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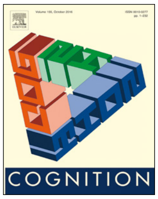

Reviews

Reward motivation influences response bias on a recognition memory task

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ABSTRACT

Reward-motivated memory has been studied extensively in psychology and neuroscience. Many recognition studies follow the same type of paradigm: stimuli are cued at encoding with high or low reward values which indicate the amount the stimulus is worth if successfully recognized on a subsequent memory test. Each incorrect endorsement of a lure at retrieval is penalized with an arbitrary value between the high and low reward value, resulting in a single false alarm rate. Studies employing this type of paradigm have reported higher hit rates for high value items compared to low value items, but generally hit rate is the only measure of memory that is reported as a function of reward value. It is currently not clear what aspects of the experimental design lead to these memory effects, and other measures, like discriminability and response bias, cannot be properly calculated when there is only a single false alarm rate, but we hypothesize that these are also susceptible to motivational manipulations. To test how reward anticipation might influence memory and response bias in this type of task, we created a novel paradigm that allowed us to calculate both by associating rewards with categories (indoor vs. outdoor scenes), thus calculating separate false alarm rate as well as hit rate at each level of reward. We report results of three experiments that varied rewards and penalties for correct and error responses for the category items. In two experiments, we replicated prior findings of higher hit rates for high compared to low reward items, but consistently across three experiments, when d' was calculated, we found no difference in memory discriminability as a function of reward. Further, Experiment 1 we found that response bias was more conservative for low reward items: participants were more likely to endorse a 'new' response to low compared to high reward items. This effect was significantly reduced in Experiment 2 and eliminated in Experiment 3 when the reward-penalty structure was manipulated to reduce bias. Our findings reveal that reward motivation can influence decisional biases thought to be independent of memory processes. The amount of the reward value for correct responses and the amount of the penalty for incorrect responses should be considered when designing experimental paradigms to study motivation-cognition interactions.

1. Introduction

Our memory system should prioritize motivationally relevant stimuli, whether appetitive or aversive, as these items are crucial for future decision making and ultimately, survival. Indeed, a now sizeable literature (for a review see Miendlarzewska, Bavelier, & Schwartz, 2016) has indicated that reward motivation can influence free recall and cued-recall (Castel, 2007; Cohen, Rissman, Suthana, Castel, & Knowlton, 2016; Madan, Fujiwara, Gerson, & Caplan, 2012; Madan & Spetch, 2012; Mather & Schoeke, 2011; Murty, LaBar, Hamilton, & Adcock, 2011; Wolosin, Zeithamova, & Preston, 2012) and that compared to low motivational salience, high motivational salience leads to increased recognition of previously seen stimuli (e.g., Adcock, Thangavel, Whitfield-Gabrieli, Knutson, & Gabrieli, 2006; Elward, Vilberg, & Rugg, 2014; Geddes, Mattfeld, Angeles, Keshavan, & Gabrieli, 2018; Han, Huettel, Raposo, Adcock, & Dobbins, 2010; Marini, Marzi, & Viggiano, 2011; Shigemune et al., 2010; Shigemune, Tsukiura, Kambara, & Kawashima, 2014; Shigemune, Tsukiura, Nouchi, Kambara, & Kawashima, 2017; Spaniol, Schain, & Bowen, 2014; Wittmann et al., 2005; Wittmann, Bunzeck, Dolan, & Düzel, 2007; Wittmann, Dolan, & Düzel, 2011; Yan, Li, Zhang, & Cui, 2017). A common way to study motivated recognition is for each stimulus to be randomly assigned a reward or punishment of high, low or no value during encoding. At retrieval, the value assigned at encoding is earned (or the punishment is avoided) when target items are correctly identified. Committing a false alarm by endorsing a lure as an 'old' target stimulus is penalized with a loss of a moderate amount, the value usually falling in between the high and low value of the target items. For example, in a paper by Spaniol

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et al. (2014), participants encoded indoor and outdoor scenes that were randomly preceded either by a high reward cue of $1.00 or a low reward cue $0.01. Later during recognition, correctly identified target items were rewarded with the amount cued at encoding, but false alarms were penalized with a loss of $0.50. The penalty for incorrect responses to lure items is to prevent liberal responding whereby participants respond 'old' to all items, gain all possible rewards, and the resulting hit rate is at ceiling. Studies utilizing this type of paradigm and reward structure have provided evidence that compared to low or no reward, high reward anticipation enhances memory for subsequently presented items, as measured by examining hit rate (i.e., correctly recognized target items), or corrected recognition subtracting out a single false alarm rate from hit rates for high and low reward items (Adcock et al., 2006; Bowen & Kensinger, 2017; Marini et al., 2011; Mather & Schoeke, 2011; Murty et al., 2011; Spaniol et al., 2014; Wittmann, Schiltz, Boehler, & Düzel, 2008). While this common approach has been fruitful for understanding how reward motivation influences hit rates, it leaves open several questions about whether reward motivation might modulate other aspects of memory, how reward anticipation could influence memory *and* response bias in a paradigm where both might be at play, and what elements of the experimental design are contributing to the effects.

