Long-Term Effects of Value-Driven Attentional Capture on Memory: Reward Influences Criterion but not Discriminability

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Abstract

Value-driven attention capture (VDAC) is the process by which stimulus features associated with reward can involuntarily draw attention in contexts beyond the original one in which those associations were trained. Attention is a critical component of effective encoding into memory so it follows that VDAC may confer an advantage in remembering later stimuli that share those reward features. The aim of this study was to investigate whether participants trained to associate a color with probabilistically high or low reward amounts in one task would show improved memory for characters presented in a previously rewarded color on a separate memory task. In a learning phase, participants identified the orientation of a horizontal or vertical line positioned within a red or green circle. One color was paired with a higher reward contingency than the other color to imbue it with greater value. In a second task, participants viewed three sequential characters and made old/new judgments on a test character. Some lists contained a character that was presented in a previously rewarded color. We found no evidence that rewarded colors improved memory, but recognizers tended to employ a more conservative criterion on lists with rewarded colors.

*Keywords*: [Click here to add keywords.]

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Reward is a powerful motivator that underlies many human behaviors and cognitive processes (**Madan, 201**7). One area in which reward has become increasingly relevant is attention. Attention has long been argued to be driven by a combination of top-down and bottom-up processes. Yet, a growing body of work has indicated that prior selection history, which includes selection driven by reward, as a third competitor involved in selective attention (**Awh, Belopolsky & Theeuwes, 2012; Theeuwes, 2010; Theeuwes, 2018**). Through a process called value-directed attentional capture (VDAC), learned stimulus-reward associations have been shown to automatically modulate attention such that reward-associated stimuli may receive greater attentional priority in spite of any current task-related goals of an observer (**Anderson, Laurent & Yantis, 2011**). Critically, VDAC may have unintended downstream effects on other related cognitive processes, including, in the case I pursue here, memory.

Value-driven attention capture was first identified by **Anderson et al. (2011**). Participants were trained using a visual search task to associate one of two target colors with a higher probability of receiving the greater of two reward amounts. Correct responses to a high-value colored target yielded an 80% chance of a high reward (5¢) and a 20% change of a low reward (1¢), whereas this contingency was revered for the low-value color. In a subsequent singleton detection task, the high- and low-rewarded colors from the training phase were presented as distractors. Trials with high-value distractors led to slower response times compared to trials with low-value distractors or distractors without any previously associated value. These results suggest that the magnitude of prior reward associated with a stimulus affected later unintentional attention capture, even when it was to the detriment of performance .

The effects of VDAC can persist from days to months after training (**Anderson et al., 2013; Della Libera & Chelazzi, 2006, 2009**) and is clearly evident in contexts in which attending to reward-associated stimuli incurs penalties, as demonstrated with oculomotor tasks (**Anderson, Laurent, & Yantis, 2012; Pearson, Donkin, Tran, Most & Le Pelley, 2015; Theeuwes & Belopolsky, 2012).** Furthermore, reward associations do not even need to be relevant to the training task. **Mine and Saiki (2015**) showed that training color-reward associations on an Eriksen flanker task where color is irrelevant or even the to-be-ignored element still results in VDAC which has implications on how effortlessly reward associations may form. Reward has also been used to focus attention on target stimuli containing rewarded stimulus features against a backdrop of other possible distractors (**Walsh, Carmel, Harper, Bolitho & Grimshaw, 2020; Schwartz, Siegel & Castel, 2020**). Altogether, VDAC has been shown to be long-lasting, automatic, and resistant to cognitive control.

Considering these strong effects of reward on attention, a natural extension of the topic would be whether reward has similar effects on processes related to attention such as working memory. It is recognized that working memory shares common resources and is extensively involved with attention **(****Chunn, 2011; Kyonaga & Egner, 2012; Chun & Turk-Browne, 2007).** A particularly relevant function of attention includes selecting or prioritizing what information is maintained in working memory **(****Oberauer, 2019)**. Thus, the automatic biasing of attention towards rewarded stimuli may enhance memory of those items at the cost of reduced attention and memory capacity for unrewarded stimuli.

