lands in between the two stimuli. This landing position is likely to reflect the unresolved competition between the representations of the stimuli (Tipper, Howard, & Jackson, 1997). In line with saccade generation models based on competitive interactions between subsets of neurons coding for possible target locations (Fecteau & Munoz, 2006; Godijn & Theeuwes, 2002), it appears that the global effect can be best described in terms of

a weighted average of activity in a saccade map. The two stimuli that appear in close proximity with a simultaneous onset produce two peaks of activity in this saccade map. The weighted average of activity that is located in between these two peaks then determines the saccade endpoint on the moment the eye movement is initiated. While stimulus-driven information can evoke peaks in the activity map, goal-directed factors can modulate this activity. Importantly, the interaction between stimulus-driven and goal-directed information determines the pattern of activity in the saccade map, with stimulus-driven information being dominant early in time and goal-directed information becoming more dominant with increasing latency (Van Zoest, Donk, & Theeuwes, 2004).

In the current study, we conducted a reward experiment and a non-reward control experiment. Both experiments consisted of the same task with and without stimulus-reward contingencies in place. During a trial, a grey target circle and a coloured distractor circle were presented simultaneously in close spatial proximity. Throughout both experiments distractors never served as targets. Participants were instructed to make a fast saccadic eye movement towards the target circle, and to ignore the coloured distractor circle. Crucially in the reward experiment the colour of the distractor circle signalled the reward magnitude available (high or low) for that particular trial. Reward delivery was dependent on making a fast saccade towards the circles. In the separate control experiment, different participants performed the same task only without the distractor-reward contingencies. The purpose of this experiment was to determine whether there were any effects of physical salience independent of reward.

On the basis of the competitive integration model (Godijn & Theeuwes, 2002), one expects stimulus-driven information to be dominant early in time and goal-driven information to become more dominant with increasing saccade latencies. As participants are provided with goal-directed information to make an eye movement to the target circle, one expects the landing position to shift more towards the target location for slower saccades. If reward value has a goal-driven effect, one expects that the effect of reward value would become evident with increasing latencies. With increasing latencies there is more and more room for top-down influences to modulate the peak activity of the reward signalling distractor and to progressively enhance the representation of the high compared with the low value distractor in the saccade map. However, if reward value has an effect even for the fastest saccades, at the time window where bottom-up processes normally operate (c.f., Godijn & Theeuwes, 2002), then one should conclude that reward value does not necessarily exert a top-down effect but instead an effect associated with bottom-up automatic processes. Based on the physical salience of the target and distractor alone, one expects two equally sized peaks of activity in the saccade map, resulting in a global effect with an average landing position perfectly in the middle of the two objects. However, if reward value exerts an early effect that is similar to classic bottom-up effects, one expects that the reward signalling distractor would be prioritized in the saccade

map. As it is assumed that the presence of a high reward signalling distractor will evoke a greater peak of activity than a stimulus associated with low reward, it is expected that the eyes are biased to land closer towards the high compared with the low reward signalling distractor. To show that the effect is dependent on the stimulus reward-contingencies introduced in the reward experiment and not on other task specific features such as physical salience, the control experiment should show a different pattern of results, without any bias towards the distractor.

METHOD

Participants

For the reward experiment, 18 participants (five males, 19–28 years of age, mean = 23.8 years, $SD = 2.4$ years) were tested at the Vrije Universiteit Amsterdam. These participants received €9.00 to compensate for participation and could earn up to a maximum of approximately €15.00 extra reward, which was delivered based on task performance. For the control experiment 14 new participants (four males, 19–34 years of age, mean = 24.4 years, $SD = 4.6$ years) were recruited and received €9.00 to compensate for participation. All participants reported having normal or corrected-to-normal vision and gave informed consent before participation. All research was approved by the Vrije Universiteit Faculty of Psychology ethics board and was conducted according the principles of the Declaration of Helsinki.

Apparatus

All participants were tested in a sound-attenuated, dimly-lit room, with their head resting on a chinrest at a viewing distance of 58 cm. A Pentium IV computer (2.3 GHz) generated all stimuli on a 21-inch SVGA monitor (resolution 1024 x 768 pixels, refreshing at 100 Hz). Monocular movements were tracked using the Eyelink 1000 system (Tower model, SR Research Ltd, Canada), an infrared video-based eye tracker that has a 1000 Hz temporal resolution and a 0.01° spatial resolution.

Design

We conducted two experiments. In the reward experiment participants made saccades as fast as possible towards a grey target circle, while the colour (red or green) of the distractor circle signalled the reward magnitude (high or low) available on that trial. In the control experiment, a group of different participants performed the same task as in the reward experiment only without the stimulus-reward contingencies.

Stimuli

Throughout both experiments a white (CIE: $x = .270$, $y = .309$; 32.7 cd/m^2) fixation dot was presented on a black (CIE: $x = .240$, $y = .323$; 1.5 cd/m^2) background at the centre of the screen. The stimulus display contained two filled circles that had the same size ($r = 0.14^\circ$), were located within the same quadrant of the screen (boarders: 0° , 90° , 180° , 270°) at the same distance (7.7°) from fixation and always positioned 3.4° visual degrees (25° polar angle) apart from each other. Instead of placing these two circles at fixed locations around the four principal axes (45° , 135° , 225° , 315°), they were placed at a random location within a quadrant. This is unlike other studies investigating the global-effect (e.g., Heeman, Theeuwes, & Van der Stigchel, 2014; Silvius & Van der Stigchel, 2013; Van der Stigchel, Heeman, & Nijboer, 2012) as we intended to reduce the influence of top-down expectancy (or guessing) of where the stimuli could appear within the visual field. Furthermore, this procedure circumvented reactivation (or planning) of eye movement trajectories from previous trials.