1.1. Assignment of reward values

Many of the studies mentioned above (for exceptions see Dunsmoor, Murty, Davachi, & Phelps, 2015; Han et al., 2010; Patil, Murty, Dunsmoor, Phelps, & Davachi, 2017) assign value to individual target stimuli, either as points or monetary rewards/punishment. The results suggest that episodic memory can be cognitively controlled to remember the high value items to a greater extent than low value items (see Cohen, Rissman, Suthana, Castel, & Knowlton, 2014; Eich & Castel, 2016 for a discussion of this). This is an adaptive feature of the memory system and memory for these stimulus-reward associations can guide future decision making (Bornstein, Khaw, Shohamy, & Daw, 2017). For example, when faced with a new stimulus, bringing back to mind specific instances of similar items that were of high reward value can aid decisions about whether this new item is safe, dangerous or worth the risk to investigate. Other times, it may be too cognitively taxing to bring to mind individual items and their respective reward value, thus to compensate, our memory system is also able to accumulate information across experiences to generate a general preference that is used to guide behavior (i.e., reinforcement learning), and can extend learned stimulus-reward association to other unknown stimuli of the same category (Dunsmoor et al., 2015; Patil et al., 2017). To reiterate, when making decisions, one can bring back to mind specific instances of highly rewarding similar stimuli, or rely on general knowledge about the reward level of the category to decide the appropriate level of engagement.

To date, few studies have examined this latter type of memory–episodic memory for items within an established high reward or low reward category (c.f. Jang, Nassar, Dillon, & Frank, 2019). In the current study, we assigned high and low reward value at the level of the category of "indoor" and "outdoor" scenes (counterbalanced) rather than assigning rewards to individual stimuli. This allowed us to examine whether the high value category stimuli would be prioritized in memory to a greater extent, like prior work has shown when each to-be-remembered stimulus is cued with a high or low reward value. A second consideration was that this novel design permitted presentation of lure stimuli from the high and low value categories. With the exception of one study focused on associative memory and cued-recall for pairs encoded with a high or low value (Wolosin et al., 2012), many prior studies that randomly assigned reward value to individual items could only calculate a single false alarm rate because lures are never paired with a reward value, and memory analyses comparing reward value were restricted to hit rates (Adcock et al., 2006; Bowen & Kensinger, 2017; Mather & Schoeke, 2011; Murty et al., 2011; Spaniol et al., 2014; Wittmann et al., 2008). This leaves open the question of whether reward effects on hit rate are driven by memory processes, such as a stronger memory trace, or decisional biases that have not been adequately and systematically assessed. Parameters from signal detection theory (Green & Swets, 1966) that require a false alarm rate at each level of the independent variable can be informative for understanding whether reward value modulates memory sensitivity–the ability to distinguish old from new items—often measured as signal detection parameter *d′*.

1.2. Influences of the false alarm penalty

When making a choice about whether to approach or avoid a new stimulus, not all decisions have equal outcomes. Whether the category is high or low in motivational (Gable & Harmon-Jones, 2010) or incentive salience (Berridge & Robinson, 2003; determined by a combination of risk and reward) can bias approach or avoid decisions. Prospect theory (Kahneman & Tversky, 1979) predicts different behavior (risk-seeking vs. risk-aversion) depending on the amount of risk and reward associated with the outcome. The impact of reward and punishment contingencies on behavior has been assessed in a number of other domains such as reaction time tasks (e.g., Knutson, Adams, Fong, & Hommer, 2001; Knutson, Westdorp, Kaiser, & Hommer, 2000), perception of ambiguous stimuli (Spaniol, Voss, Bowen, & Grady, 2011; Voss, Rothermund, & Brandtstädter, 2008), and working memory (Taylor et al., 2004), but few studies have manipulated this factor in the context of an episodic recognition memory task. Two such study controlled decision bias in an episodic memory task by including a penalty for incorrect 'old' responses that matched the amount given for a correct 'new' response (Sun, Gu, & Yang, 2018; Wolosin et al., 2012). Specifically, in the study by Sun et al., (2018), in addition to rewarding hits, new words correctly judged as new (i.e., correct rejections) were rewarded with 2 yuan, but new words incorrectly judged as old (i.e., false alarms) were penalized 2 yuan. No formal analysis of response bias was reported in the paper so it is unclear whether this manipulation was successful. Wolosin et al. (2012) examined cued-recall of paired associates and rewarded correct "old" decisions, but penalized incorrect false alarms with the same monetary value, depending on the value the pair had been encoded with. They found that corrected recognition (hit rate minus false alarm rate) was significantly greater for high reward compared to low reward pairs, but again no analysis for response bias was reported. In another study, Han and colleagues (Han et al., 2010) presented reward information at the time of retrieval, not during encoding, and all correctly identified target items were rewarded with $1.00 and all false alarms were penalized with a loss of $1.00. The authors reported no effect of reward on memory sensitivity (*d′*) or response bias (*c*). Finally, in several prior experiments (Adcock et al., 2006; Bowen & Kensinger, 2017; Marini et al., 2011; Mather & Schoeke, 2011; Murty et al., 2011; Spaniol et al., 2014; Wittmann et al., 2008), all false alarm responses were penalized with the same set amount while 'new' responses had no impact on participant earnings, whether the 'new' response is subsequently correct or incorrect. These elements of the experimental design could influence participant decisions at the time of retrieval. For example, a weak memory trace could lead participants to use the 'new' response more often depending on the reward contingencies of the task. This would influence reported memory results from prior studies by impacting response bias—the tendency to favor one response over another—often measured as signal detection parameter criterion (*c*), but this is an understudied area in this literature.

