Visual Cognition

Cognitive control and counterproductive oculomotor capture by reward-related stimuli

Daniel Pearson[a], Chris Donkin[a], Sophia C. Tran[a], Steven
B. Most[a] & Mike E. Le Pelley[a]

[a] School of Psychology, University of New South Wales,
Sydney, NSW, Australia
Published online: 04 Feb 2015.

CrossMark

Click for updates

PLEASE SCROLL DOWN FOR ARTICLE

whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden. Terms & Conditions of access and use can be found at http://www.tandfonline.com/page/terms-and-conditions

Routledge
Taylor & Francis Group

Cognitive control and counterproductive oculomotor capture by reward-related stimuli

**Daniel Pearson, Chris Donkin, Sophia C. Tran,
Steven B. Most, and Mike E. Le Pelley***

School of Psychology, University of New South Wales, Sydney, NSW,
Australia

Two experiments investigated the extent to which value-modulated oculomotor capture is subject to top-down control. In these experiments, participants were never required to look at the reward-related stimuli; indeed, doing so was directly counterproductive because it caused omission of the reward that would otherwise have been obtained. In Experiment 1, participants were explicitly informed of this omission contingency. Nevertheless, they still showed counterproductive oculomotor capture by reward-related stimuli, suggesting that this effect is relatively immune to cognitive control. Experiment 2 more directly tested whether this capture is controllable by comparing the performance of participants who either had or had not been explicitly informed of the omission contingency. There was no evidence that value-modulated oculomotor capture differed between the two conditions, providing further evidence that this effect proceeds independently of cognitive control. Taken together, the results of the present research provide strong evidence for the automaticity and cognitive impenetrability of value-modulated attentional capture.

Keywords: Visual attention; Reward learning; Reinforcement learning; Eye movements; Attentional capture.

It is well established that the extent to which stimuli capture attention is influenced by their physical salience. For example, a stimulus is more likely to capture attention if it has an abrupt onset (Yantis & Jonides, 1984), or distinctive colour (Theeuwes, 1992). More recently, however, it has been demonstrated that physical salience is not the whole story: attentional capture is also influenced by

previous experience of stimuli and their relationships with other events (Anderson, Laurent, & Yantis, 2011a, 2011b; Anderson & Yantis, 2012; Della Libera & Chelazzi, 2009; Della Libera, Perlato, & Chelazzi, 2011; Kiss, Driver, & Eimer, 2009; Le Pelley, Pearson, Griffiths, & Beesley, 2014; Le Pelley, Vadillo, & Luque, 2013; Theeuwes & Belopolsky, 2012: for a recent review, see Le Pelley, Beesley & Griffiths, 2014).

Of particular relevance for the current investigation, experience of a predictive relationship between a stimulus and high-value reward increases the likelihood that the stimulus will capture attention, independently of its physical salience. A particularly clear demonstration of this is provided by the visual search task of Anderson et al. (2011a). During an initial training phase, participants searched for a red or green target circle among an array of six differently coloured circles and were required to make speeded responses indicating the orientation of a line segment within the target circle. Participants earned a monetary reward for correct responses made within 600 ms. Crucially, the amount earned on each trial depended on the colour of the target (red or green). One of the target colours (the *high-value colour*) was paired with high reward (5¢) on 80% of trials and low reward (1¢) on 20% of trials. The other, *low-value colour* was paired with high reward on 20% of trials and low reward on 80% of trials.

In a subsequent test phase, the target was now defined by its unique shape: either a diamond among five circles, or a circle among five diamonds. As in the training phase, participants responded to the orientation of the line inside the target shape, but they no longer received rewards. Crucially, on some trials one of the nontarget shapes (termed the distractor) in this test display was coloured either red or green. All other shapes were black, making the distractor a colour singleton. Participants were explicitly informed that colour was irrelevant to this task and should be ignored, and that the target would never be red or green. Nevertheless, response times in the test phase were influenced by the colour of the distractor. Specifically, responses were slower when the distractor was rendered in the high-value colour than in the low-value colour.

Since the distractor stimulus presented in the test display of Anderson et al.'s (2011a) task was physically salient (by virtue of its status as a colour singleton), we might expect it to capture attention on the basis of this physical salience, and hence slow responding to the target (Theeuwes, 1992, 1994). However, the finding that a distractor that was previously associated with high reward interfered with performance more strongly than a distractor previously associated with smaller reward suggests that physical salience cannot be the only determinant of attentional capture here, since the physical salience of these different distractors was matched across participants (by counterbalancing of the high- and low-value colours). The implication is that the likelihood of attentional capture is also influenced by the magnitude of the reward that is associated with the distractor, independently of its physical salience. In other words, these findings suggest that learning about reward value changes the likelihood of

capture that would otherwise be produced by physical salience (see also Kiss et al., 2009). We term this effect *value-modulated attentional capture*.

Stimuli that capture attention also tend to capture eye movements; this is known as oculomotor capture (e.g., Ludwig & Gilchrist, 2002; Theeuwes, De Vries, & Godjin, 2003). Consistent with this suggestion, value-modulated capture has also been observed in studies of eye gaze. Theeuwes and Belopolsky (2012; see also Anderson & Yantis, 2012) used a design that was conceptually similar to that of Anderson et al. (2011a). In an initial training phase, participants received high reward for making rapid saccades towards a particular shape (the high-value shape) and low reward for making rapid saccades to a different, low-value shape. In a subsequent test phase, the onset of the high-value shape was more likely than the low-value shape to elicit oculomotor capture. That is, participants were more likely to make eye movements towards the onset of the high-value shape when it appeared as a distractor in a visual search task.

In both of these demonstrations of value-modulated capture, the reward-related stimuli had been *task-relevant* during the initial training phase, since they had defined the targets that participants were required to respond to in order to receive reward. For example, in the study by Theeuwes and Belopolsky, participants were required to make a rapid eye movement towards the high- or low-value shape in the training phase to obtain reward. This raises the possibility that the value-modulated capture observed in the test phase might simply reflect a "carry-over" of an automatic oculomotor response developed during the training phase. More specifically, during training participants received a larger reward for making a saccade to the high-value shape than the low-value shape. This would provide greater drive for reinforcement learning of an automatic response of making a rapid saccade to the high-value stimulus whenever it is presented. If I have consistently received 10¢ for looking at a particular shape over the previous 100 trials, it is perhaps no surprise that I should continue to look at it in future (for a short time at least), even if doing so is no longer required by the task.

Notably, however, Le Pelley, Pearson, et al. (2014) recently demonstrated an influence of reward learning on attentional and oculomotor capture by stimuli that had *never* been task-relevant for participants. In the final experiment of this series, on every trial participants were required to move their eyes to the location of a grey diamond-shaped target among grey circles (see Figure 1) as quickly as possible. A distractor circle could be rendered in either a high-value or low-value colour (red or blue, with assignment counterbalanced across participants). Fast eye movements to the target diamond earned large reward (10¢) when the distractor appeared in the high-value colour, and 1¢ when the distractor was in the low-value colour. Importantly, however, if at any point participants' gaze was registered in a relatively large region surrounding the distractor, the reward on that trial was cancelled; these were termed *omission trials*.
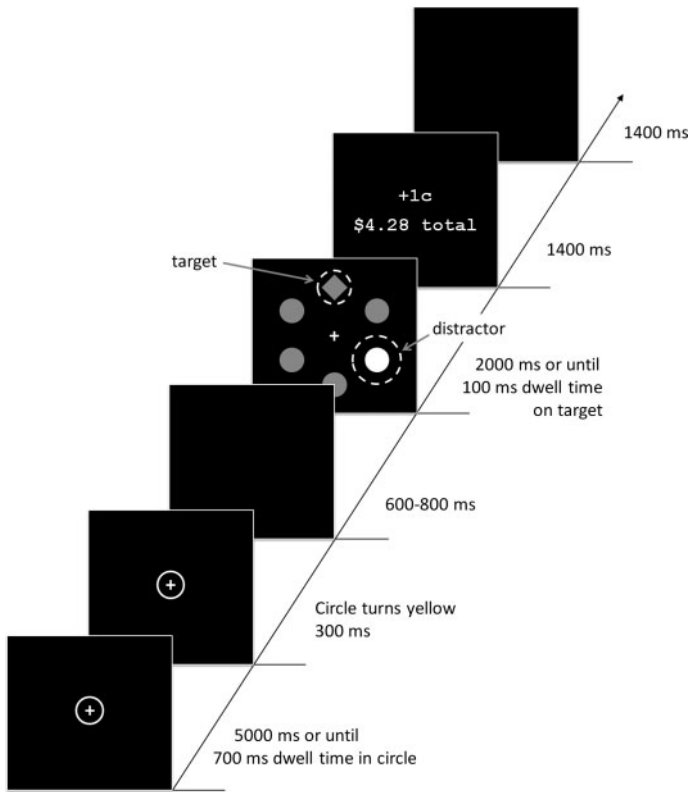
Figure 1. Sequence of trial events in the study by Le Pelley et al. (2014) and the current experiments. Participants responded by moving their eyes to the diamond target. One of the nontarget circles could be a colour singleton distractor, rendered in red or blue (shown in white in the figure). Dotted lines (not visible to participants) indicate the region of interest (ROI) around the target and distractor within which eye gaze was defined as falling on the corresponding stimulus. Fast, correct responses received monetary reward, depending on the distractor colour. A high-value distractor colour reliably predicted large reward; a low-value colour reliably predicted small reward; when there was no colour-singleton distractor present, large and small reward were equally likely. If any gaze fell within the distractor ROI (or, on distractor-absent trials, an equivalent ROI positioned around a randomly-chosen circle), the trial was deemed an omission trial and no reward was delivered.