The two circles always consisted of a grey (CIE: $x = .264$, $y = .316$; 6.2 cd/m^2) target circle and a red (CIE: $x = .534$, $y = .328$; 5.9 cd/m^2) or green (CIE: $x = .295$, $y = .530$; 8.5 cd/m^2) distractor circle. In the reward experiment the colour of the distractor circle signalled the reward magnitude (high or low) available on that trial, whereas there were no associations with reward in the control experiment. In the reward experiment, one of the distractor colours signalled high reward (10 eurocents), while the other colour signalled low reward (1 eurocent). Colour-reward contingencies were counterbalanced across participants. If saccades were accurate (see Latency Threshold and Accuracy) and faster than the saccade latency threshold (which was dynamically adjusted, see Latency Threshold and Accuracy), the white (CIE: $x = .270$, $y = .309$; 32.7 cd/m^2) feedback text “+ € 10 ct” ($\sim .4^\circ \times 1.0^\circ$) or “+ € 1 ct” ($\sim .4^\circ \times .9^\circ$) was shown for high and low reward distractor trials, respectively. Note that no reward feedback was shown in the control experiment. If the landing position of the saccade was considered inaccurate a 500 Hz warning tone was played for 100 ms simultaneously with the visually presented feedback text “More accurate” ($\sim .4^\circ \times 1.6^\circ$). If the saccade latency exceeded the saccade latency threshold a 500 Hz warning tone was played for 100 ms simultaneously with the visually presented feedback text “Too slow” ($\sim .4^\circ \times 1.0^\circ$).

Procedure

Participants signed the informed consent and the eye tracker was calibrated. If at any point eye movements would drift, another calibration procedure would be performed. Participants were asked to keep their head still during the trials, but were free to move their head during the breaks between blocks.

Both experiments began with a practice block followed by 10 experimental blocks. In the reward experiment, during the practice block, the distractor circle

was coloured yellow (CIE: $x = .386$, $y = .518$; 13.0 cd/m^2) or blue (CIE: $x = .173$, $y = .123$; 4.5 cd/m^2) in order to prevent the formation of any bias with regard to the reward associated red and green coloured distractors used in the main part of the experiment. In the control experiment, during the practice block, the distractors were coloured red and green, as these colours were never associated with reward. Furthermore, in the control experiment, during practice, participants were informed on a trial-by-trial basis towards which circle their eye movement landed closest to. The main part of both experiments consisted of 320 trials divided into 10 equally sized blocks. Within a block, reward distractor type (high/low), the quadrant in which the stimuli appeared (1–4) and distractor position relative to the target (clockwise/counterclockwise) were balanced.

A trial (see [Figure 1](#)) started with a drift correction in which participants were required to press the spacebar while fixating the fixation cross. To indicate the start of the trial the fixation cross was replaced by the fixation dot. After a random variable interval of 500–1000 ms the fixation dot was removed, immediately followed by the simultaneous appearance of the two circles. Subjects were instructed to move their eyes towards the grey target circle as fast as possible while ignoring the distractor circle. Before the reward experiment, participants were informed that the distractor colour was predictive of the available reward for that trial. It was also stressed that the distractor had to be ignored and that an eye movement had to be made as fast as possible towards the grey target. Once the first saccade was made, the circles remained present on the screen for 100 ms followed by the visually presented feedback for 400 ms. After each block the mean saccade latency of that particular block was displayed along with the saccade latency threshold for the first trial of the following block. In addition the amount of reward obtained in that particular block and the accumulated reward amount over all blocks was displayed on the screen in the reward experiment only. The feedback screen that appeared between blocks remained visible until a key was pressed. Including the calibration procedure and breaks, participants were able to finish the experiment within approximately 50 minutes.

Latency threshold and accuracy

At stimulus display onset, participants were instructed to make an eye movement towards the grey target circle and ignore the coloured distractor circle. It was emphasized that eye movements had to be made as fast as possible and in the reward experiment participants were made explicitly aware that in order to obtain the reward for that trial, eye movements had to be faster than a dynamically adjusting saccade latency threshold. For each participant, the saccade latency threshold was based on the latencies in the 20 previous trials. From the latencies of these 20 trials, the 75th percentile was calculated and set as the latency