1.3. The current study

To summarize, in the current study we address several factors described above that have not been systematically manipulated in previous recognition research. We assess how reward influences different aspects of memory and response bias in a paradigm where both may be in effect. In Experiment 1, assignment of high or low reward value was done at the level of the category (i.e., indoor and outdoor scenes), rather than to individual stimuli. This experimental manipulation permits the calculation of hit rates at each level of the independent variable to compare results to previous studies, but additionally the calculation of a false alarm rate for each level of reward and measures of memory discriminability and response bias. In Experiment 2, the amount of the false alarm penalty was manipulated to determine whether this affects the level of response bias for high compared to low reward category items. Finally, in Experiment 3, to better understand participant strategy, all correct and error responses were rewarded or punished, respectively, so both 'old' and 'new' responses had an impact on the financial outcome of the trial. These experimental manipulations test the conditions under which we can replicate the previously-observed beneficial effects of reward on hit rates, and modelling the recognition data using signal detection parameters allows the separate assessment of reward effects on individual ability to distinguish between categories of items and decision processes at retrieval (Macmillan & Creelman, 2005). Specific details and the hypotheses are reported in the individual experiment sections below. Raw data for each experiment is available on the Open Science Framework (https://osf.io/p26qy/).

Table 1
Participant characteristics for all three experiments.

Characteristic	Experiment 1 (*N* = 30)	Experiment 2 (*N* = 37)	Experiment 3 (*N* = 41)
Number of male participants	6	7	8
Age (years)	21.1 (4.44)	20.1 (1.96)	21.59 (3.31)
Age range	18–33	18–25	18–34
Ethnicity	4 Hispanic	5 Hispanic	4 Hispanic
Race	2 African American 8 Asian 18 Caucasian	11 Asian 21 Caucasian 5 other/more than one	4 African American 9 Asian 25 Caucasian 3 other/more than one
Education (years)	14.2 (2.02)	13.8 (1.66)	13.8 (1.79)
Shipley	31.5 (3.84)	30.2 (3.06)	30.5 (3.68)
BIS	26.6 (3.30)	20.7 (4.02)	20.8 (4.00)
BAS-drive	14.3 (2.11)	10.6 (2.29)	11.6 (2.06)
BAS-reward responsivity	23.4 (2.85)	17.6 (1.85)	17.5 (1.87)
BAS-fun seeking	15.7 (2.61)	11.9 (1.78)	11.7 (2.55)
TRAIT	33.6 (9.27)	32.4 (8.59)	36.8 (10.11)
STAI-1	28.5 (8.41)	29.9 (8.08)	34.3 (10.34)
STAI-2	29.0 (10.77)	28.8 (7.25)	31.7 (8.85)
BDI	3.0 (3.45)	2.2 (1.91)	3.7 (5.31)
Digit symbol	66.9 (9.69)	71.2 (10.63)	72.8 (10.04)
Earnings short delay	\$3.18 (\$0.97)	\$3.08 (\$1.74)	\$10.11 (\$2.21)
Earnings long delay	\$2.26 (\$0.89)	\$1.74 (\$1.29)	\$7.90 (\$2.40)
Total earnings	\$5.44 (\$1.56)	\$4.83 (\$2.70)	\$18.01 (\$4.66)

Note: Table reflects averages and standard deviations are in parentheses. Shipley = vocabulary test; BIS = behavioral inhibition system; BAS-Drive = behavioral approach system drive subscale; BAS-Reward Responsivity = behavior approach system reward responsivity subscale; BAS-Fun Seeking = behavioral approach system fun seeking subscale; TRAIT = Spielberg State-Trait Anxiety Inventory trait anxiety subscale; STAI-1 = Spielberg State-Trait Anxiety Inventory state anxiety subscale on day 1 of experiment; STAI-2 = Spielberg State-Trait Anxiety Inventory state anxiety subscale on day 2 of experiment; BDI = Beck Depression Inventory; Earning short delay = average earnings on day 1 retrieval task; Earnings long delay = average earnings on day 2 retrieval task; Total Earnings = sum of Earnings short delay and Earnings long delay. See methods section for a brief description and the reference of each questionnaire.

2. Experiment 1

We sought to replicate and extend prior rewarded recognition research by creating a paradigm where stimuli within an entire category (e.g., indoor vs. outdoor scenes) are associated with high or low reward value. This paradigm produced separate false alarm rates at each level of the independent variable permitting analysis of hit rates, but also memory sensitivity and response bias. In this experiment, the amount of the penalty for committing a false alarm was the same for both categories of items. We had several hypotheses: 1) to replicate prior findings that high reward would increase hit rates compared to low reward; 2) this effect would be particularly pronounced at the longer retention interval, in line with evidence that reward strengthens memory after a delay, due to engagement of hippocampally dependent consolidation processes modulated by dopamine (Adcock et al., 2006; Brown, Basile, Templer, & Hampton, 2019; Lisman & Grace, 2005; Shohamy & Adcock, 2010; Spaniol et al., 2014); 3) memory sensitivity would follow the same pattern as hit rate, and the discrepancy in memory sensitivity for high compared to low reward items would be larger after a longer retention interval; and 4) response bias would become more conservative over time—more willing to endorse the 'new' response at the longer delay when memory signals are less strong—but that high reward category items would elicit a more liberal response bias—more willing to endorse the 'old' response. Whether a reward by retention interval interaction on response bias would emerge, was an open question.