Thus, while the distractor predicted reward magnitude, it was not the stimulus to which participants were required to respond in order to obtain that reward. Hence throughout the entire experiment, the distractor was irrelevant with respect to participants' goal of obtaining reward. Indeed, participants were never rewarded if they looked at or near the distractor. Nevertheless, even under these conditions participants developed an attentional bias towards high-value distractors. Specifically, high-value distractors produced significantly more omission trials than did low-value distractors. That is, participants were more likely to

make eye movements towards high-value distractors than low-value distractors, even though doing so was directly counterproductive because if these eye movements occurred, the reward was omitted.

Given that the value-modulated attentional capture bias observed by Le Pelley, Pearson, et al. (2014) is directly counterproductive to participants' goal of maximizing reward, it seems to reflect an automatic process, rather than a result of strategic control over attentional selection. However, the role of top-down selection strategies in singleton capture is a contentious issue (Folk & Remington, 1998; Theeuwes, 1994; Yantis, 2000). In particular, Folk and Remington have argued that deployments of attention typically, if not always, stem from implementations of a top-down attentional control setting. Leaving value-related effects to one side for a moment, consider the situation in which participants' task is to search for a shape singleton target, but participants' attention is captured by a colour singleton distractor (Theeuwes, 1992). On Folk and Remington's account, the task requirement (search for a shape singleton target) causes participants to engage "singleton detection mode" (Bacon & Egeth, 1994). However, this search mode is not completely selective, and so the distractor will sometimes capture attention because it is also a singleton (albeit on a different dimension to the target). Hence this pattern of capture can be viewed as a stimulus-driven modulation of a top-down selection strategy.

We raise this debate merely to demonstrate that the potential role of strategic processes in attentional capture is interesting and nuanced. Returning to the issue of counterproductive value-modulated capture, the current experiments investigate whether participants can use strategic control to overcome this effect if they are given more encouragement to do so. In the earlier study by Le Pelley, Pearson, et al. (2014), participants were not explicitly informed about the omission contingency embedded in the task—i.e., they were not told that looking at the distractor caused omission of the reward—and none of the participants reported awareness of this contingency at the end of the experiment. This raises the possibility that if participants were made explicitly aware of the omission contingency from the outset, they might be able to adopt an alternative selection strategy that would allow them to overcome the counterproductive effect of value-modulated capture. Experiment 1 tested this possibility.

EXPERIMENT 1

Method

Participants.   Twenty-six first-year psychology students from the University of New South Wales (UNSW) participated in exchange for course credit. They also received a performance-related monetary bonus ($M = 18.81$ AUD, SEM = 0.69 AUD).

Apparatus.   Participants were tested individually using a Tobii TX300 eye-tracker, with 300 Hz temporal and 0.15° spatial resolution, mounted on a 23 inch monitor running at 60 Hz. Participants' heads were positioned in a chinrest 60 cm from the screen. For gaze-contingent calculations, the experiment script sampled the eye-tracker every 10 ms. Current gaze location was defined as the average gaze location during the preceding 10 ms sample. The eye-tracker was calibrated using a 5-point procedure prior to the practice phase, prior to the training phase, and after six training blocks.

Stimuli.   The experiment used a variant of the additional singleton paradigm (Theeuwes, 1991, 1992). Stimuli were identical to those used by Le Pelley, Pearson, et al. (2014). Each trial consisted of a fixation display, a search display, and a feedback display (Figure 1). All stimuli were presented on a black background. The fixation display consisted of a white cross (subtending 0.5 degrees of visual angle, dva) presented centrally, inside a white circle (diameter 3.0 dva). The search display comprised the fixation cross surrounded by six filled shapes (2.3×2.3 dva) positioned at equal intervals around an imaginary circle with diameter 10.1 dva (with the first position directly above the fixation cross). Five of these shapes were circles, and one was a diamond. The diamond and four of the circles were rendered in grey. The remaining circle (the distractor) was rendered either in red, blue, or the same shade of grey as the other shapes (CIE x, y chromaticity coordinates of .595/.360 for red, .160/.116 for blue, and .304/.377 for grey). The values of red and blue had similar luminance ($\sim$42.5 cd/m^2), which was higher than that of the grey (32 cd/m^2). The feedback display showed the reward earned on the previous trial, and total earnings. Importantly, if any gaze had been registered on the distractor circle, causing a reward omission, the message "You looked at the circle" appeared alongside the feedback that the reward was 0¢ on that trial. If response time (RT) was greater than the "soft-timeout" threshold (see below), the message "Too slow" appeared alongside the feedback that the reward was 0¢.

Design.   For half of the participants, red acted as the high-value colour and blue acted as the low-value colour; this assignment was reversed for the other half of participants. Experiment 1 involved 10 blocks of 48 trials, for a total of 480 experimental trials. Each block contained 20 trials with a distractor rendered in the high-value colour, 20 trials with a distractor in the low-value colour, and eight "distractor-absent" trials on which there was no colour singleton in the display. Trial order within a block was randomized. The location of the target and the distractor were randomly determined on each trial, with the constraint that the distractor never appeared adjacent to the target.

A small circular region of interest (ROI) with diameter 3.5 dva was defined around the diamond target; a larger ROI (diameter 5.1 dva) was defined around the distractor. A response was registered when participants had accumulated 100

ms of dwell time inside the target ROI. Responses with RTs slower than a soft-timeout threshold earned no reward; this threshold was 600 ms for the first block, and 500 ms for the remaining nine blocks. Crucially, if any gaze fell inside the distractor ROI prior to a response being registered, even for a single 10 ms period, the trial was recorded as an omission trial and no reward was delivered. On distractor-absent trials, one of the grey circles (that was not adjacent to the target) was chosen at random; gaze falling inside an ROI around the selected grey circle caused an omission trial in exactly the same way as if the selected circle had been a distractor.[1]

Reward was delivered if RT was faster than the soft-timeout threshold and no gaze was registered in the distractor ROI: 10¢ if the high-value distractor was present, 1¢ if the low-value distractor was present, and an equal likelihood of 10¢ or 1¢ on distractor-absent trials.

Procedure. Participants were informed that their task was to move their eyes to the diamond shape, and that they could earn 0¢, 1¢ or 10¢ on each trial "depending on how fast and accurate" their response was. They were informed that responses slower than 500 ms would receive no reward (in fact the threshold was 600 ms during the first block, while participants got used to the task). Participants were also explicitly told, both in written instructions and verbally by the experimenter, that: "On most trials, one of the circles will be coloured. If you accidentally look at this circle before you look at the diamond, you will receive no reward. So you should try to move your eyes straight to the diamond". Participants completed eight practice trials with a yellow distractor, and no rewards, followed by the experimental trials. They received a short break after every 96 trials.

Each trial began with presentation of the fixation display. Participants' gaze location was superimposed on this display as a small yellow dot. Once participants had recorded 700 ms dwell time inside the circle surrounding the fixation cross, or if 5 s had passed, the cross and circle turned yellow and the dot marking gaze location disappeared. After 300 ms the screen blanked, and after a random interval of 600, 700 or 800 ms the search display appeared. The trial terminated when a response was registered (see Design), or after 2 s (hard timeout). The feedback display then appeared for 1400 ms, informing participants (1) whether they had caused a reward omission or made a slow

---

[1] Allowing for omissions on distractor-absent trials is useful, because it permits a valid test of the influence of stimulus salience on oculomotor capture, by comparing the rate of omissions on trials featuring a salient distractor with the rate on distractor-absent trials. This comparison controls for causes of omission trials that are not related to distractor salience (e.g., inaccuracy in the recording of gaze location, random eye movements by the participant, etc.), since these will be equal on trials with a salient distractor and distractor-absent trials.

response, (2) how much money they earned on that trial, and (3) total earnings so far. Inter-trial interval was 1400 ms.