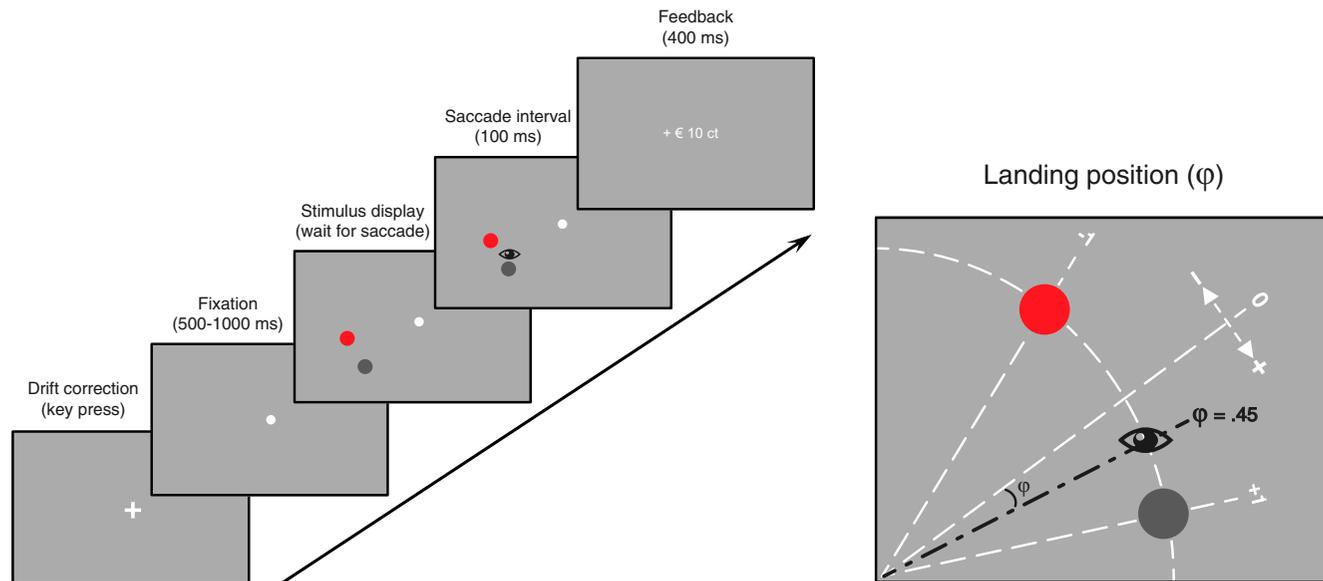


Figure 1. Schematic representation of trial sequence and timing on the left. Schematic representation of how saccade landing position was calculated on the right. The “midline angle” exactly in the middle of both circles served as the null ($\phi = 0.0$) reference. Saccades landing towards the target circle ($\phi = 1.0$) were defined as having a positive landing position and saccades landing towards the distractor circle ($\phi = -1.0$) as having a negative landing position. In the figure an example saccadic angle of $\phi = .45$ is shown. Dashed lines were not visible in the actual stimulus display. Note that the reward feedback screen was not present in the control experiment.

threshold for the next trial. Obtaining reward depended on saccade latency and accuracy in landing position. In order to be considered accurate, the first saccades had to land in one of three imaginary circles ($r = 1.7^\circ$) (one around the target, one around the distractor and one around the point exactly in the middle of the target and the distractor). We implemented this accuracy constraint so that participants made saccades towards the stimuli presented on the screen. Saccades landing closer to the distractor instead of the target were considered accurate and not explicitly punished, because this would slow down overall latencies making it more difficult to investigate the global effect. In the reward experiment, if the first saccade was accurate and faster than the dynamic saccade latency threshold, participants received the reward that was signalled by the colour of the distractor circle on that trial.

Preprocessing

An eye movement was considered a saccade when either eye velocity exceeded $35^\circ/\text{s}$ or eye acceleration exceeded $9500^\circ/\text{s}^2$ and end points were defined as the location where velocity fell below this threshold. First, all trials in which the first saccade was not accurate were not further analyzed. Second, trials with a landing position of more than two and a half standard deviations away from the participants' mean were excluded from the analysis. Third, trials were filtered on saccadic latency with a minimum of 80 ms (anticipatory saccades) and a maximum of 450 ms (too slow saccades). Saccade latency was defined as the interval between the presentation of the circles and the initiation of the first saccadic eye movement.

Landing position of the first eye movement was calculated as a proportion of the angle between the target and the distractor. The geometric point exactly in the middle of the two circles served as the null reference for the landing position ($\varphi = 0.0$). Saccades that landed towards the target were defined as having a positive landing position and saccades that landed towards the distractor were defined as having a negative landing position. The grey target circle had position one ($\varphi = 1.0$) and the reward signalling distractor had position minus one ($\varphi = -1.0$). To compensate for small drift ($< 1^\circ$) of the eye movements from fixation at the start of the saccade, the actual starting point of the saccade was used to calculate the landing position (φ). A schematic representation of how saccade landing position was calculated is shown in [Figure 1](#).

Statistical analysis

All trials after preprocessing were categorized into high and low reward distractor type trials. Two tailed t -tests were performed for landing position and saccade latency to examine the effect of reward distractor type (high/low).

To investigate the time course of our reward manipulation on saccade landing position, the trials of each participant were divided into four latency quartiles for the high and low reward trials separately (i.e., data were Vincentized). A repeated measures ANOVA with reward distractor type (high/low) and latency bin (1–4) was performed on landing position.

In relation to reward learning effects, we examined the landing position for high and low reward distractor trials over time (blocks). In order to retain a sufficient number of trials per cell we grouped consecutive blocks such that the analysis was performed on five blocks. A repeated measures ANOVA with reward (high/low) and block (1–5) as factors was performed on landing position.

Furthermore we investigated the more transient, trial-by-trial, priming effect of the reward signalling distractors. For this analysis, we examined the difference in landing position given that the identity of the distractor changed or remained the same in two consecutive trials. The first trial of each block was excluded, since no trial directly preceded these trials. A repeated measures ANOVA with distractor repetition (same/different) and current reward distractor type (high/low) as factors was performed on landing position.

With regard to the control experiment, we compared the landing position and the saccade latency with the reward experiment by means of two-tailed independent samples *t*-tests. Furthermore, a repeated measures ANOVA with factor latency bin (1–8) was performed on landing position. Because there was no reward assigned to either of the colours, we collapsed over red and green distractor trials to retain a sufficient amount of data per cell to divide the data of the control experiment into eight quantiles.