2.1. Methods

2.1.1. Participants

The study was approved by the Institutional Review Board at Boston College and all participants gave informed consent. Participants were recruited using advertisements posted on the Boston College SONA participant pool, flyers around Boston College campus, or online job postings on Boston University's website. Participants were compensated \$10/h, or \$11/h after January 1st, 2017 (reflecting a change in Massachusetts minimum wage) for their time, in addition to earning monetary rewards for their performance on the memory task (see Bowen & Kensinger, 2017 for a discussion of interactions between participant payment and performance-based reward). Participants were not aware of the performance bonus until they arrived for the study to ensure that these performance-based rewards were not an incentive for participation. To reduce confounds associated with neurological and psychiatric disorders, and to minimize possible sample differences across the three experiments, all interested participants completed a medical screening questionnaire to assess past and current medical conditions. Any individual who had sustained a head injury resulting in loss of consciousness, reported a current or prior neuropsychological or psychiatric diagnosis (e.g., epilepsy, depression), or current medication (e.g., anxiolytic) that could affect central nervous system function, were not scheduled for an appointment. A total of 35 participants were tested, but 5 were excluded from analyses due to either computer error or failing to complete session 2. Participant characteristics for the final analyzed sample of 30, including scores on the questionnaires described below, are reported in Table 1.

2.1.2. Questionnaires

We first collected basic demographic information including date of birth, sex, years of education, ethnicity, race, marital status, and employment status.

We also collected a modified version of the Beck Depression Inventory (BDI; Beck, Steer, & Carbin, 1988) excluding a question about suicidality and one about sexual behavior to determine whether participants were experiencing any depressive symptoms. We set a score of 13 on this measure as exclusionary prior to data collection, but all participants who are included in the experimental analyses ultimately had scores of 12 or less. We also collected the Spielberger State-Trait Anxiety Inventory (STAI; Spielberger, Gorsuch, Lushene, & Vagg, 1970) as a self-report measure of anxiety, the Behavioral Inhibition/Avoidance Scales (BIS/BAS; Carver & White, 1994) to assess avoidance and approach motives, the vocabulary test of the Shipley Institute of Living Scale (Shipley, 1940) and the Digit Symbol subtest of the Wechsler Adult Intelligence Scale (WAIS-III; Wechsler, 1997) which measures visual-motor speed and complexity, and motor coordination. Questionnaires were completed using pen and paper and scored by a research assistant.

2.1.3. Design

There were two within-subject manipulations: Reward (high, low) and retention interval (short [10 min], long[24-h]). Half of the items were tested at the short delay and half at the long delay.

2.1.4. Stimuli and apparatus

Stimuli consisted of 240 indoor and outdoor scenes used in previous reward and memory studies ((Bowen et al., 2020); Bowen & Kensinger, 2017; Spaniol et al., 2014), originally from a picture database in CorelDraw. None of the images contained humans or animals. The 240 images were split into 2 lists of 120 images (60 indoor, 60 outdoor) and assigned to target or lure status, high or low reward, left or right response key at encoding, and tested at the short or long delay, which resulted in 16 counterbalancing conditions. The order of trials within a stimulus list was randomized for each person. *E*-Prime (Psychology Software Tools, Inc.) was used for stimulus presentation and response collection on a desktop computer with a 17″ screen. Stimuli were presented centrally against a black background with all text in white 20-point Arial font.

2.1.5. Paradigm

During encoding, participants viewed indoor and outdoor scenes and were told their memory for these images would be tested, half during session 1, and the other half when they returned the following day for session 2. Participants were also informed that images from one category were worth a high reward of $0.25, and the other category worth a low reward of $0.01, if correctly recognized on the memory test. For half the participants the high reward category was indoor scenes and the low reward category was outdoor scenes. The other half of participants received the reverse assignment. During retrieval, participants were reminded they could earn the high or low reward depending on the category, if they correctly identified an image as old, and were also informed that incorrect ‘old’ responses (i.e., false alarms to either high or low reward category items) would be penalized with a loss of -$0.13. Participants were again given a brief reminder of the retrieval instructions at the beginning of session 2.

2.1.6. Procedure

Fig. 1 depicts the general paradigm and specific details for all three experiments. The study took place over two consecutive days. The duration of session 1 was approximately 1 h, and duration of session 2 approximately 30 min. Upon arrival for session 1, participants read and signed the consent form and completed the BDI. Participants were then given instructions about the task, followed by 10 practice encoding trials which were not included in the analysis.

During the encoding phase, participants viewed the images one at a time, were asked to make an ‘indoor’ or ‘outdoor’ judgment via button press when the image appeared on the screen, and were informed their memory for these items would be tested on a subsequent recognition task. Participants viewed each image for 2000 ms. The words ‘indoor’ and ‘outdoor’ were placed on the screen below the image so participants did not need to remember the response-key mapping.

After encoding, participants completed demographics, STAI, the Shipley vocabulary test, Digit Symbol, and BIS/BAS for a filled retention interval of approximately 10 min. Twelve (6 target, 6 lure) practice retrieval trials were then completed, followed by the experimental task. During retrieval, the images were randomly presented one at a time, half targets and half lures. During each image presentation, participants were asked to make a sure-new to sure-old judgment using numbers 1–6 on the keyboard and the trial advanced only after a response was made. Participants were encouraged to use the full confidence scale, but their confidence did not affect their earnings. For each correct ‘old’ response (responses 4, 5 or 6), participants earned the monetary reward the image was associated with, and to deter participants from liberal responding false alarms were penalized with a monetary loss. Participants only received feedback about their earnings at the end of the retrieval task and upon completion were paid in cash for their time in addition to their performance-based rewards.