After the visual search task finished, we assessed participants' awareness of the colour–reward contingencies. Participants were told that the amount that could be won on each trial depended on the colour of the coloured circle in the search display. They were then presented with a red and blue circle, in random order, and for each were asked to indicate whether they would earn 1¢ or 10¢ when that stimulus was presented, and to rate their confidence in this decision from 1 to 5.

Finally, participants completed two questionnaires: the Attentional Control Scale (ACS: Derryberry & Reed, 2002) and the Barratt Impulsiveness Scale Version 11 (BIS-11: Patton, Stanford, & Barratt, 1995). Data from these questionnaire measures were inconclusive and are not pursued further here, but for the sake of completeness are discussed further in the accompanying Supplementary Materials I.

Data analysis.   Preliminary analysis of eye gaze data followed exactly the procedures used by Le Pelley, Pearson, et al. (2014). Specifically, the first two trials of the visual search task, and the first two trials after each break, were discarded. Hard timeouts (2.3% of all trials) were also discarded. Finally, we also excluded all trials on which valid gaze location was registered in less than 25% of the 10 ms samples between presentation of the search display and registering of a response (1.2% of all trials). For remaining trials, averaging across participants, valid gaze location was registered in 96.9% (SEM 1.0%) of samples, suggesting very high fidelity of the gaze data on these trials.

Analysis of saccade latencies used the raw data from the eye-tracker (sampled at 300 Hz, rather than the 100 Hz used for gaze-contingent calculations). For these analyses, we further excluded all trials on which no eye gaze was recorded within 5.1 dva (100 pixels) of the fixation point during the first 80 ms after presentation of the search display. Saccade latency was then found by identifying the first point at which five consecutive gaze samples lay more than 5.1 dva from the fixation point. Saccades faster than 80 ms were excluded from further analyses. The extra exclusions described in this paragraph resulted in loss of an additional 8.3% of trials.

Results

Figure 2A shows the proportion of omission trials across training. Unsurprisingly, trials with a colour-singleton distractor generated more omissions than distractor-absent trials. Most importantly, there were more omission trials when the display contained a high-value distractor than when it contained a low-value distractor. The data in Figure 2A were analysed using a 3 (distractor type: high-value, low-value, absent) × 10 (block) analysis of variance (ANOVA). There was
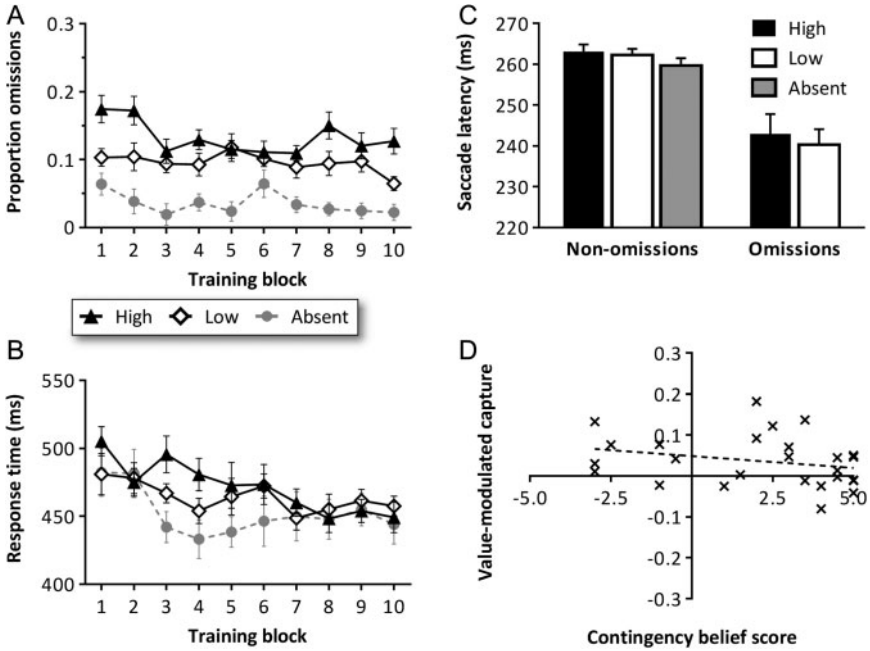
Figure 2. (A) Mean proportion of omission trials and (B) mean response time across the 10 training blocks of Experiment 1, for high-value, low-value, and distractor-absent trials. Reward was more likely to be omitted, and response times were slower, on trials with the high-value distractor than trials with the low-value distractor. (C) Mean saccade latencies on omission and non-omission trials, averaged across training blocks. Saccade latencies were generally slower for non-omission trials than omission trials. On non-omission trials, latencies were shortest on distractor-absent trials, but did not differ significantly on high- and low-value distractor trials. All error bars show within-subjects SEM. (D) Scatterplot of value-modulated oculomotor capture (vertical axis; calculated as proportion of omissions on high-value trials minus proportion of omissions on low-value trials) against contingency belief score (horizontal axis; calculated as explained in main text). Dotted line shows line of best fit.

a significant main effect of distractor type, $F(2,50) = 36.3$, $p < .001$, $\eta_p^2 = .59$, and a significant main effect of block, $F(9,225) = 2.20$, $p = .023$, $\eta_p^2 = .08$, with proportion of omissions tending to fall as training progressed. The distractor type × block interaction was not significant, $F(18,450) = 1.15$, $p = .30$, $\eta_p^2 = .04$.

Planned pairwise *t*-tests, averaging across training blocks, were used to further analyze the main effect of distractor type. Each type of coloured distractor produced more reward omissions than for distractor-absent trials—high-value vs. absent: $t(25) = 7.86$, $p < .001$, $d = 1.54$; low-value vs. absent: $t(25) = 5.95$, $p < .001$, $d = 1.17$. Crucially, trials with the high-value distractor produced more omissions than trials with the low-value distractor, $t(25) = 2.98$, $p = .006$, $d = 0.58$.

A similar pattern was observed in RTs (Figure 2B); as noted earlier, a response was registered when 100 ms of dwell time had accumulated inside the

target ROI. On average, RTs were longer for trials featuring a high-value distractor than those with a low-value distractor (and fastest for distractor-absent trials). For these data, 3×10 ANOVA revealed a significant main effect of distractor type, $F(2,50) = 7.68$, $p = .001$, $\eta_p^2 = .24$, and a significant main effect of block, $F(9,225) = 2.04$, $p = .036$, $\eta_p^2 = .08$, with RTs tending to fall as training progressed. The distractor type × block interaction was not significant, $F(18,450) = .98$, $p = .48$, $\eta_p^2 = .04$. Follow-up t-tests, averaging across training blocks, revealed that RTs were fastest on distractor-absent trials—high-value vs. absent: $t(25) = 3.27$, $p = .003$, $d = .64$; low-value vs. absent: $t(25) = 2.58$, $p = .016$, $d = .51$. Importantly, the trend towards slower RTs for high-value distractors ($M = 470$ ms) than low-value distractors ($M = 463$ ms) approached significance, $t(25) = 1.86$, $p = .074$, $d = .37$.

Figure 2C shows saccade latencies on omission trials, and non-omission trials (i.e., trials on which participants did not look at the distractor), averaged across training blocks. Saccade latencies for distractor-absent omission trials are not shown—even though omissions could occur on these trials (see Design)—because there were so few of these trials (10 of 25 participants registered zero trials in this category, so mean saccade latencies could not be calculated for these participants). Saccade latency was generally shorter on omission trials than non-omission trials: this was true for trials with a high-value distractor, $t(25) = 3.34$, $p = .003$, $d = .66$, and with a low-value distractor, $t(25) = 4.80$, $p < .001$, $d = .94$. For non-omission trials, saccade latency was shortest on distractor-absent trials—high-value vs. absent: $t(25) = 2.14$, $p = .042$, $d = .42$; low-value vs. absent: $t(25) = 2.11$, $p = .045$, $d = .41$. There was no significant difference in saccade latency on trials with a high-value versus low-value distractor: on non-omission trials, $t(25) = 1.02$, $p = .32$, $d = .20$; on omission trials, $t(25) = .36$, $p = .72$, $d = .07$.