To this end, a number of studies have investigated whether reward influences visual working memory, with mixed results. In a study by **Gong and Li (2014),** participants completed a change blindness task featuring reward-associated colors before and after engaging in the value-training procedure used by **Anderson et al., (2011).** The authors found enhanced discriminability in the change-blindness task post-training compared to pre-training. Likewise, **Infanti, Hickey and Turatto (2015)** had participants complete a partial report visual working memory task spanning retention times of 50 ms and 800 ms following the training procedure of **Anderson et al. (2011)**. While they failed to find similar enhancements to accuracy as **Gong and Li (2014**), they did find an interference effect when reward-associated stimuli were presented in proximity to the memory target across iconic and visual working memory spans.

In explaining these findings, some have suggested that reward may act on visual working memory by speeding visual processing (**O’Brien & Raymond, 2012**) or by increasing working memory capacity (**Kawasaki &Yamaguchi, 2013**). Others have suggested that reward shifts attentional allocation between items as a trade-off (**Morey, Morey & Rouder, 2011).** One study by **Sandry and Ricker** (2020) investigated whether the orientation of attention towards a list item might increase maintenance of that item in visual working memory at the expense of other items. Participants were presented three sequential shapes where one item was sometimes be rendered in red, indicating increased rewards for that trial. On 2-alternative forced choice recognition that followed each trial, there was no effect on accuracy, but response times to reward-colored items were shorter. The authors concluded that prioritized items were being better maintained in working memory.

However, there are a number of gaps left by the study. As with other studies in this domain, the possible effects of reward on response bias are not explicitly addressed, making overall accuracy hard to interpret (**Bowen, Marchesi & Kensinger, 2020**). Furthermore, unlike prior studies that utilized separate training and test phases, participants in **Sandry and Ricker’s (2020)** experiment were rewarded per trial, limiting any interpretations about the long-term effects of reward in this task.

The aim of the current study was to more precisely examine the impact of reward processing on involuntary aspects of working memory with combined analyses of response time, discriminability, and response bias. We used the value-learning procedure of **Anderson et al. (2011**), followed by with a visual working memory task similar to **Sandry and Ricker (2015**). In the learning phase, two reward amounts (high and low) were associated with two target colors (red and green). In the transfer phase, participants were presented with a series of three characters followed by a test probe that asked whether the probed item was a new or old item. In some lists, one item was be presented in a high- or low-value color. In lists with a colored item, the probe could be for the colored item, or it could be for a non-colored item. This experiment expands on **Sandry and Ricker’s (2015**) study in a few ways. By ensuring that rewards are only delivered in a previous training phase and not in the test phase, we ensure parity between our findings and those of VDAC literature. Furthermore, by using an old/new judgement task, we can separate the effects of reward on discriminability and criterion placement, both for rewarded items and for unrewarded items in proximity to a rewarded item.

We propose two hypotheses. First, if reward enhances attention in a way that boosts working memory representation, we expect to see faster response times and/or greater discriminability for items rendered in a high reward color. Alternatively, if reward-association does not boost memory, but instead simply leads to strategic shifts in response bias, we expect to see a a shift in response bias that patterns after reward color. Such a result might be anticipated by **Bowen et al. (2020**), who found that increasing reward magnitude led to a liberal criterion shift, or more willingness to endorse an item as old, which would concur with other studies finding improvements to hit rates. Thus, we predict a similar relation between reward magnitude and response bias.

**Methods**

*Participants*

Data from sixty-two Six Students (XX) Seventy students (47 female, 1 other, 20 male) from the University of Illinois at Urbana-Champaign participated in the online study in exchange for course credit. Mean age was 19.75 (ranging from 19 to 22) Data from two participants were omitted due to recording errors. We selected our sample size according to prior effect sizes (Cohen’s *d* = 0.3) found from a similar study by **Sandry, Schwark, and MacDonald (2014**). All participants had normal or corrected-to-normal vision, as well as normal color vision.