RESULTS

Exclusions

In the reward experiment, the exclusion criteria led to a total loss of 6.8% of the trials. With regard to landing position, 5.9% of the data were discarded due to inaccurate eye movements and 0.01% due to a difference angle of more than two and a half standard deviations away from the calculated mean. With regard to saccade latency, 0.73% of the trials were discarded because latency onset was shorter than 80 ms and 0.16% of the trials were discarded because latency onset was longer than 450 ms.

In the control experiment the exclusion criteria led to a total loss of 6.1% of the data. More specifically, 3.8% of the data were discarded due to inaccurate eye movements, 1.2% due to a difference angle of more than 2.5 standard deviations away from the participants mean, 0.57% because of anticipatory (latency < 80 ms) saccades and 0.61% because of too slow (latency > 450 ms) saccades.

Reward

Participants earned between €9.59 and €13.41 (mean = €12.23, $SD = €0.92$) monetary reward. Paired samples t -test showed that there was no difference in the likelihood of receiving a reward for high versus low reward distractor trials ($t(17) = 1.47$, $SE = 1.97$, $p = .16$).

Distractor reward effect

A two tailed paired-samples t -test on landing position for high versus low reward distractor type showed a significant effect ($t(17) = 2.35$, $SE = 0.79$, $p < .05$), with saccades landing closer to the high versus low reward signalling distractor. Even though overall saccades landed significantly closer to the target than to the distractor (for high mean $\varphi = 0.11$, $SD = 0.17$ and for low mean $\varphi = 0.26$, $SD = 0.18$), in the high reward condition the eyes landed significantly closer to the distractor than in the low reward condition. [Figure 2](#) shows the frequency distributions of the landing positions for the high and low reward signalling distractor conditions separately. A two tailed paired-samples t -test for high and low reward distractor type saccade latency showed a significant effect ($t(17) = 4.45$, $SE = 0.67$, $p < .001$). Although the absolute difference between conditions was only 3.0 ms, saccades in the high reward signalling distractor condition (mean = 202.0 ms, $SD = 15.1$ ms) were reliably faster than in the low reward signalling distractor condition (mean = 205.0 ms, $SD = 15.0$ ms).

To investigate the time course of the high and low reward distractor type landing positions, for each participant we divided the high and low reward trials in four latency bins. A repeated measures ANOVA on landing position with reward distractor type (high/low) and latency bin (1–4) as factors showed a significant main effect of reward distractor type ($F(1,17) = 5.64$, $p < .05$) and latency bin ($F(3,51) = 127.03$, $p < .001$). There was no significant interaction between reward distractor type and latency bin ($F(3,51) = 2.31$, $p = 0.11$ Greenhouse-Geisser corrected). The main effect of reward showed a sustained difference in landing position between the high and low reward distractor conditions (see [Figure 3](#)). The main effect of latency bin showed that saccades with the shortest latencies (bin 1), landed closest to the distractor and saccades with the longest latencies (bin 4) landed closest to the target. From bin 1 to bin 4 the landing position gradually shifted from the distractor location towards the target location as indicated by a significant linear trend ($F(1,17) = 204.48$, $p < .001$). Planned two tailed t -tests indicated that the fastest saccades did not show the typical global effect (i.e., a mean landing position on the *midline*, $\varphi = 0$). The landing positions of the fastest saccades in the high reward distractor condition (mean $\varphi = -0.13$, $SD = 0.15$) deviated significantly ($t(17) = 3.70$, $p < .01$, $d = 1.8$) away from the *midline* (i.e., $\varphi = 0$) and the landing position of

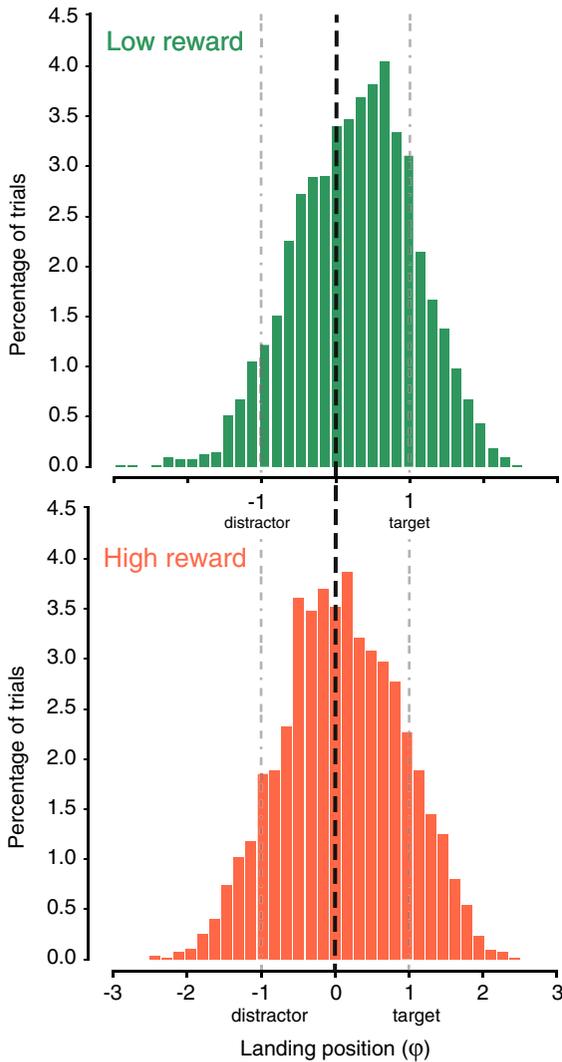


Figure 2. Frequency plots of landing position for the low (above) and high (below) distractor reward condition. The target was presented at $\phi = 1$ and the reward signalling distractor was presented at $\phi = -1$. Note that in the high reward condition, the distribution is skewed more to the distractor than in the low reward condition.