Finally, we assessed whether the value-modulated capture effect observed in proportion of omissions (our primary dependent variable) was related to participants' awareness of the colour–reward contingencies, as measured in the awareness test that was delivered following training. For each colour, if a participant selected the correct reward magnitude then their *contingency belief score* was given by multiplying their confidence rating by +1; if they selected the incorrect reward magnitude, their confidence rating was multiplied by −1. For example, if a participant responded that the high-value colour was paired with the high-value reward with a confidence of 3, then their contingency belief score for this colour would be 3. If instead they responded that the high-value colour was paired with the low-value reward with a confidence of 2, their contingency belief score for this colour would be −2. Contingency belief scores were averaged across the two colours, and fell on a range from + 5 (very confident of the correct colour–reward contingencies) to −5 (very confident of the incorrect contingencies). Figure 2D shows a scatterplot of contingency belief scores against the difference in proportion of omissions on high- and low-value distractor trials (which is our primary measure of value-modulated capture),

collapsed across blocks. There was no evidence of a positive correlation between these measures; Pearson's $r(24) = -.26$, $p = .20$.

Discussion

Participants showed more oculomotor capture by high-value stimuli than low-value stimuli, even though they were explicitly informed that looking at the distractor stimuli would result in the omission of a reward. This finding suggests that counterproductive value-modulated attentional capture persists even when participants are made explicitly aware that this capture causes the omission of reward. The implication is that the influence of reward on attentional capture is the result of an automatic attentional process that operates despite efforts to the contrary. Additional support for this interpretation is provided by the finding that the magnitude of value-modulated capture was not related to participants' explicit beliefs regarding the colour–reward contingencies.

Mean saccade latency in Experiment 1 was generally shorter on omission trials (i.e., trials on which participants looked at the distractor before looking at the target) than on non-omission trials (trials on which participants did not look at the distractor prior to looking at the target). Similar findings of faster saccades on capture trials than non-capture trials have previously been taken to suggest that the onset of the search display typically results in programming of two saccades: (1) a voluntary saccade to the target, and (2) a reflexive saccade to the salient distractor, which captures attention automatically (Theeuwes, Kramer, Hahn, Irwin, & Zelinsky, 1999). Latencies for saccades to the distractor are then shorter because these reflexive eye movements are made before the voluntary saccade to the target is ready. However, on a proportion of trials there is no reflexive eye movement to the distractor; on these trials, the (slower) voluntary saccade to the target proceeds. Alternative accounts of why reflexive eye movements might not occur, and further discussion of the saccade latency data, are postponed until the General Discussion.

Some aspects of the data of Experiment 1 bear further consideration. The first issue relates to the role of learning in this task. The difference in behaviour on high-value versus low-value trials must reflect learning about reward predictions, since (across participants) this was the only difference between distractor stimuli. However, the size of the value-modulated capture effect showed a rather noisy pattern across blocks, rather than the gradual learning curve that one might intuitively expect. In particular, the distractor type × block interaction was not significant, suggesting that the size of the critical effect did not change significantly across blocks. This null result may simply reflect noise in the block-by-block data; alternatively, it may point to the possibility that the influence of reward learning on attentional capture developed early and did not change greatly over the course of training.

A second issue relates to the magnitude of the value-modulated capture effect. While Experiment 1 demonstrates that the counterproductive influence of reward on attentional capture persists when participants are explicitly informed of the omission contingency embedded in the task, it does not rule out the possibility that this explicit knowledge allowed participants to exercise *partial* control over attentional capture by value-related singletons. That is, explicitly informing participants may have reduced value-modulated capture without eliminating it entirely. In order to test this possibility, Experiment 2 investigated whether the magnitude of the value-modulated capture effect was influenced by whether or not participants were explicitly informed of the omission contingency.

EXPERIMENT 2

In Experiment 2, half of the participants were informed of the omission schedule, as in Experiment 1, while the other half of participants were not informed about the omission schedule, as in Le Pelley, Pearson et al.'s (2014) previous study. All other aspects of the experiment were the same for the two groups. If value-modulated capture is partially controllable, the effect of reward on attentional capture should be smaller for participants who were explicitly informed of the omission contingency, compared to those who did not receive such information. However, if value-modulated capture proceeds relatively automatically, there should be no difference in the size of the effect between the two conditions.

Method

Participants, apparatus and stimuli.   Sixty participants completed Experiment 2. Of these, 47 were first-year UNSW psychology undergraduates participating in exchange for course credit and 13 were recruited from the UNSW community in exchange for 15 AUD. All participants also received a performance-related monetary bonus ($M = 18.24$ AUD, SEM = 0.51 AUD). Apparatus and stimuli were as for Experiment 1.

Design and procedure.   Half of the participants were assigned to the "Explicit" group. These participants received exactly the same treatment as those in Experiment 1: they were explicitly informed of the omission contingency in their initial instructions, and received explicit feedback on each omission trial that reward was zero because they had looked at the distractor circle. The other half of participants were assigned to the "Implicit" group: these participants were treated exactly the same, except the instructions made no mention of the omission contingency. Instead, as in Le Pelley, Pearson et al.'s (2014) study, they were informed that the amount of reward they received on each trial would be determined by "how fast and accurately you move your eyes

to the diamond". For these participants, feedback on omission trials simply stated that reward was zero without providing a reason why (as in Le Pelley, Pearson, et al., 2014). Within each group, half of participants had red as the high-value colour and blue as the low-value colour, and this assignment was reversed for the other half. Participants were assigned to groups and colour-counterbalance conditions in an intermixed way based on their order of arrival. All other details of Design and Procedure not mentioned here were as for Experiment 1.

   Data analysis.   As in Experiment 1, the first two trials of the visual search task, the first two trials after each break, and hard timeouts (3.1% of all trials) were discarded. Trials on which valid gaze location was registered in less than 25% of the 10 ms samples between presentation of the search display and registering of a response were also excluded. For one participant (in group Implicit) this latter condition resulted in exclusion of 55% of all trials, as compared to a mean of 1.7% (SEM = 2.4%) for remaining participants. This was due to generally poor tracking of gaze for this participant, with only 67% of all gaze samples registered. As a conservative measure we therefore excluded all data from this poorly-tracked participant (we note that doing so makes no difference to the pattern of significant and non-significant effects reported below).[2] Averaging across remaining participants, valid gaze location was registered in 97% (SEM = 0.7%) of the 10 ms samples between presentation of the search display and registering of a response, suggesting very high fidelity of the gaze data. Saccade latencies were calculated as described for Experiment 1; the additional exclusions implicated in this analysis resulted in loss of a further 9.0% of trials. Analyses relating to the questionnaire measures (ACS and BIS-11) are described in the accompanying Supplementary Materials I.

Results

Figures 3A and 3B show the proportion of omission trials across training for the two groups. It is clear from the figures that trials with a colour-singleton distractor (whether high- or low-value) generated more omissions than distractor-absent trials in both groups. Paired *t*-tests, averaging across training blocks, confirmed that the relevant contrasts were highly significant for group Explicit [high-value versus absent, $t(29) = 6.52$, $p < .001$, $d = 1.19$; low-value versus absent, $t(29) = 5.20$, $p < .001$, $d = .95$] and for group Implicit [high-value versus

---

[2] There were no such problems with the tracking of any participant in Experiment 1, where the lowest overall percentage of successfully tracked samples was 83%; for this participant, only 8.1% of trials were excluded as a consequence of not having at least 25% of tracked samples.
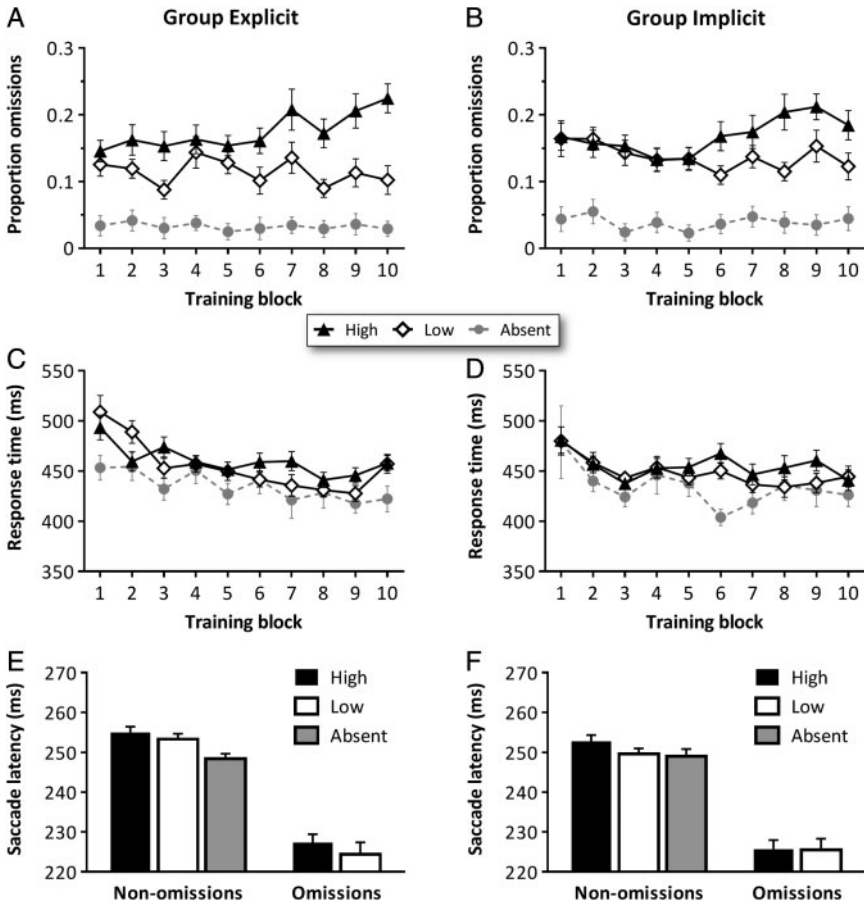
Figure 3. Data from Experiment 2, for group Explicit (left column) and group Implicit (right column). (A and B) Mean proportion of omission trials and (C and D) mean reaction time across the 10 training blocks. Reward was more likely to be omitted, and response times were slower, on trials with the high-value distractor than trials with the low-value distractor. This effect did not differ significantly between groups. (E and F) Mean saccade latencies on omission and non-omission trials, averaged across the latter half of training blocks. Latencies did not differ significantly between the groups. Overall, latencies were slower for non-omission trials than omission trials. On non-omission trials, latencies were shortest on distractor-absent trials, and longest for trials with a high-value distractor. All error bars show within-subjects SEM.