*Materials*

The study was run online on a university server. Stimuli were created with the JsPsych 6.2.0 library in Javascript **(de Leeuw, 2015)**. While we could not control for individual screen differences, participants with monitor resolution below 480p x 480p were excluded from running the experiment.

*Procedure*

The experiment took about an hour to complete and was comprised of two parts.

*Training Task*

In the training phase, participants completed a visual search task in which they identified the orientation of a horizontal or vertical bar position within a green or red target circle. Each trial began with a fixation cross lasting between 400 to 600 ms. The search display was presented for 1000 ms or until participant response and consisted of 6 black lines each contained within a uniquely colored circle. The stimuli were arranged in an equidistant circle around the fixation cross, as shown in **Figure X**. Five of the six lines were randomly orientated in a diagonal direction (+45° or -45°) and each was encompassed by a non-target colored circle (cyan, blue-violet, black, magenta, and gold; colors are reported according to html color names). The target line was oriented either horizontally or vertically and was defined by a green or red circle; only one target was presented in each trial. The target was equally likely to appear in any of the six positions. Participants were instructed to search for a red of green target circle and to report as quickly and as accurately as possible the orientation of the line inside the circle by pressing “Z” for horizontal or “M” for vertical. After the search display was presented, participants received feedback using a point display for 1500 ms. Participants received “+2 points” or “+10 points” for correct responses and “Miss” for wrong or late responses along with a running total of how many points they had earned thus far in the experiment.

For each participant, one of the two target colors (red and green) was randomly assigned as the high-value color, and the other as the low-value color. Correct responses to high-value targets had an 80% chance of receiving a higher reward amount of 10 points and a 20% chance of receiving a lower reward amount of 2 points, with the opposite assignment for low-value targets. Thus, the training phase imbued one color with a (probabilistically) high value and the other color with low value.

Participants completed 10 practice trials with the option to repeat those trials before moving to the experimental trials. Participants completed 200 experimental trials divided in 4 blocks. Between blocks, participants were given a 30-second break screen that reported overall accuracy and the total number of points they have earned.

*Transfer phase*

The test used a rapid serial visual presentation (RSVP) procedure, with each list followed by a yes-no recognition trial. Each trial began with a fixation cross lasting between 400 to 600 ms. Then, three different characters were sequentially presented for 500 ms each followed by a 500 ms mask, as shown in **figure X**. We used a set of 90 unique characters from taken from the Brussels Artificial Character Sets (**Vidal, Content, & Chetail, 2017**), which are a set of standardized characters that emulate features of various languages without being identifiable to participants. Within each trial, characters were randomly sampled without replacement from the total stimulus set, but characters were repeated between trials. Characters were mostly presented in black but, on some trials, one character was presented in red or green. We refer to these items as high-reward items and low-reward items, corresponding to their status during the training phase, but it should be noted that participants did not receive any rewards in this phase, so the reward color had no bearing on the task.

To maximize the number of critical trials, we adjusted the proportion of old vs. new trials and the ratio of low- high- and no-reward trials. Across 200 experimental trials, we used a 3:2 ratio between old and new trials (120 old: 80 new). For reward colors, we used a 3:3:2 ratio between low-, high-, and no-reward trials (75 high-value: 75 low-value: 50 no-reward). For old trials, there were an equal proportion of targets in the 1st, 2nd, and 3rd serial positions. For color trials, there were also an equal proportion of colored items in the 1st, 2nd, and 3rd serial positions. (*needs review for clarification – talk about proportion of trials or the actual number of trials for each category and combination*)

After the three to-be-remembered items were presented, a test item was presented for 2500 ms or until participant response. Participants were prompted to press “Z” if the test item was an old item previously presented in the list or “M” if the test item was a new item that was not presented in the list. After each response, feedback was displayed for 1500 ms with “Correct” for correct responses or “Miss” for wrong or late responses. However, unlike the training phase, participants did not receive any points. Again, the color of any list items were no longer relevant in this phase.

Participants completed 10 practice trials with the option to repeat before moving to the experimental trials. Participants completed 200 experimental trials divided in 4 blocks. Between blocks, participants were given a 30-second break screen that reported overall accuracy.