2.2. Results

2.2.1. Encoding task performance

Due to a computer error, analyses on the indoor/outdoor encoding judgment included only 27 participants. Separate paired *t*-tests revealed no differences for the high compared to low reward category items on accuracy or reaction time on this judgment, $t(26) \leq 1.36$, $p \geq .19$, $r = 0.30$. Average accuracy was 0.99 ($SE = 0.01$) and median reaction time was 826 ms ($SE = 99$ ms).

2.2.2. Recognition performance

Average hit rates, false alarm rates, discriminability measure *d′*, response bias measure *c*, and median reaction times are shown in Table 2. Within-subject 2 (reward: high, low) x 2 (retention interval: short, long) repeated-measures ANOVAs were conducted for each of these dependent variables. Analyses were collapsed across the confidence rating scale and when the lowest confidence responses (responses 3 & 4) were excluded from analyses, the patterns remained the same. A six-point receiver operating characteristic (ROC) curve of the hit and false alarm rate is depicted in Fig. 2-Top.

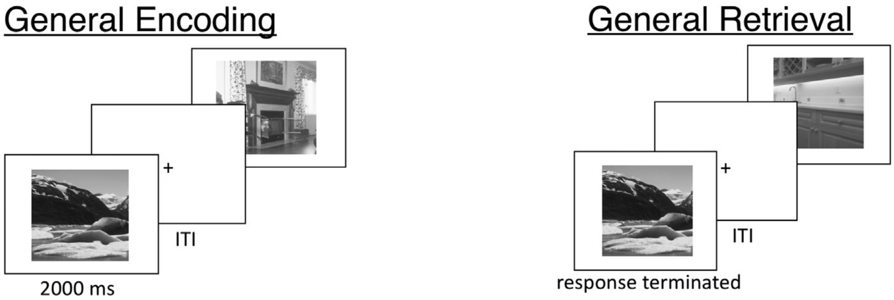
2.2.2.1. Reaction time. A significant effect of retention interval emerged, $F(1, 29) = 5.30$, $p = .03$, $\omega_p^2 = 0.122$, such that reaction times were slower at the short ($M = 2004$ ms, $SE = 109$ ms) compared to the long delay ($M = 1833$ ms, $SE = 98$ ms). No other effects were significant, $F(1, 29) \leq 1.03$, $p \geq .32$, $\omega_p^2 \leq 0.001$.

2.2.2.2. Hit rate. A main effect of reward, $F(1, 29) = 6.49$, $p = .02$, $\omega_p^2 = 0.150$, revealed that hit rates were higher for high reward ($M = 0.57$, $SE = 0.02$) compared to low reward category items ($M = 0.50$, $SE = 0.03$). There was also a significant main effect of retention interval, $F(1, 29) = 53.32$, $p < .001$, $\omega_p^2 = 0.628$, indicating higher hit rates at the short ($M = 0.60$, $SE = 0.02$) compared to the long ($M = 0.47$, $SE = 0.02$) delay. The interaction did not reach significance, $F(1, 29) = 1.60$, $p = .22$, $\omega_p^2 = 0.019$, .

2.2.2.3. False alarm rate. The main effect of reward was significant, $F(1, 29) = 4.88$, $p = .04$, $\omega_p^2 = 0.111$, with false alarm rates higher for high reward ($M = 0.24$, $SE = 0.02$) compared to low reward category items ($M = 0.20$, $SE = 0.02$). Neither the main effect of retention interval $F(1, 29) = 0.02$, $p = .90$, $\omega_p^2 = -0.033$, nor the interaction, $F(1, 29) = 0.08$, $p = .78$, $\omega_p^2 = -0.031$ were significant.

2.2.2.4. Discriminability. There was a significant main effect of retention interval, $F(1, 29) = 43.17$, $p < .001$, $\omega_p^2 = 0.576$ indicating that discriminability was higher at the short ($M = 1.15$, $SE = 0.07$) compared to the long ($M = 0.80$, $SE = 0.06$) delay. Neither the main effect of reward, $F(1, 29) = 0.03$, $p = .87$, $\omega_p^2 = -0.032$, nor the interaction $F(1, 29) = 1.29$, $p = .27$, $\omega_p^2 = 0.009$, were significant.

2.2.2.5. Response bias. In signal detection terms, values of *c* equal to zero indicate no response bias, positive values of *c* indicate a conservative criterion and negative values indicate a liberal criterion. A one sample *t*-test indicated that all four means entered into the ANOVA described below were significantly *greater* than zero indicating an overall conservative criterion for high and low reward and at the



Study parameters	Exp. 1	Exp. 2	Exp. 3
Encoding Task	Indoor/outdoor ITI: 1250, 2250, or 3250 ms	Indoor/outdoor ITI: 1250, 2250, or 3250 ms	Judgment of learning: 1(sure forget) – 6(sure remember) ITI: 1250, 2250, or 3250 ms
Retrieval Task	Confidence: 1(sure new) – 6(sure old) ITI: 100, 150, 200, 250 ms	Confidence: 1(sure new) – 6(sure old) ITI: 100, 150, 200, 250 ms	Old, New, Skip If Skip: Old, New Confidence 1(not confident) – 6(totally confident) ITI: 1000, 1500, 2000, 2500 ms
Reward structure	+$.25 high reward hit +$.01 low reward hit	+$.25 high reward hit +$.01 low reward hit	+$.24 high reward hit or correct rejection +$.09 low reward hit or correct rejection If Skip +$.08 high reward; +$.03 low reward
Penalty structure	-$.13 all false alarms	-$.25 high reward false alarm -$.01 low reward false alarm	-$.24 high reward false alarm or miss -$.09 low reward false alarm or miss