absent, $t(28) = 6.61$, $p < .001$, $d = 1.23$; low-value versus absent, $t(28) = 5.58$, $p < .001$, $d = 1.04$].

Of more interest is the finding that a value-modulated oculomotor capture effect was evident in each group: by the end of training, there were more omission trials when the display contained a high-value distractor than when it contained a low-value distractor. Crucially, there was no evidence that this effect

was any smaller in group Explicit than group Implicit. In fact, collapsing over blocks, the mean difference was numerically greater in group Explicit ($M = .062$, SEM = .024) than in group Implicit ($M = .033$, SEM = .018).

These data were analysed using a 2 (group: Explicit, Implicit) × 2 (distractor type: high-value, low-value) × 10 (block) ANOVA. This revealed a main effect of distractor type, $F(1,57) = 9.4$, $p = .003$, $\eta_p^2 = .14$, demonstrating a significant value-modulated oculomotor capture effect overall. There was also a significant distractor type × block interaction, $F(9,513) = 3.87$, $p < .001$, $\eta_p^2 = .06$, with the size of the value-modulated capture effect increasing over the course of training. Importantly, group did not exert a main effect [$F(1,57) = 0.13$, $p = .72$, $\eta_p^2 = .002$] or interact with any other variable: for group × distractor type, $F(1,57) = .96$, $p = .33$, $\eta_p^2 = .02$; for group × block, $F(9,513) = 1.17$, $p = .31$, $\eta_p^2 = .02$; for group × distractor type × block, $F(9,513) = .47$, $p = .89$, $\eta_p^2 = .01$. The implication is that the explicit instructions regarding the omission contingency did not influence the magnitude of value-modulated capture, or the likelihood of capture by the colour singletons more generally.

An important finding of the analysis presented above is that the group × distractor type interaction was not significant ($p = .33$); this is the key finding suggesting that the magnitude of value-modulated capture did not differ between the two groups. To determine whether this result was due to a lack of statistical power or the presence of a null effect, we carried out a Hierarchical Bayesian analysis of the proportion of omission trials. The key result is that the data are 5.39 times more likely under the null hypothesis, where the difference in omission rates between high- and low-value distractors is the same in both Explicit and Implicit groups. We report the full results of the analysis in the accompanying Supplementary Materials II, but note that this analysis yields very strong evidence for a difference in omission rates between high- and low-value distractors.

We also performed paired t-tests, averaging across training blocks, to investigate whether there was a main effect of high- versus low-value distractor type (demonstrating value-modulated oculomotor capture) in each group. The effect of distractor type was significant in group Explicit, $t(29) = 2.58$, $p = .015$, $d = .47$, but fell short of conventional significance for the Implicit condition, $t(28) = 1.80$, $p = .083$, $d = .33$. The significant distractor type × block interaction in the omnibus ANOVA reported earlier indicates that the effect of distractor type increases over the course of training, as the colour–reward contingencies become established more strongly. Consistent with this suggestion, if analysis is restricted to the latter half of training, then the value-modulated capture effect is significant in both groups: $t(29) = 2.92$, $p = .007$, $d = .53$, for Explicit, $t(28) = 2.83$, $p = .009$, $d = .52$, for Implicit.

The RT data (Figures 3C and 3D) show a broadly similar pattern. In both groups, responses are generally faster on distractor-absent trials than on trials with a colour-singleton distractor, regardless of whether it is a high- or low-value

distractor. Paired *t*-tests, averaging across training blocks, confirmed that the relevant contrasts were highly significant for group Explicit [high-value versus absent, $t(29) = 5.33$, $p < .001$, $d = .97$; low-value versus absent, $t(29) = 4.66$, $p < .001$, $d = .85$] and for group Implicit [high-value versus absent, $t(28) = 3.49$, $p = .002$, $d = .65$; low-value versus absent, $t(28) = 3.27$, $p = .003$, $d = .61$]. Of more interest is the finding that both groups responded more slowly on high-value than low-value trials, at least over the latter half of training, and there is little evidence for a difference in the size of this value-modulated effect between groups. A 2 (group) × 2 (distractor type: high-value, low-value) × 10 (block) ANOVA revealed that the main effect of distractor type fell short of significance, $F(1,57) = 3.04$, $p = .087$, $\eta_p^2 = .05$. However, there was a significant distractor type × block interaction, $F(9,513) = 2.36$, $p = .013$, $\eta_p^2 = .04$, showing that the pattern of RTs changed as training progressed. Notably, a follow-up 2 × 2 × 5 ANOVA, restricted to the latter half of training, revealed a highly significant main effect of distractor type, $F(1,57) = 13.1$, $p < .001$, $\eta_p^2 = .19$. However, neither of these analyses found a main effect of group, and nor did it interact with any other variable: all $ps \geq .19$, $\eta_p^2 s \leq .026$. Paired *t*-tests averaging over the latter half of blocks revealed a significant effect of distractor type in both group Explicit, $t(29) = 2.42$, $p = .022$, $d = .44$, and group Implicit, $t(28) = 2.79$, $p = .009$, $d = .52$.

The analyses of omission trials and RTs revealed evidence for a value-modulated capture effect over the latter half of training, in both groups. Figures 3E and 3F show saccade latencies for omission and non-omission trials averaged over this latter half of training. It is clear that, in both groups, saccade latencies were significantly shorter on omission trials than non-omission trials, regardless of distractor type, all $ps < .001$. A 2 (group) × 3 (distractor type: high-value, low-value, absent) ANOVA was used to analyse saccade latencies on non-omission trials. This revealed a main effect of distractor type, $F(2,114) = 8.57$, $p < .001$, $\eta_p^2 = .13$, but no main effect of group, $F(1,57) = .06$, $p = .81$, $\eta_p^2 = .001$, and no interaction, $F(2,114) = 1.56$, $p = .21$, $\eta_p^2 = .027$. Collapsing across groups, pairwise *t*-tests revealed that saccade latencies on non-omission trials were fastest when the display did not contain a colour singleton distractor: high-value versus absent, $t(58) = 3.88$, $p < .001$, $d = .51$; low-value versus absent, $t(58) = 2.21$, $p = .031$, $d = .29$. Moreover, latencies were slower for trials with a high-value distractor than a low-value distractor, $t(58) = 2.07$, $p = .043$, $d = .27$. For saccade latencies on omission trials, a 2 (group) × 3 (distractor type: high-value, low-value) ANOVA revealed no significant effects, all $Fs < 1$, all $ps \geq .60$.