*Posttest questionnaire*

Following completion of the experiment, participants responded to a brief questionnaire to evaluate whether they were aware of the reward contingency in the learning phase and whether they used any particular strategy on the visual working memory task. We first asked if participants were aware that the color of targets in the learning phase was associated with the rewards they received on any given trial. Next, we presented participants with a list of 10 working memory strategies adapted from **Morrison, Rosenbaum, Fair, and Chein (2016)** and asked which strategies they used. Participants were free to select any number of the strategies listed.

**Results**

We present our analysis using Bayes factor tests. The Bayes factors presented here represent the ratio of the probability of our data given an effect is present to the probability of our data given an effect is not present. For example, a Bayes factor of 10 would be interpreted as the alternative hypotheses being 10 times more likely than the null hypotheses given the data. Conversely, a Bayes factor of 0.10 would be interpreted as the null hypotheses being 10 more likely than the alternative hypothesis given the data. All analyses were done using BayesFactor version X.X in R using the default settings.

*Learning Phase*

Mean response time to high- and low-reward targets did not differ significantly, though participants tended to respond faster to high-reward targets than low reward targets [mean difference = 4.2 ms, *t*(61) = 1.202, *p* = .234, BF = .275]. **To examine the effect of reward as** participants progressed through training, we binned the data in four bins of 50 trials each corresponding to the four trials blocks. There was a main effect of trial block [*F*(3, 488) = 12.535, p < .001, BF = 1.67×10­19] but no interaction between reward and trial block [*F*(3, 488) = 0.307, p < .820, BF = 1.17×10­17. This suggests that while participants responded faster with more trials, reward had no effect. The response times by reward condition and trial block are presented in Figure X.

We applied the same analyses to accuracy towards high- and low-reward targets. Mean accuracty to high- and low-reward targets did not differ significantly [mean difference < 0.00 ms, *t*(61) = 0.081, *p* = .935, BF = 0.099]. We again binned the data in four blocks of 50 trials each. There was a main effect of trial block [*F*(3, 488) = 9.782, p < .001, BF = 1.44×10­9] but no interaction between reward and trial block [*F*(3, 488) = 0.736, p =.531, BF = 1.17×10­17. **18529865.** Again, this suggests that while there was an effect of practice on accuracy, there was no effect present of reward or any interaction. Accuracy by reward condition and trial block are presented in Figure X.

*Transfer Phase*

The main point of interest was learned reward associations learned from the training phase would carry over and affect performance in the visual working memory test phase. We specifically examined, discriminability as measured in *d*’ (**Green & Swets, 1966**), criterion (c), and response time as a function of serial position of the target, colored list items, and the reward magnitude of any colored list items. For our d-prime calculations, we additionally performed edge correction, according to [**edge correction method here**]

Discriminability according to the serial position of the target and the position of colored list item are shown in Figure X. To examine the overall effect of reward color on hit rate, we collapsed responses for each participant by taking the median response time of all lists in which the test item was the colored item in the list for each reward condition (e.g., a list with test and color item in serial position 1). This was compared to the control condition where there are no colored items. Means for these collapsed groups are shown in Figure X. A one-way (reward color: high, low, control) repeated measures ANOVA was performed on the raw *d’* values. No significant difference was found between reward conditions [***F*(3, 488) = 9.782, p < .001, BF = 1.44×10­9**]. Bonferroni post hoc tests also confirmed that there were no differences between high- and low-reward associated colors [mean difference = -X.XX, *SE* = XX, p = .XX], the high-reward associated color and the control [mean difference = -X.XX, *SE* = XX, p = .XX]; and the low-reward associated color and the control [mean difference = -X.XX, *SE* = XX, p = .XX].

We further analyzed the effect of reward association according to individual serial positions. For each of the three serial positions (SP1, SP2, SP3) we compared responses between lists with the colored item corresponding to the test item against the respective control list for each serial position. We again found no significant differences between color conditions for serial serial position 1 [*F*(3, 488) = 9.782, p < .001, BF = 1.44×10­9]; serial position 2 [*F*(3, 488) = 9.782, p < .001, BF = 1.44×10­9]; and serial position 3 [*F*(3, 488) = 9.782, p < .001, BF = 1.44×10­9].