the fastest saccades in the low reward distractor condition (mean $\phi = -0.08$, $SD = 0.17$) showed a trend ($t(1,17) = 1.90$, $p = .07$, $d = .92$) for deviating away from the *midline*. These results indicate that with increasing latency the landing

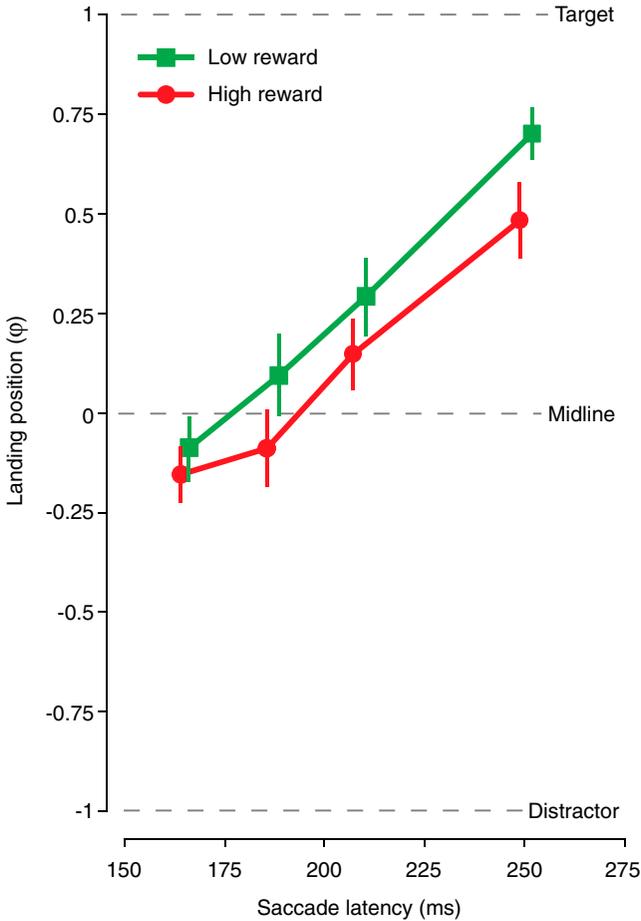


Figure 3. Mean landing position of the first saccade divided into four latency bins for the high and low reward distractor condition. Error bars represent 95% within-subject confidence intervals.

position of the first saccade shifted from a location near the distractor to a location near the target.

Furthermore, we determined how the difference in landing position developed over the course of the experiment, as participants were more exposed to the stimulus-reward contingencies. A repeated measures ANOVA with reward distractor type (high/low) and block (1–5) as factors showed a significant effect of block ($F(4,68) = 6.52, p < .001$) and reward ($F(1,17) = 5.70, p < .05$). Notably there was no significant interaction between reward and block ($F(1,17) = 1.13, p = .35$), indicating that the difference between saccades made in the high and low reward conditions remained constant over the course of the experiment (see Figure 4).

Interestingly, the reward information already showed a near significant effect in the first block of the experiment ($t(17) = 1.88, p = .077, d = 0.91$), with saccades landing closer to the high compared to the low reward signalling distractor. With regard to the main effect of block (1–5), as indicated by a significant linear trend ($F(1,17) = 10.28, p < .01$), the landing position shifted more and more away from the target. This shift towards the midline (i.e., the global effect becoming more global) was probably related to our dynamically adjusted latency threshold, which made participants make faster and faster saccades towards the end of the experiment.

Trial-by-trial reward priming

To investigate inter-trial reward priming we examined the difference in landing position given that the identity of the distractor changed or remained the same in two consecutive trials. A repeated measures ANOVA with distractor repetition (same/different) and current reward distractor type (high/low) as factors showed a main effect of current reward distractor type ($F(1,17) = 5.26, p < .05$), reflecting the reward effect on landing position. Yet crucially for the

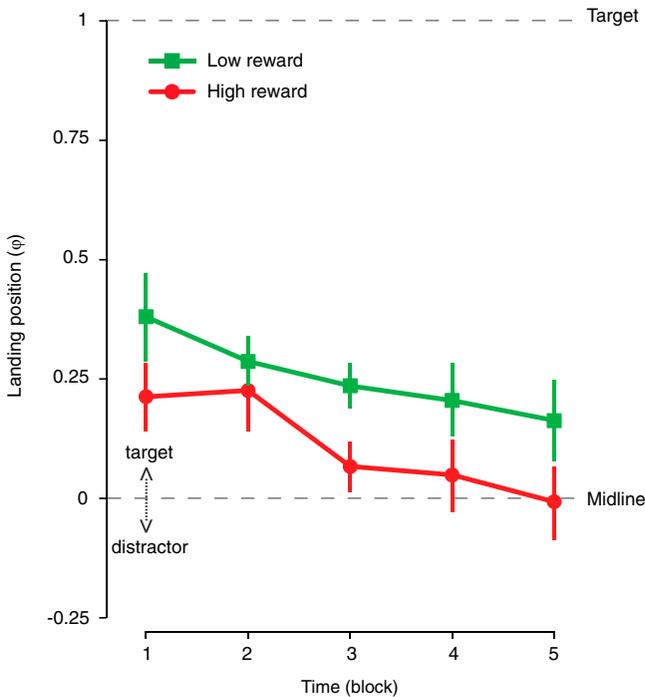


Figure 4. Mean landing position (ϕ) plotted over time (blocks) for the high and low reward distractor condition. Error bars represent 95% within-subject confidence intervals.