Finally, Figure 4 shows a scatterplot of contingency belief scores (calculated as in Experiment 1) against the value-modulated capture effect in proportion of omissions. There was no significant correlation between these measures, either in each group considered separately [$r(28) = .25$, $p = .18$ for group Explicit; $r(27) = .059$, $p = .76$ for group Implicit] or in the sample considered as a whole, $r(57) = .17$, $p = .21$.
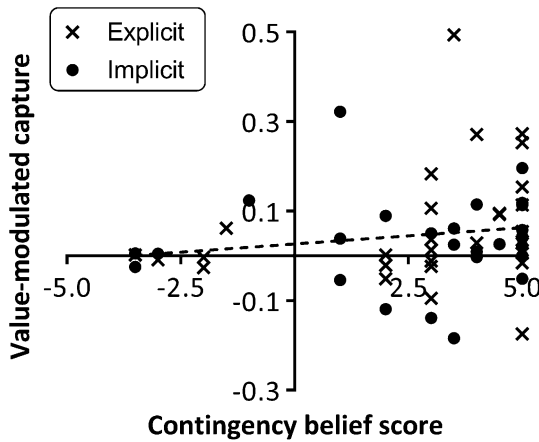
Figure 4. Scatterplot of value-modulated oculomotor capture (vertical axis; calculated as proportion of omissions on high-value trials minus proportion of omissions on low-value trials) against contingency belief score (horizontal axis; calculated as explained in main text), for participants in each group of Experiment 2. Dotted line shows line of best fit across all participants.

Discussion

The omission and RT data for group Explicit replicated the finding of Experiment 1: value-modulated oculomotor capture by task-irrelevant stimuli persists even when participants know that looking at these stimuli results in omission of reward. The comparison between groups Implicit and Explicit suggests further that providing explicit information regarding the omission contingency makes no difference at all to oculomotor capture in this task. Visual comparison of the data from the two groups (Figure 3) might suggest differences between them. For example, it appears that value-modulated oculomotor capture may have emerged more slowly in the Implicit group; for this group, the effect of value on capture was significant only for the latter half of training, whereas for the Explicit group the effect was significant when collapsed across all training blocks. However, none of these apparent between-group differences were borne out by the statistical analyses; there were no significant main effects or interactions involving the group factor. Thus the appropriate conclusion here is that we have no evidence that informing about the omission contingency affects the magnitude of value-modulated capture, and likewise no evidence that it exerts a more general effect on the likelihood that a colour singleton will capture eye gaze, independent of value-prediction. Notably, a Bayesian analysis indicated that the lack of a difference in value-modulated capture between the two groups was not due to a lack of statistical power to detect a difference, but rather to the presence of a genuine null effect. The implication, then, is that singleton capture in this task, and (more specifically) value-modulated capture by

task-irrelevant stimuli, reflects the operation of an automatic process that lies outside participants' volitional control.

The analysis of saccade latencies in Experiment 2 revealed a broadly similar pattern to that seen in Experiment 1, and by Le Pelley, Pearson et al. (2014). Latencies were generally shorter on omission trials than on non-omission trials, and on non-omission trials latencies were shorter on distractor-absent trials than on trials featuring a salient distractor. Experiment 2 also found evidence for a value-modulated effect on saccade latencies. Specifically, on non-omission trials, latencies were significantly longer on trials featuring a high-value distractor than a low-value distractor; a similar pattern was observed by Le Pelley, Pearson et al. (2014). Once again, we postpone more detailed discussion of these data to the General Discussion. However, it is worth noting at this point that analyses found no evidence for a difference between groups Implicit and Explicit in the pattern of saccade latencies. The implication is that whatever processes give rise to the patterns of latencies that were observed are unaffected by instruction regarding the consequences of making such saccades.

GENERAL DISCUSSION

The two experiments reported here investigated the counterproductive influence of reward learning on attentional capture. These experiments used a visual search task in which the colour of a colour-singleton distractor predicted the size of the reward that could be obtained for making an eye movement towards a shape-singleton target. Crucially, the reward-related stimuli in this task were never the targets towards which participants were required to direct their attention; that is, the reward-related stimuli were task-irrelevant throughout training. In fact, looking at these reward-related stimuli was directly counterproductive because doing so resulted in omission of a reward that would otherwise have been gained. Despite this, both experiments found evidence of value-modulated oculomotor capture. Participants were more likely to look at distractors that predicted high-value reward than those that predicted low-value reward, even though doing so meant that they were more likely to miss out on high-value rewards. In both experiments, participants were also slower to move their eyes to the target location on trials with a high-value distractor. This pattern is again counterproductive because slower responses were less likely to be rewarded (due to the timeout thresholds in force in the task).

Experiment 1 demonstrated that the counterproductive value-modulated oculomotor capture effect persisted despite participants being explicitly informed about the omission contingency, both in their initial instructions and every time an omission occurred during the task. Experiment 2 assessed whether information regarding the omission contingency had any influence on the size of the counterproductive value-modulated capture effect, by comparing groups of

participants who received or did not receive explicit information. The results demonstrated that informing participants of the omission contingency had no effect on the magnitude of value-modulated oculomotor capture. The implication is that participants were unable to use strategic attentional control to minimize capture by high-value distractors. Moreover, there was no consistent relationship between the magnitude of value-modulated oculomotor capture and participants' explicitly reported beliefs regarding the colour–reward contingencies measured at the end of the task. Taken together, these findings suggest that the pattern of counterproductive capture that we have observed here and elsewhere (Le Pelley, Pearson, et al., 2014) is a product of an automatic and involuntary process that is cognitively impenetrable.

Attentional control and singleton capture

While the current experiments have demonstrated that volitional cognitive control does not influence the extent to which value modulates attentional capture, it remains unclear whether such volitional processes are involved in the more general case of capture by salient singletons; that is, when the physical salience of a stimulus *produces* attentional capture. Across the current experiments and those of Le Pelley, Pearson, et al. (2014), oculomotor capture was observed on a minority of trials: even a high-value distractor produced oculomotor capture (leading to reward omission) on only around 20% of trials at most (see Figures 2 and 3). So in the majority of trials, participants did not look at the physically salient distractor prior to moving their eyes to the target. The implication is that a colour singleton distractor does not *necessarily* produce oculomotor capture. Why might this be the case?

As noted earlier, Theeuwes et al. (1999) suggested that presentation of a display containing a salient singleton distractor typically results in independent programming of two eye movements: (1) a (slow) voluntary saccade to the target, and (2) a (fast) reflexive saccade to the distractor, which captures attention automatically. However, they argued that attentional capture by the distractor, and the programming of the two saccades, are stochastic processes. Hence there will be a proportion of trials on which the distractor does not capture attention, and further trials on which it does capture attention but a reflexive saccade is not programmed. On these trials participants will not suffer oculomotor capture, and will instead make a voluntary eye movement directly to the target. This model accounts for the fact that not all trials produced omissions, and that saccade latencies were generally faster on omission trials (when oculomotor capture occurred) than on non-omission trials (when it did not).

However, certain aspects of our data do not sit so well with this account. If the programming of voluntary and reflexive saccades is independent (as suggested by Theeuwes et al., 1999), then on non-omission trials the saccade latency should simply reflect the time required to program and make a voluntary saccade

to the target. It should not be influenced by other stimuli present in the display. However, in both experiments reported here, saccade latencies on non-omission trials were significantly longer for distractor-present than distractor-absent displays. Moreover, in Experiment 2 (and in Le Pelley, Pearson et al., 2014) there was a value-modulated effect on non-omission saccade latencies, which were significantly longer on trials featuring a high-value distractor than a low-value distractor. The implication is that the time taken to program and make an eye movement to the target is influenced by whether the display contains a physically salient distractor, and by whether that distractor predicts high or low reward.

Our findings fit better with a recent account proposed by Sawaki and Luck (2010, 2014), termed the *signal suppression hypothesis,* which combines elements of both stimulus-driven and top-down theories of attentional control. This model was developed to account for a series of event-related potential (ERP) findings that implicate an attentional suppression mechanism in visual search (Hickey, Di Lollo, & McDonald, 2009; Kiss, Grubert, Petersen, & Eimer, 2012; Qi, Zeng, Ding, & Li, 2013; Sawaki & Luck, 2010; for review, see Sawaki & Luck, 2014). According to this hypothesis, physically salient singletons are always detected by the visual system and generate an "attend-to-me" priority signal, which attracts a shift of attention to the stimulus. However, the attend-to-me signal can be suppressed by a top-down inhibitory mechanism prior to the deployment of attention, thereby cancelling the attentional shift. On this account, then, reward omission does not occur on every distractor-present trial because on a proportion of trials this top-down inhibition acts to prevent oculomotor capture.[3] The finding of slower saccade latencies on non-omission trials when a salient colour-singleton distractor was present (relative to distractor-absent trials) might then reflect a temporal cost of activating this inhibitory mechanism. However, we note that explicitly informing participants of the omission contingency in Experiment 2 did not influence the extent to which oculomotor shifts were made to the salient distractors. Therefore, it appears that if an attentional suppression mechanism is implicated in preventing oculomotor capture by physically salient distractors, it is not under participants' volitional control.

