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

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.

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

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.

Training Phase

RT

Mean response time (RT) to high- and low-value target did not differ significantly. However, participants tended to respond faster towards high-value targets compared to low-value targets (mean difference = X.X ms, t(XX) = X.XX, p = .XX). To see whether there may be an effect of training over the course of the training phase, further binned mean responses over four 50-trial blocks. There was no interaction between reward and trial bin [F(X.XX = X.XX, p = X.XX] indicating that the effect of reward on RT did not significantly change over the duration of the training phase. However, there was a a main effect of trial bin [F(X.XX = X.XX, p = X.XX] indicating that participants responded faster as the training progressed, irrespective of reward. Response times by reward condition and trial block are presented in Figure X.

Accuracy

Mean accuracy to high- and low-value target did not differ significantly. However, participants tended to respond more accurately towards high-value targets compared to low-value targets (mean difference = X.X ms, t(XX) = X.XX, p = .XX). Furthermore, There was no interaction between reward and trial bin [F(X.XX = X.XX, p = X.XX] but there was a a main effect of trial bin [F(X.XX = X.XX, p = X.XX] indicating that participants responded more accurately as training progressed, irrespective of reward. Accuracy by reward condition and trial block are presented in Figure X.

Test Phase

Hit Rate

We first analyzed hit rates according to the serial position of the target and reward conditions. Hit rates are shown in Figure X. Using a 3 x 3 (target serial position x reward condition) ANOVA, we found a main effect of target serial position [stats]. We found an expected serial position effect where responses to the first and last items in the list were higher than responses to the middle item. There [was/was no] main effect of reward on hit rate. Furthermore, there [was/was no] interaction between serial position and reward condition.

To more precisely characterize our main variable of interest, which was whether reward improves memory, we collapsed the hit rate for each participant according to reward condition. That is to say, we calculated the collapsed hit rate as the proportion of correct responses for all “old” trials with a colored item. We found no difference in hit rate between reward conditions.

False Alarm Rate

We next analyzed false alarm rates. Because there is no corresponding target position on “new” trials, we instead analyzed false alarms according to the serial position for each colored item, as this will be later used for our analysis of dprime and criterion. There [was/was no] main effect of the serial position of the rewarded item, and there [was/was no] main effect of reward condition. and there [was/was no] interaction between them.

To more precisely characterize our main variable of interest, which was whether reward improves memory, we collapsed the hit rate for each participant according to reward condition. That is to say, we calculated the collapsed hit rate as the proportion of correct responses for all “old” trials with a colored item. We found no difference in hit rate between reward conditions.

Discriminability

We next analyzed discriminability. We calculated discriminability according to d prime, which was calculated by subtracting the hit rates for each serial position and subtracting by the corresponding false alarms for list with the corresponding color position. For example, to calculate the dprime of a list where the target is in the 1st serial position and the colored item is in the 2nd serial position, we subtracted participant hit rates on lists with the target in position 1 and the colored item in position 2, by “new” lists where the colored item is in position 2. There [was/was no] main effect of the serial position of the rewarded item, and there [was/was no] main effect of reward condition. and there [was/was no] interaction between them.

The analysis of interest was participants’ subsequent performance on the transfer phase by reward condition. We first analyzed mean hit rates, false alarm rates for each participant, and from that, we derived respective d-prime and criterion values. Hit rates were calculated as the proportion of “old” responses towards the total number of “old” lists for a particular reward condition. False alarm rate were calculated as the proportion of “old” responses towards the total number of “new” trials for each reward condition. Hit rates and false alarm rates are shown in figure X. There was no significant difference in hit rate or false alarm rate between conditions, though participants tended to exhibit lower false alarm rates for higher rewarded conditions. The hit rate and false alarm rates for each participant were used to calculate the a dprime and criterion value for each participant by reward condition. dprine and criterion are shown in Figure X. Again, there was no significant different in dprime or criterion, though most notably, participants tended to respond more conservatively in the higher-reward condition, which seems to be primarily driven by the differences in hit rate.

Results in progress

Training Phase

RT

Accuracy

Test Phase

RT

Hit Rate

False Alarm Rate

Discriminability

Criterion