present analysis, there was a significant interaction between distractor repetition and current reward distractor type ($F(1,17) = 8.82, p < .01$), indicating that the landing position for high and low reward distractor trials is modulated by whether the distractor on the current trial is the same or different with regard to the previous trial. Subsequent two-tailed t -tests showed that the landing position in a high reward distractor trial resulted in a significantly larger deviation towards this high reward distractor ($t(17) = 2.64, SE = 0.03, p < .05$) when it was preceded by a high reward distractor trial (same) compared to the condition in which it was preceded by a low reward distractor trial (different). This suggests that a high reward signalling distractor has a strong inter-trial priming effect on landing position of the current trial. Crucially, landing position did not significantly differ on current low reward signalling distractor trials ($t(17) = 1.29, p = .21$), depending on whether these were preceded by high (different) or low (same) reward signalling distractors. As is clear from Figure 5, priming only occurred for the high and not for the low reward signalling distractor. The high reward signalling distractor colour in the previous trial, caused saccades to land significantly closer to the high reward signalling distractor in the current trial compared to the situation in which a low reward signalling distractor was presented in the previous trial. Possibly the high reward value that was coupled to the high reward signalling distractor colour caused reward priming over trials, such that the eyes were attracted significantly stronger to the high reward signalling distractor if the

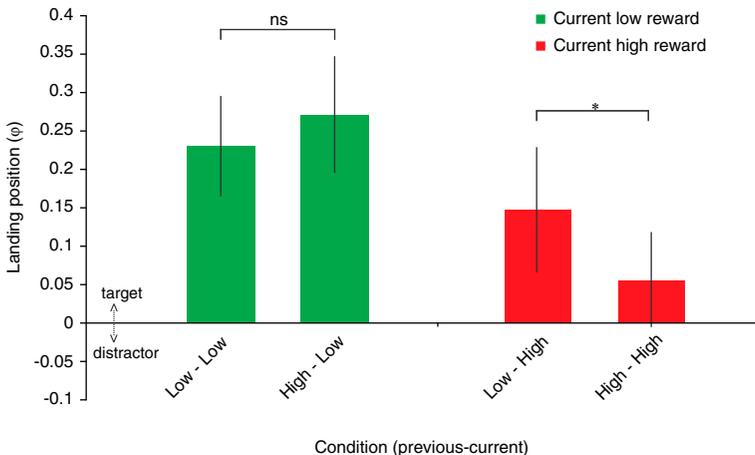


Figure 5. Mean landing position (ϕ) for current low (green) and high (red) reward distractor present trials, following previous low (Low-Low and Low-High) and high (High-Low and High-High) reward distractor trials. Note that reward priming is only observed for repeated presentation of high reward distractors (High-High). Error bars represent 95% within-subject confidence intervals.

distractor identity remained the same compared with a distractor identity switch.

Control experiment

In the control experiment, a new group of 14 participants performed the same task as the main experiment *without* the stimulus-reward contingencies. The purpose of this experiment was to ensure that the global bias towards distractors in the main experiment was due to their association with reward and not to differences in physical salience. Note that in the main experiment the target colour was always grey while the distractors were always coloured. As in the main experiment, we asked participants in the control experiment to make saccades as fast as possible towards the grey target circle. However, unlike in the main experiment, no rewards were given indicating that there was no association between the colour of the distractor and a possible reward.

A between experiment *t*-test showed that in the control experiment saccades landed significantly closer to the target ($t(30) = 18.0$, $SE = 0.05$, $p < .001$) than in the reward experiment. Also, participants were overall slower in the control experiment ($t(30) = 4.00$, $SE = 6.44$, $p < .001$). The saccade latencies of the control experiment were divided into eight quantiles which allowed us to compare the saccades latencies of the fastest saccades in the main experiment with those in the control experiment. An ANOVA on landing position with latency bin (1–8) as a factor showed a significant linear trend ($F(1,13) = 95.77$, $p < .001$) with saccades landing progressively closer towards the target location with increasing latencies. Crucially, a planned two-tailed *t*-test showed that the fastest saccades in the control experiment already showed a significant bias ($t(13) = 5.98$, $SE = 0.25$, $p < .001$) away from the midline (i.e., $\varphi = 0$) towards the grey target circle (see [Figure 6](#)). This is unlike the results of the main experiment, where we observed a bias for the fastest saccades to land closer to the reward signalling distractor. The effect in the control experiment was robust, with 12 out of 14 participants showing a strong bias for landing closer towards the grey target circle for the fastest saccades (mean landing position between $\varphi = 0.22$ and $\varphi = 0.82$), while the two other subjects showed the typical global effect (mean $\varphi = -0.05$ and $\varphi = -0.06$). Together these results suggest that in the main experiment it was the reward association and not physical salience that caused the eyes to be attracted more to the reward signalling distractors.