The signal suppression hypothesis may also provide a useful framework for understanding the processes underlying the influence of reward value on attentional capture. For instance, it may be that the repeated association of a salient stimulus with a high-valued reward enhances the stimulus's attend-to-me signal beyond what would be produced by its physical characteristics alone.

---

[3] In fact, the two accounts offered here as to why omissions do not occur on every distractor-present trial (stochasticity of attentional capture and saccade programming, and top-down inhibition of attentional capture) are not mutually exclusive. It is quite possible that both contribute.

Alternatively, the relationship of the stimulus with reward may reduce the efficacy of the top-down inhibitory mechanism that is able to prevent capture. An effect of value on one or both of these mechanisms may underlie the increased rate of oculomotor capture by singletons associated with high-value rewards observed in the current experiments. Similarly, the finding of a value-modulated effect on saccade latencies on non-omission trials could also result from either a stronger attend-to-me signal for high-value distractors (which would require greater inhibition to overcome) or a reduction in the efficacy of the inhibitory process. In this regard, it is perhaps noteworthy that neither experiment found evidence of a value-modulated effect on saccade latencies on omission trials (i.e., trials on which the distractor produced oculomotor capture). That is, on omission trials, saccade latency was not significantly different for high-value and low-value distractors. This could be taken as evidence that the strength of the distractor's attend-to-me signal is not influenced by reward prediction, since a stronger signal should produce more rapid capture. However, this interpretation is speculative, because it rests on a null result. In particular, since the number of omission trials for each participant was relatively small, the experiments may have lacked sensitivity to detect a difference on this measure. Future research using ERP techniques will allow us to distinguish between these different components of attentional control more clearly, and hence to determine whether and how they are influenced by reward learning.

Differences between experiments, and the role of learning

Participants in Experiment 1, and those in group Explicit of Experiment 2, received identical treatment. While both of these samples produced significant evidence of value-modulated oculomotor capture in proportion of omission trials (our primary measure), the pattern by which this effect emerged was somewhat different in the two cases. In particular, for group Explicit of Experiment 2 the size of the value-modulated capture effect tended to increase systematically over the course of training (supported by a significant distractor type × training block interaction in the omnibus ANOVA performed on these data; see Figure 3A). In contrast, there was no corresponding interaction in Experiment 1, with no obvious systematic change in the value-modulated capture effect over training blocks (see Figure 2A).

   Given that—to reiterate—the treatment received by these participant samples was identical, any differences in the resulting data must reflect random noise. If anything, we would argue that the lack of an interaction between distractor value and training block in Experiment 1 is the anomalous result here. This is because any systematic differences in behaviour on trials featuring high-value versus low-value distractors in these experiments *must* reflect learning about the rewards with which distractors were associated, since (across participants) this was the only difference between these distractors. Hence across participants, the

true size of the value-modulated capture effect must begin at zero and increase as training proceeds. One interpretation for the lack of an interaction with block in Experiment 1 is that the influence of reward learning developed unusually early in this experiment (i.e., within the first blocks) and did not change greatly thereafter; an alternative is that this null result simply reflects unusual noise in the block-by-block data.

However, there is a danger here of becoming sidetracked by the minutiae of the data: of course we should expect variability across experiments, and we should not attach undue weight to it. The most important findings of these experiments are reliable. Firstly, a significant value-modulated oculomotor capture effect occurs even when participants are explicitly informed that looking at the distractor will result in omission of reward, and this effect replicates across both experiments, with medium effect size. Secondly, inclusion of these instructions does not alter the size of this value-modulated effect, and the Bayesian analysis of Experiment 2 suggests that this reflects a genuine null effect, rather than being a consequence of random noise and a lack of power to detect a true difference.

Signal-value versus response-value as a determinant of attentional capture

In the current experiments (and those of Le Pelley et al., 2014), the high-value colour was a *signal* of large reward, since a large reward could be obtained only when the high-value colour was present in the stimulus array. Similarly, the low-value colour was a reliable signal of small reward. Hence the colours differed in terms of their signal-value. However, the *response* of orienting eye gaze to either colour produced exactly the same outcome (zero reward, as a result of the omission contingency). Hence the colours did not differ in their response-value. The finding of greater oculomotor capture by the high-value colour therefore suggests that it is signal-value, rather than response-value, that is the crucial determinant of value-modulated capture. In the terminology of conditioning research, these data suggest that value-modulated capture is a process of Pavlovian, rather than instrumental, conditioning.

However, there is a caveat to this interpretation. As noted in the Introduction, the colour-singleton distractors that predicted reward value in the current task were physically salient, and therefore likely to have automatically captured participants' covert attention (Theeuwes, 1992, 1994). It is well-established that covert shifts of attention can occur independently of overt eye movements (Posner, 1980). Thus there may have been a subset of trials on which participants shifted their covert attention to the salient distractor, but did not make an eye movement to this distractor before successfully looking at the target, and hence did not cause a reward omission. Consequently covert shifts of attention to the distractor may have been paired with reward; in particular, trials containing the high-value versus low-value distractor would differentially reward participants

for such shifts of covert attention. This differential reinforcement could—via a process of instrumental conditioning—increase the likelihood of covert shifts to the high-value distractor in future. And if we assume that this tendency to covertly attend to high-value distractors occasionally results in an eye movement toward the distractor, this may account for the observation of more omissions on high-value than low-value trials.

The omission contingency of the current task protects against this account to an extent. If a covert attentional bias produces an oculomotor shift to the distractor, this will cause omission of the reward on that trial. Instrumental conditioning processes should therefore be driven to reduce the likelihood of such oculomotor shifts in the future. Therefore the possible relationship between a covert bias and an oculomotor bias is subject to a negative feedback loop, which reduces the likelihood that instrumental conditioning of covert attention is responsible for the value-modulated capture effects observed here.

Further evidence that instrumental conditioning of covert attention is not necessary for value-modulated capture by task-irrelevant stimuli comes from a recent study by Failing and Theeuwes (submitted). These researchers used a procedure related to that of the current studies, but in which each of the stimuli in the search array was presented in a unique colour. As in the current experiments, whether a response to the target received a small or large reward depended on whether the array contained a red or blue distractor. Crucially, however, as these value-predictive distractors were not colour singletons (since all stimuli were coloured), they would not be expected to capture covert attention based on their physical salience. Nevertheless, Failing and Theeuwes still found evidence of value-related attentional capture by these distractors, with slower responses to the target on trials where a high-value distractor was present than on trials where a low-value distractor was present. These data suggest that reward learning is sufficient to *produce* attentional capture even by non-salient stimuli. And since this study used non-salient stimuli that should not capture covert attention, it rules out the account via instrumental conditioning of covert attention advanced in the previous paragraphs. Taken together, our findings and those of Failing and Theeuwes therefore strongly suggest that value-modulated capture by task-irrelevant stimuli is a product of Pavlovian, not instrumental, conditioning.

Different procedures for studying value-modulated attentional capture

Finally, we note an important difference between the current procedure for studying value-modulated capture and that developed by Anderson et al. (2011a, 2011b). The procedure used by Anderson et al. had a training phase during which rewards were delivered, dependent on the stimuli present in the search array. Value-related capture by these stimuli was then assessed in a subsequent test phase in which no rewards were delivered. In contrast, the current task had

only a single phase in which rewards were available throughout. This approach has a number of advantages. Most importantly, the availability of reward on every trial allowed us to implement an omission contingency. This should have produced the greatest drive for participants to use cognitive control to suppress attentional capture by distractors, since such capture resulted in loss of reward. Consequently, the fact that participants do not suppress attention to high-value distractors under such circumstances lends extra strength to an interpretation of the value-modulated capture effect in terms of an automatic process (as compared to if we had used an unrewarded test phase, in which case there would be no financial penalty for attending to distractors and hence less drive to suppress attention to them). Secondly, in the unrewarded test phase of Anderson et al.'s procedure, the relationship between stimuli and rewards that was established during the preceding training phase no longer holds. As such, any value-related effects are liable to dissipate as reward learning extinguishes (e.g., see Anderson et al., 2011a). In contrast, in our procedure every trial is both a training trial (on which reward learning can occur) and a test trial (on which the effects of that learning on capture can be measured). Hence the observed effect of value-modulated capture will not extinguish, but instead should persist indefinitely as long as training is continued. Hence this procedure allows us to achieve a good signal-to-noise ratio in measures of value-modulated capture, as suggested by the medium to large effect sizes that are typically obtained.