Fig. 1. Depiction of the general procedures at encoding and retrieval.
Note. The table highlights the paradigm details for each experiment. Study parameter "Encoding Task" and "Retrieval Task" indicate the judgment participants were asked to make while the image was displayed on the screen. The ITI indicates the duration of the crosshairs between each stimulus. Study parameter "Reward structure" indicates the value of the high and low categories and amount that could be earned for different types of correct responses on the recognition task. The parameter "Penalty structure" indicates the monetary amount deducted from participants for different types of incorrect responses. Hits = correct "old" judgment to target images; Correct rejection = correct "new" judgment to lure images; False alarm = incorrect "old" judgment to lure images; Miss = incorrect "new" judgment to target images.

Table 2
Recognition memory results for all three experiments.

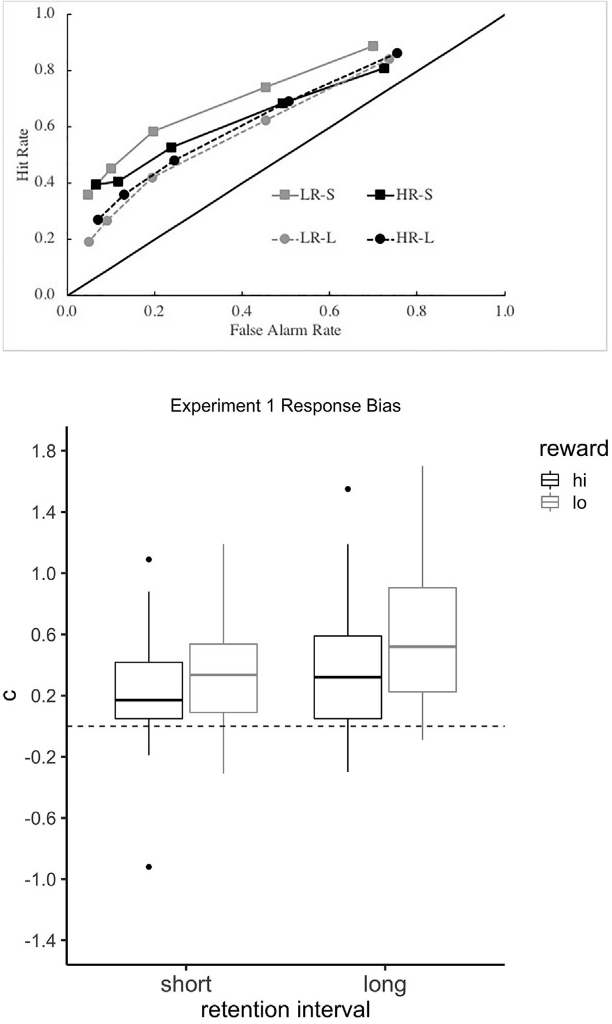
Condition	Experiment 1	Experiment 2	Experiment 3
Hit rate			
HR-S	0.62 (0.14)	0.64 (0.19)	0.78 (0.17)
LR-S	0.59 (0.16)	0.60 (0.19)	0.77 (0.19)
HR-L	0.51 (0.15)	0.50 (0.20)	0.69 (0.19)
LR-L	0.42 (0.15)	0.46 (0.20)	0.68 (0.18)
False alarm rate			
HR-S	0.24 (0.13)	0.26 (0.16)	0.22 (0.15)
LR-S	0.20 (0.12)	0.24 (0.16)	0.18 (0.14)
HR-L	0.25 (0.15)	0.39 (0.15)	0.26 (0.19)
LR-L	0.20 (0.12)	0.25 (0.15)	0.25 (0.19)
d′			
HR-S	1.12 (0.42)	1.09 (0.81)	1.78 (0.86)
LR-S	1.18 (0.52)	1.10 (0.83)	1.91 (0.92)
HR-L	0.84 (0.43)	0.61 (0.62)	1.39 (0.76)
LR-L	0.75 (0.35)	0.68 (0.51)	1.37 (0.81)
c			
HR-S	0.22 (0.38)	0.17 (0.40)	0.02 (0.43)
LR-S	0.36 (0.40)	0.28 (0.38)	0.10 (0.50)
HR-L	0.39 (0.47)	0.32 (0.47)	0.08 (0.58)
LR-L	0.60 (0.44)	0.46 (0.53)	0.10 (0.52)
Reaction time			
HR-S	2029 (729)	1899 (700)	n/a
LR-S	1978 (562)	1851 (682)	n/a
HR-L	1866 (576)	1989 (1135)	n/a
LR-L	1799 (563)	1950 (1169)	n/a

Note. HR = high reward; S = short delay; LR = low reward; L = long delay; *d′* = signal detection measure of discriminability; *c* = signal detection parameter 'criterion' a measure of response bias; Reaction Time values are medians, all other values are means; Standard deviations shown in parentheses. n/a = not available due to programming error.

short and long delay, $t(29) \geq 4.53$, $p \leq .001$, $r \geq 0.643$. A main effect of reward, $F(1, 29) = 6.72$, $p = .02$, $\omega_p^2 = 0.156$, revealed that response bias values were significantly less positive for high reward ($M = 0.30$, $SE = 0.07$) compared to low reward ($M = 0.48$, $SE = 0.07$) category items. There was also a significant main effect of retention interval, $F(1, 29) = 14.34$, $p < .001$, $\omega_p^2 = 0.301$, indicating less positive response bias values at the short ($M = 0.29$, $SE = 0.06$) compared to the long ($M = 0.49$, $SE = 0.07$) delay. The interaction did not reach significance, $F(1, 29) = 0.42$, $p = .52$, $\omega_p^2 = -0.019$, but see Fig. 2-Bottom for a graphical depiction of the values from the interaction.