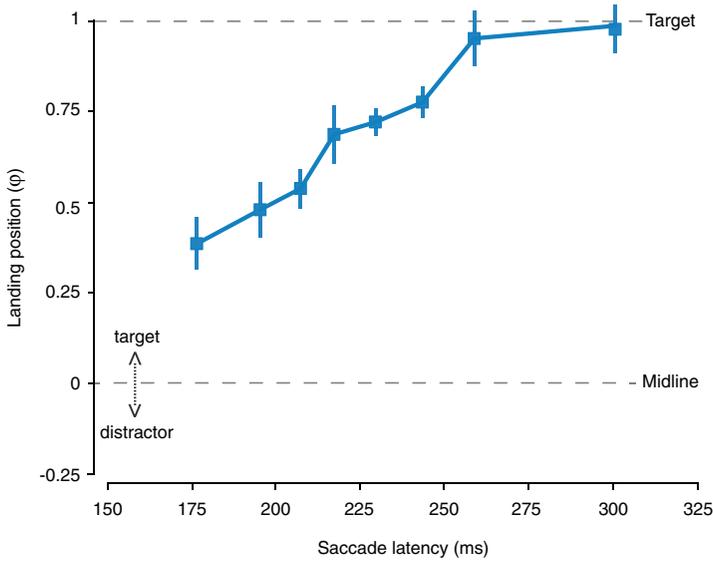


Figure 6. Mean landing position (ϕ) of saccades in the control experiment divided into eight latency bins. Note that the fastest eye movements already show a bias towards the target (i.e., $\phi > 0$). Error bars represent 95% within-subject confidence intervals.

DISCUSSION

In the present study we investigated whether reward-signalling distractors, that never served as targets, were able to attract the eyes in the context of the global effect paradigm. Participants were instructed to make an eye movement to the target circle as fast as possible, while the colour of the distractor circle signalled the reward available for that trial. We show that even though participants made fast saccades towards the target, their eyes landed significantly closer to the stimulus that signalled the availability of a high compared to the low reward. This reward effect was already present in the first block and remained stable throughout the experiment. The time course analysis indicated that this effect did not change with increasing latency, suggesting that the reward information carried by the distractors was present over the full latency range. Crucially, instead of landing exactly in between the equally salient target and distractor (i.e., the classic global effect), the fastest eye movements (around 165 ms) landed closer to the reward signalling distractor than to the equally salient target. Results of a control experiment without any reward signalling stimuli provided strong evidence that it was the reward association and not another specific task feature (e.g., physical salience) that caused the eyes to be attracted more to the reward signalling distractors. In addition to this sustained reward effect, we show trial-by-trial reward priming with saccades landing significantly closer to the high

reward signalling distractor but not to the low reward signalling distractor if the same value distractor was presented for two consecutive trials. Together these results imply that reward signalling stimuli elicit a rather automatic and involuntary effect on the oculomotor system that manifests itself very early in time.

Our results are consistent with other studies demonstrating that reward learning influences oculomotor behaviour (Anderson & Yantis, 2012; Theeuwes & Belopolsky, 2012). These studies have shown that, following a training-phase, distractor stimuli associated with high reward attracted the eyes more strongly than the very same distractor stimuli when associated with low reward. However, unlike these previous studies, the reward signalling distractor stimuli in the present study were never targets and were never actively searched in a preceding training-phase. Nevertheless, we show a sustained reward effect, with the eyes landing significantly closer to the high compared with the low reward signalling distractor. Crucially, this implies that oculomotor capture by reward associated distractor stimuli is not dependent on whether the distractor was previously a target in an earlier training-phase or not.

This is consistent with Le Pelley et al. (in press) who showed that in a visual search task with multiple distractors, relative to a low reward signalling distractor a high reward signalling distractor captured attention and the eyes more, even though the distractors were not actively searched. In multiple behavioural experiments, Le Pelley et al. (in press) showed that participants responded slower in a visual search task, when a high versus a low reward signalling distractor was present. In a follow-up eye tracking experiment, initial saccades went significantly more often to the high compared with the low value distractor, while participants were searching for a target stimulus. Consistent with Le Pelley et al. (in press) we also observed an effect of reward on the initial saccades. While Le Pelley and colleagues utilized a visual search task with multiple distractors (of which the reward signalling distractors were more salient than the other non-target elements) and a fixed latency threshold of 600 ms, we investigated very fast eye movements (as fast as 165 ms) in the context of the global effect paradigm. Our results showed that the eyes were more attracted by high compared to low reward signalling distractors and that this effect remained stable over latency bins and the course of the experiment. Notably, the fastest eye movements landed closer towards the reward signalling distractor instead of landing in the middle (i.e., typical global effect) or landing closer towards the target. Furthermore, we showed that high and not low reward signalling distractors elicited a reward priming effect, with the eyes being attracted more by high value signalling distractors after repeated presentation. Together these studies provide converging evidence that previous selection of reward-associated items in a training-phase may not be the driving force behind reward capture in a later testing-phase. Rather, the simple correlation of stimuli with reward causes

the eyes to be drawn more to those stimuli, even if they never served as targets before.