More generally, the different procedures used to study value-modulated capture can be seen as complementary. They demonstrate that pairing with high-value reward increases the likelihood of capture by a stimulus that has been task-relevant but no longer predicts reward (Anderson et al., 2011a, 2011b), and by a stimulus that predicts reward but is task-irrelevant (current data; Le Pelley, Pearson, et al., 2014; Failing & Theeuwes, submitted). The experiments reported here highlight the automaticity, and cognitive impenetrability, of the attentional process underlying these effects. This is noteworthy, because it has been argued that the same process underlies the involuntary attentional capture by drug-related stimuli observed in recovering addicts (Anderson, Faulkner, Rilee, Yantis, & Marvel, 2013), and the magnitude of this capture is known to predict likelihood of relapse (e.g., Cox, Hogan, Kristian, & Race, 2002; Marissen et al., 2006; Waters et al., 2003). The implication of the current studies is that instruction is likely to be ineffective in reducing the magnitude of such maladaptive attentional biases, and that implicit attentional retraining may instead be required for a full resolution.

Supplementary materials

Supplementary Materials (Analysis of questionnaire data and Hierarchical Bayesian analysis of Experiment 2) are available via the "Supplementary" tab on the article's online page (http://dx.doi.org/10.1080/13506285.2014.994252).

REFERENCES

Anderson, B. A., Faulkner, M. L., Rilee, J. J., Yantis, S., & Marvel, C. L. (2013). Attentional bias for nondrug reward is magnified in addiction. *Experimental and Clinical Psychopharmacology*, *21*, 499–506. doi:10.1037/a0034575

Anderson, B. A., Laurent, P. A., & Yantis, S. (2011a). Learned value magnifies salience-based attentional capture. *Plos One*, *6*, e27926. doi:10.1371/journal.pone.0027926.t001

Anderson, B. A., Laurent, P. A., & Yantis, S. (2011b). Value-driven attentional capture. *Proceedings of the National Academy of Sciences of the United States of America*, *108*, 10367–10371. doi:10.1073/pnas.1104047108

Anderson, B. A., & Yantis, S. (2012). Value-driven attentional and oculomotor capture during goal-directed, unconstrained viewing. *Attention, Perception, and Psychophysics*, *74*, 1644–1653. doi:10.3758/s13414-012-0348-2

Bacon, W. F., & Egeth, H. E. (1994). Overriding stimulus-driven attentional capture. *Perception & Psychophysics*, *55*, 485–496. doi:10.3758/BF03205306

Cox, W. M., Hogan, L. M., Kristian, M. R., & Race, J. H. (2002). Alcohol attentional bias as a predictor of alcohol abusers' treatment outcome. *Drug and Alcohol Dependence*, *68*, 237–243. doi:10.1016/S0376-8716(02)00219-3

Della Libera, C., & Chelazzi, L. (2009). Learning to attend and to ignore is a matter of gains and losses. *Psychological Science*, *20*, 778–784. doi:10.1111/j.1467-9280.2009.02360.x

Della Libera, C., Perlato, A., & Chelazzi, L. (2011). Dissociable effects of reward on attentional learning: From passive associations to active monitoring. *PLoS One*, *6*, e19460. doi:10.1371/journal.pone.0019460.g002

Derryberry, D., & Reed, M. A. (2002). Anxiety-related attentional biases and their regulation by attentional control. *Journal of Abnormal Psychology*, *111*, 225–236. doi:10.1037/0021-843X.111.2.225

Failing, M. F., & Theeuwes, J. (submitted). Don't let it distract you: How information about the availability of reward affects attentional selection. *Journal of Experimental Psychology: Human Perception & Performance*.

Folk, C. L., & Remington, R. (1998). Selectivity in distraction by irrelevant featural singletons: Evidence for two forms of attentional capture. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 847–858. doi:10.1037/0096-1523.24.3.847

Hickey, C., Di Lollo, V., & McDonald, J. J. (2009). Electrophysiological indices of target and distractor processing in visual search. *Journal of cognitive neuroscience*, *21*, 760–775. doi:10.1037/0096-1523.29.1.121

Kiss, M., Driver, J., & Eimer, M. (2009). Reward priority of visual target singletons modulates event-related potential signatures of attentional selection. *Psychological Science*, *20*, 245–251. doi:10.1111/j.1467-9280.2009.02281.x

Kiss, M., Grubert, A., Petersen, A., & Eimer, M. (2012). Attentional capture by salient distractors during visual search is determined by temporal task demands. *Journal of cognitive neuroscience*, *24*, 749–759. doi:10.1016/j.actpsy.2010.02.006

Le Pelley, M. E., Beesley, T., & Griffiths, O. (in press). Associative learning and derived attention in humans. In R. A. Murphy & R. C. Honey (Eds.), *The Wiley Blackwell Handbook on the cognitive neuroscience of learning*. Chichester: Wiley.

Le Pelley, M. E., Pearson, D., Griffiths, O., & Beesley, T. (2014, November 24). When goals conflict with values: Counterproductive attentional and oculomotor capture by reward-related stimuli. *Journal of Experimental Psychology: General*. Advance online publication. http://dx.doi.org/10.1037/xge0000037

Le Pelley, M. E., Vadillo, M. A., & Luque, D. (2013). Learned predictiveness influences rapid attentional capture: Evidence from the dot probe task. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 39, 1888–1900. doi:10.1037/a0033700

Ludwig, C. J. H., & Gilchrist, I. D. (2002). Stimulus-driven and goal-driven control over visual selection. *Journal of Experimental Psychology-Human Perception and Performance*, 28, 902–912. doi:10.1037/0096-1523.28.4.902

Marissen, M. A. E., Franken, I. H. A., Waters, A. J., Blanken, P., van den Brink, W., & Hendriks, V. M. (2006). Attentional bias predicts heroin relapse following treatment. *Addiction*, 101, 1306–1312. doi:10.1111/j.1360-0443.2006.01498.x

Patton, J. H., Stanford, M. S., & Barratt, E. S. (1995). Factor structure of the Barratt Impulsiveness Scale. *Journal of Clinical Psychology*, 51, 768–774. doi:10.1002/1097-4679(199511)51:6<768::AID-JCLP2270510607>3.0.CO;2-1

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, 32(1), 3–25. doi:10.1080/00335558008248231

Qi, S., Zeng, Q., Ding, C., & Li, H. (2013). Neural correlates of reward-driven attentional capture in visual search. *Brain Research*, 1532, 32–43. doi:10.1016/j.brainres.2013.07.044

Sawaki, R., & Luck, S. J. (2010). Capture versus suppression of attention by salient singletons: Electrophysiological evidence for an automatic attend-to-me signal. *Attention, Perception, & Psychophysics*, 72, 1455–1470.

Sawaki, R., & Luck, S. J. (2014). How the brain prevents and terminates shifts of attention. In G. R. Mangun (Ed.), *Cognitive electrophysiology of attention* (pp. 16–29). San Diego, CA: Academic Press.

Theeuwes, J. (1991). Cross-dimensional perceptual selectivity. *Perception & Psychophysics*, 50, 184–193. doi:10.3758/BF03212219

Theeuwes, J. (1992). Perceptual selectivity for color and form. *Perception & Psychophysics*, 51, 599–606. doi:10.3758/BF03211656

Theeuwes, J. (1994). Endogenous and exogenous control of visual selection. *Perception*, 23, 429–440. doi:10.1068/p230429

Theeuwes, J., & Belopolsky, A. V. (2012). Reward grabs the eye: Oculomotor capture by rewarding stimuli. *Vision Research*, 74, 80–85. doi:10.1016/j.visres.2012.07.024

Theeuwes, J., De Vries, G.-J., & Godijn, R. (2003). Attentional and oculomotor capture with static singletons. *Perception & Psychophysics*, 65, 735–746. doi:10.3758/BF03194810

Theeuwes, J., Kramer, A. F., Hahn, S., Irwin, D. E., & Zelinsky, G. J. (1999). Influence of attentional capture on oculomotor control. *Journal of Experimental Psychology: Human Perception and Performance*, 25, 1595–1608. doi:10.1037/0096-1523.25.6.1595

Waters, A. J., Shiffman, S., Sayette, M. A., Paty, J. A., Gwaltney, C. J., & Balabanis, M. H. (2003). Attentional bias predicts outcome in smoking cessation. *Health Psychology*, 22, 378–387. doi:10.1037/0278-6133.22.4.378

Yantis, S. (2000). Goal-directed and stimulus-driven determinants of attentional control. In S. Monsell & J. Driver (Eds.), *Attention and performance XVIII* (pp. 73–103). Cambridge, MA: MIT Press.

Yantis, S., & Jonides, J. (1984). Abrupt visual onsets and selective attention: Evidence from visual search. *Journal of Experimental Psychology: Human Perception and Performance*, 10, 601–621. doi:10.1037/0096-1523.10.5.601