We applied the same analyses to criterion values. Collapsed criterion means are shown in figure X. A one-way (reward color: high, low, control) repeated measures ANOVA was performed on the collapsed raw c values. No significant difference was found between reward conditions [***F*(3, 488) = 9.782, p < .001, BF = 1.44×10­9**]. Bonferroni post hoc tests also confirmed that there were no differences between high- and low-reward associated colors [mean difference = -X.XX, *SE* = XX, p = .XX], the high-reward associated color and the control [mean difference = -X.XX, *SE* = XX, p = .XX]; and the low-reward associated color and the control [mean difference = -X.XX, *SE* = XX, p = .XX]. While no significant differences were found, there was a general trend towards more conservative responses as reward magnitude increased.

When analyzing by individual serial positions, we again found no significant differences in criterion between color conditions for serial position 1 [*F*(3, 488) = 9.782, p < .001, BF = 1.44×10­9]; serial position 2 [*F*(3, 488) = 9.782, p < .001, BF = 1.44×10­9]; and serial position 3 [*F*(3, 488) = 9.782, p < .001, BF = 1.44×10­9]. A 3-way ANOVA indicates there was a main effect of serial position, but not main effect of reward or an interaction between serial position and reward.

Lastly, collapsed criterion means are shown in figure X. A one-way (reward color: high, low, control) repeated measures ANOVA was performed on the collapsed raw c values. No significant difference was found between reward conditions [***F*(3, 488) = 9.782, p < .001, BF = 1.44×10­9**]. Bonferroni post hoc tests also confirmed that there were no differences between high- and low-reward associated colors [mean difference = -X.XX, *SE* = XX, p = .XX], the high-reward associated color and the control [mean difference = -X.XX, *SE* = XX, p = .XX]; and the low-reward associated color and the control [mean difference = -X.XX, *SE* = XX, p = .XX]. While no significant differences were found, there was a general trend towards more conservative responses as reward magnitude increased.

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**General Discussion**

The purpose of this experiment was to examine if and how reward associated stimuli can affect visual working memory performance in a task where previously learned reward-associations are no longer relevant. To this end, we trained participants to associate one of two target colors in a singleton identification task based on a study by Anderson (2011). Participants then engaged in a visual working memory tasked adapted by Sandry where three characters were presented followed by an old/new recognition test prompt. In this phase, one of the characters in some lists were rendered in a color corresponding to the high- and low-value rewarded targets from the training phase. We predicted that participants would show enhanced discriminability towards list items corresponding to high-rewarded colors compared to low-rewarded colors or no color at all. Results from study shows that contrary to our prediction, reward-associated items did not appear to enhance discriminability. Instead, participants appeared to have adopted a more conservative criterion towards lists with rewarded colors. Participants tended to show a stronger bias for “new” responses towards items associated with higher rewards compared to low or non-colored items without any significant change to discriminability.

Our results expands upon the value-driven attentional capture literature and it’s relevance towards memory by illustrating how supposed enhancements to memory as a result of vdac may possibly reflect memory decisions, rather than actual memory enhancement. Prior work (e.g., Sandry, Bowen etc.) illustrates the effect of reward on a per-item basis, we attempt to illustrate whether possible carryover effects of VDAC in novel experiment tasks, which has already been demonstrated (Mine and Saiki, Le Pelley etc.) may apply to memory performance. Participants were not given rewards in the memory task, and were even instructed that color had no relevance to the task. Yet, participants seemingly employed a strategic shift. Unexpectedly however, this conservative shift runs contrary to that of other studies such as that by Bowen et al., who found more conservative response biases for low reward items compared to high reward items. This is particularly interesting as studies of those designs have typically implemented penalty contingencies such that responding with a false alarm to a reward-associated item results in a greater penalty as well, hence participants shifting their mental resources towards maintenance of the high-value item is a particularly effective strategy for minimizing loss. Yet no such penalty structure was present in our design, effectively eliminating any benefit in adopting a more conservative strategy towards lists with rewarded items.