2.2.2.6. *Memory confidence*. As an exploratory analysis, to examine whether the strength of the memory trace for low and high reward items led to changes in criterion, the proportion of trials for the 'guess old' and 'guess new' responses were calculated. Specifically, when confidence is low and participants use the "guess" response, they may respond with 'guess new' more often for low compared to high reward items simply because of the experimental reward structure where the rational behavior would be to respond old to all high-reward category items and new to all low-reward category items. In contrast to this prediction, a Reward (high, low) x Memory (old, new) interaction on the proportion of guess responses was not significant, $F(1, 29) = 0.013$, $p = .91$, $\omega_p^2 = -0.032$, but there was a main effect of memory, $F(1, 29) = 19.70$, $p < .001$, $\omega_p^2 = 0.377$, such that participants used the 'guess new' response more often ($M = 0.22$, $SE = 0.03$) than the 'guess old' response ($M = 0.13$, $SE = 0.02$), regardless of high and low value status. The main effect of reward on the proportion of guess responses was not significant, $F(1, 29) = 0.30$, $p = .59$, $\omega_p^2 = -0.023$.

We additionally calculated the proportion of 'sure new' and 'sure old' to test whether there were differences in the use of the high confidence responses for high compared to low reward category items. A Reward (high, low) x Memory (old, new) ANOVA on the proportion of confident responses revealed a significant interaction, $F(1, 29) = 8.19$, $p = .01$, $\omega_p^2 = 0.19$. Participants used the 'sure new' response more often for low ($M = 0.21$, $SE = 0.04$) compared to high reward category items ($M = 0.18$, $SE = 0.30$), $t(29) = 1.97$, $p = .06$, $r = 0.34$, and the



Experiment 1 Response Bias

Fig. 2. Recognition data from experiment 1.
Note. Top) A 6-point ROC curve plotting hit and false alarm rate as a function of reward value (high, low), and retention interval (short, long) at each confidence level. Square markers indicate the short delay, and round markers the long delay. High reward trials indicated by the black ink, low reward by the gray ink. Bottom) Box plots of the response bias values (*c*) as a function of 4 task conditions. Hi = high reward; Lo = low reward; c = signal detection parameter criterion. In signal detection, values of *c* above zero reflect a "conservative" criterion indicating a bias for the "new" response, and values of *c* below zero are indicative of a "liberal" criterion indicating a bias toward the "old" response.

'sure old' response more often for high reward ($M = 0.20$, $SE = 0.02$) compared to low reward category items ($M = 0.16$, $SE = 0.02$), $t(29) = 2.45$, $p = .02$, $r = 0.41$. There was no significant main effect of reward, $F(1, 29) = 0.23$, $p = .63$, $\omega_p^2 = -0.02$, or memory, $F(1, 29) = 0.16$, $p = .70$, $\omega_p^2 = -0.03$.

2.3. Discussion

The first goal of Experiment 1 was to use a novel paradigm to test the conditions under which we could replicate and extend prior findings of reward effects on memory. In line with our first hypothesis, we replicated many other studies reporting a higher hit rate for high reward compared low reward items (e.g., Adcock et al., 2006; Bowen, Ford, Grady, & Spaniol, 2020; Castel, 2007; Spaniol et al., 2014; Wolosin et al., 2012), suggesting that this effect is robust and not reliant on individual stimuli being cued by a reward value. However, we did not replicate prior reward x retention interval interactions (Spaniol et al., 2014). The novel aspect of this paradigm was assigning all stimuli within a category (indoor or outdoor scenes) to high or low reward status in order to address our second goal of creating a false alarm rate at each level of reward value. This enabled us to assess the effect of reward on memory sensitivity (calculated as *d′*) and response bias (calculated as *c*). In addition to higher hit rates, high reward items elicited a higher false alarm rate and ultimately there was no effect of reward on sensitivity for high compared to low value items, contrary to our hypothesis. Our prediction that there would be a greater bias toward the "new" response (i.e., more conservative or relaxed criterion for saying "new") at the longer retention interval was supported, but there was also an effect of reward on response bias. Participants had a greater bias toward the "old" response (i.e., more liberal or relaxed criterion for saying 'old') when making judgments about high compared to low reward items. It should be noted, that the response bias values were conservative overall, in all conditions, with mean values of *c* greater than zero (see Fig. 2-Bottom). Prior studies have not been able to assess these latter two measures because previous paradigms had only a single false alarm rate.