With regard to the time course of saccades, the results of the present study are in line with a recent study investigating the influence of top-down control on the global effect (Heeman et al., 2014). Similar to the present study, participants were instructed to make an eye movement to a specifically coloured target circle, while ignoring a differently coloured distractor circle. A significant linear effect was observed for saccades landing closer to the target circle with increasing latency. A comparable linear effect, with saccades landing closer to the target with increasing latency, was observed in both the reward and the control experiment. This increasing target bias is in line with the idea that goal-driven information becomes more dominant with increasing latencies (Van Zoest, Donk, & Theeuwes, 2004). However, the reward values introduced in the reward experiment cause a notable difference with regard to the landing position of the fastest saccades. Compared with a baseline condition in which participants had not received a target instruction, Heeman et al. show that the fastest saccades were already biased towards the target (i.e., $\varphi > 0$), results which are strikingly similar to the results of our control experiment. In the reward experiment, we observe a bias towards the reward signalling distractors (i.e., $\varphi < 0$) for the fastest saccades. Although we cannot rule out the possibility that there are goal-driven effects at the 165 ms saccade latencies in the reward experiment, a possible top-down effect at these early time intervals is out weighted by the automatic effect of the reward signalling stimulus. This implies that reward can exert an effect very early in time that might be considered involuntary, since it counteracted the current task-goal.

In terms of the earlier described competitive integration model (Godijn & Theeuwes, 2002), these results indicate that early in time the reward signalling distractor evoked a larger peak of activity in the saccade map compared with the target. Crucially, based on the physical stimulus properties of the target and distractor alone, one expects two equally sized peaks of activity in the saccade map, resulting in a global effect with an average landing position perfectly in the middle of the two circles (i.e., $\varphi = 0$). However, although both the target and the distractors had the same physical salience, the reward value associated with the distractor made it more “salient” compared to the target. The reward value coupled to the distractors possibly altered their representation on a salience map and increased the priority of the distractor over that of the target very early in time.

The sustained reward effect with saccades landing closer to the high compared with the low reward signalling distractor can similarly be explained in the context of the competitive integration framework. That is, the high reward distractor signals a higher value than the low reward distractor and therefore evokes a greater peak of activity in the saccade map. This relative difference caused the average activity in the saccade map to be located closer the distractor

on trials during which the high compared with the low value distractor was present. Furthermore, the enlarged peak evoked by the high compared with the low reward distractor is responsible for an absolute increase of average activity in the saccade map, causing the saccade threshold to be reached earlier. This might explain the observed latency difference. As suggested by Theeuwes and Belopolsky (2012), it is possible that reward value lowered the threshold for making a saccade, especially since we made use of a dynamic threshold to ensure that saccades were made progressively faster in order to obtain reward. In addition to the sustained reward effect, the competitive integration model can also explain why saccades landed significantly closer to the target with increasing saccade latency. Since the model assumes goal-driven control to improve with increasing latency, the peak of activity that is evoked by the target will be progressively enhanced with increasing saccade latency. Overall, the current results can be well explained in the context of the competitive integration model, with a very early factor enhancing higher reward value associated stimuli and a goal-driven factor enhancing target activity with increasing latency.

In addition to the sustained reward effect, we investigated the transient process of reward priming by examining the difference in landing position given that the identity of the distractor changed or remained the same in two consecutive trials. As is clear from [Figure 5](#), saccades landed significantly closer to the high reward signalling distractor when it was preceded by a high compared with a low reward signalling distractor. Crucially, no such effect was observed for the low reward signalling distractor, indicating that inter-trial priming was driven by the reward value of the stimulus. Furthermore, it is important to realize that the priming that we observed is not the more often described type of priming during which repeated presentation of attended stimulus features facilitates detection of such features (see Kristjánsson & Campana, 2010, for a review). Instead, here it was the distractor that drew the eyes when it was repeatedly presented, although participants were constantly making eye movements to the same target stimulus. In the context of the global effect paradigm, Meeter and Van der Stigchel (2013) also showed inter-trial priming, demonstrating that repeating the object colours improved the target representation such that after target repetition, the eyes tended to land closer to the target. They claimed that inter-trial priming caused a bottom-up boost of the target representation. In our study however, repeating a trial with a high reward signalling distractor caused the eyes to move away more from the target and more towards the distractor. This suggests that in line with the target boost mechanism of Meeter and Van der Stigchel (2013), inter-trial reward priming caused a similar bottom-up boost of the distractor representation, increasing the priority of the reward signalling distractor.

This hypothesis regarding the origin of inter-trial priming is consistent with a reward study by Hickey, Chelazzi, and Theeuwes (2010), who showed that high versus low reward associated colours automatically captured selective attention on a trial-by-trial basis. In this study, the additional singleton paradigm was used

and participants received either a high or a low reward for correct answers. Reward delivery was random on a trial-by-trial basis and the colours of items in the display could remain the same or swap, with the colour of the target becoming the colour of the distractors. The results showed that only after receiving a high reward, responses were fast when the target colour remained the same, but slow when the colours swapped. The high reward value associated with the target features caused visual attention to be biased towards those features in the upcoming trial. Even in a second experiment, where it was most beneficial for participants to abandon the current reward attentional set, they counterproductively continued to select the stimulus characterized by the colour previously associated with the high reward value. Thus, despite being counterproductive, the association of a colour with the high reward value automatically changed the visual salience of stimuli in a way that is strong enough to negate the impact of endogenous strategic deployment of attention. These results are very much in line with the present study, since we show an increased bias towards the high reward signalling distractor after repeated presentation, although participants maintained a strategic attentional set to make an eye movement towards the target at all times. Although here, the high and low reward value were consistently coupled to the same colour and these colours never served as target colours, we also show that a high and not a low reward signalling stimulus automatically attracts attention and the eyes when it is shown on two consecutive trials.

In sum, the present study shows that the global effect is influenced by the mere presence of a stimulus that signals the availability of reward. Our data show the effect of the reward signalling stimulus is already present at the fastest saccade latencies suggesting an early, involuntary and automatic modulation of the oculomotor system by reward signalling stimuli.

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