Our current paradigm offers new insights into understanding reward and memory interaction, but there are areas that ought to be addressed. Firstly, due to the nature of our dual learning and transfer phases, we had to reduce the number of trials for participants. This poses two problems. Reducing the number of learning trials may reduce any overall effect of VDAC in our paradigm. While experiments by Anderson (**XXX**) have previously demonstrated persistent VDAC effects in as few as 240 trials, there exists no literature to our knowledge detailing how few trials are needed to ensure successful VDAC transfer in such a vastly different task. Furthermore, reducing the number of transfer phase trials while also using a within-subjects design for three conditions (high, low, and control) also has the consequence of reducing the number of experimental trials per experimental cell. With only 5 trials for each of our critical trials, d-prime and response time calculations may be biased due to frequent error corrections. In the case of our drift diffusion analysis, we collapsed across trials containing a list item in any condition. Yet even this collapsing only yields at best 45 trials per condition which yields “low precision” estimate for v, and falls well below recommended trial counts for *a* (Lerche, Voss & Nagler, 2016).

Other concerns could include the fact that our control consisted of no-color trials. As has been replicated in other literature, using non-rewarded or non-target controls has proven particularly useful for ensuring any possible change in performance towards rewarded items is strictly a function of reward-magnitude and not a result of the colors being more physically salient.

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Tables

Table 1

[Table Title]

|  |  |  |  |
| --- | --- | --- | --- |
| Response Measure | *F*(2,122) | *p* | BF |
| Response Time (ms) | 0.129 | .971 | 0.0618 |
| Hit Rate |  |  |  |
| False Alarm Rate |  |  |  |
| Discriminability (*d’*) | 0.402 | .670 | 0.0790 |
| Criterion (c) | 1.784 | .172 | 0.261 |

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Response Time | | |  | Discriminability | | |  | Criterion | | |
| Response Measure | *F*(2,122) | *p* | BF |  | *F*(2,122) | *p* | BF |  | *F*(2,122) | *p* | BF |
| Serial Position 1 | 0.637 | .52 | .0952 |  | 0.345 | .709 | .0729 |  | 3.317 | .039\* | 1.04 |
| Serial Position 2 | 0.394 | .675 | .0761 |  | 1.928 | .150 | .2959 |  | 4.58 | .012\* | 3.11 |
| Serial Position 3 | 0.12 | .887 | .0610 |  | 4.514 | .128\* | 2.583 |  | 7.184 | .001\*\* | 26.5 |

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Response Time | | |  | Discriminability | | |  | Criterion | | |
| Response Measure | *F*(2,122) | *p* | BF |  | *F*(2,XX) | *p* | BF |  | *F*(2,XX) | *p* | BF |
| Sp1 high: sp1 vs. control: sp1 | 123 | 123 | 123 |  | 123 | 123 | 123 |  | 123 | 123 | 123 |
| Sp2 high: sp2 vs. control: sp2 | 456 | 456 | 456 |  | 456 | 456 | 456 |  | 456 | 456 | 456 |
| Sp3 high: sp3 vs. control: sp3 | 789 | 789 | 789 |  | 789 | 789 | 789 |  | 789 | 789 | 789 |
| Sp1 low: sp1 vs. control: sp1 | 123 | 123 | 123 |  | 123 | 123 | 123 |  | 123 | 123 | 123 |
| Sp2 low: sp2 vs. control: sp2 | 456 | 456 | 456 |  | 456 | 456 | 456 |  | 456 | 456 | 456 |
| Sp3 low: sp3 vs. control: sp3 | 789 | 789 | 789 |  | 789 | 789 | 789 |  | 789 | 789 | 789 |

Figures title:

Figure 1. [Include all figures in their own section, following references (and footnotes and tables, if applicable). Include a numbered caption for each figure. Use the Table/Figure style for easy spacing between figure and caption.]

For more information about all elements of APA formatting, please consult the APA Style Manual, 6th Edition.