The results of this first experiment indicate no difference in memory sensitivity for high compared to low reward category items. Instead, memory for high versus low reward items influenced decision biases at retrieval. We hypothesized that reward would influence *memory* processes because knowledge of the reward at the time of encoding would allow sufficient time to re-prioritize the memory trace for high reward items, particularly at the longer retention interval. The only pieces of evidence of this pattern were that participants used the highest confidence 'old' response more often for high reward items, indicative of a strong memory trace, and the highest confidence 'new' response more often for low reward items, indicative of strong novelty signals, rather than a weak memory trace, for this class of stimuli. Further, participants opted to use the "guess new" response more often than "guess old" regardless of the reward value of the category. These findings provide some evidence that participants are relying on memory signals at least to some extent when making old/new decisions during the task in line with previous studies where the stimulus itself does not convey any reward information. The interesting question is why, compared to low reward items, high reward items led to a relatively more liberal response bias toward the "old" response. We propose two potential explanations for the reward effects on decisional biases. First, it is possible that the general-memory signals of the high reward category are too strong to suppress, leading participants to use the 'sure old' response to a greater extent for high reward items because of these signals. For instance, participants may remember seeing other high-reward outdoor scenes and these memory signals may lead them to confidently endorse an unseen outdoor scene. At the time of retrieval this leads to relatively more liberal responding and ultimately higher hit rates, as well as false alarm rates for this category of items. Additionally, because these mnemonic signals are strong, this pattern would emerge despite an increase in the amount of false alarm penalty. An alternative account is that participants are making rational financial decisions. Responding 'old' to low reward items, if correct, yields a reward of only $0.01, but if incorrect, incurs a penalty of -$0.13 so it may not seem worth the risk to say 'old' when the penalty is so steep. Similarly, responding 'old' to high reward category items, if correct, yields a reward of $0.25, but if incorrect, incurs a penalty of only −$0.13. Indeed, in one study that included a false alarm penalty that matched the amount of possible reward there were no effect of reward on response bias, and no effect on memory discriminability (Han et al., 2010), but this study only utilized one level of reward (i.e., $1.00). In Experiment 2 we manipulate the amount of reward and the false alarm penalty to empirically test the latter hypothesis and more generally examine whether the amount of the false alarm penalty biases responses for one class of stimuli over the other.

3. Experiment 2

In Experiment 2, all aspects of the experimental design were identical to Experiment 1, with the one exception that the amount of the penalty for committing a false alarm was not static across trials. Instead, the penalty for a false alarm matched the reward value for a hit. In other words, participants earned a high reward for correctly identifying old items of a particular category (e.g., indoor scenes), but were then penalized the same amount for committing a false alarm to items of that category. This design allowed us to adjudicate between two alternatives: if the reward-related liberal response bias is related to difficulty in suppressing approach motivation toward those items, then the response bias differences should remain; by contrast, if participants are able to flexibly adjust their response strategies to maximize their financial gains, then the response bias differences should disappear.

3.1. Methods

3.1.1. Participants

The recruitment methods and exclusionary criteria were the same as those described in Experiment 1. Participants gave informed consent, were paid \$11/h for participation, but were unaware of the performance contingent rewards until given task instructions. A total of 48 participants were tested, but 6 were excluded from analyses due to either computer error or failing to complete session 2, and 5 additional participants were excluded for BDI scores above 13 resulting in a sample of 37 participants. Table 1 details the participant characteristics and scores on the questionnaires (described in Experiment 1). With the exception of the Digit Symbol, questionnaire data were collected online using REDCap. (https://projectredcap.org/software/).

3.1.2. Paradigm

Participants viewed indoor and outdoor scenes and were given the same instructions and encoding task detailed for Experiment 1. During retrieval, participants were informed that correct ‘old’ responses (i.e., hits) would result in the reward as specified during the encoding task, but that incorrect ‘old’ responses (i.e., false alarms) would be penalized with a monetary loss of \$0.25 for the high reward category images, and a loss of \$0.01 for low reward category images.

3.2. Results

3.2.1. Encoding task performance

Separate paired *t*-tests indicated neither accuracy nor reaction time significantly differed for the high compared to low reward category items on the indoor/outdoor encoding judgment, $t(36) \leq 0.98, p \geq .33, r = 0.16$. Average accuracy was 0.99 ($SE = 0.003$) and median reaction time was 719 ms ($SE = 42$ ms).

3.2.2. Recognition performance

Within-subjects 2 (reward: high, low) x 2 (retention interval: short, long) repeated-measures ANOVAs were calculated for hit rates, false alarm rates, discriminability measure *d′*, and response bias measure *c*, and median reaction times. Values of the dependent variables at each level of the independent variables are reported in Table 2, and a six-point ROC curve of the hit and false alarm rate is depicted in Fig. 3-Top.

3.2.2.1. Reaction time. Reaction times at retrieval were not modulated by reward, retention interval, and there was no significant interaction, $F(1, 36) \leq 0.59, p \geq .45, \omega_p^2 \leq -0.011$. The overall median reaction time at recognition was 1922 ms ($SE = 138$).

3.2.2.2. Hit rate. There was a main effect of retention interval, $F(1, 36) = 45.87, p < .001, \omega_p^2 = 0.541$, such that hit rates were higher after a short delay ($M = 0.62, SE = 0.03$) compared to a long delay ($M = 0.48, SE = 0.03$). Neither the main effect of reward, $F(1, 36) = 2.41, p = .13, \omega_p^2 = 0.036$, nor the interaction $F(1, 36) = 0.01, p = .91, \omega_p^2 = -0.027$, were significant. When responses were restricted to high confidence only (excluding trials given a confidence rating of 3 or 4), the hit rate for high ($M = 0.68, SE = 0.03$) compared low ($M = 0.60, SE = 0.04$) reward items was significant, $F(1, 36) = 4.99, p = .03, \omega_p^2 = 0.095$.

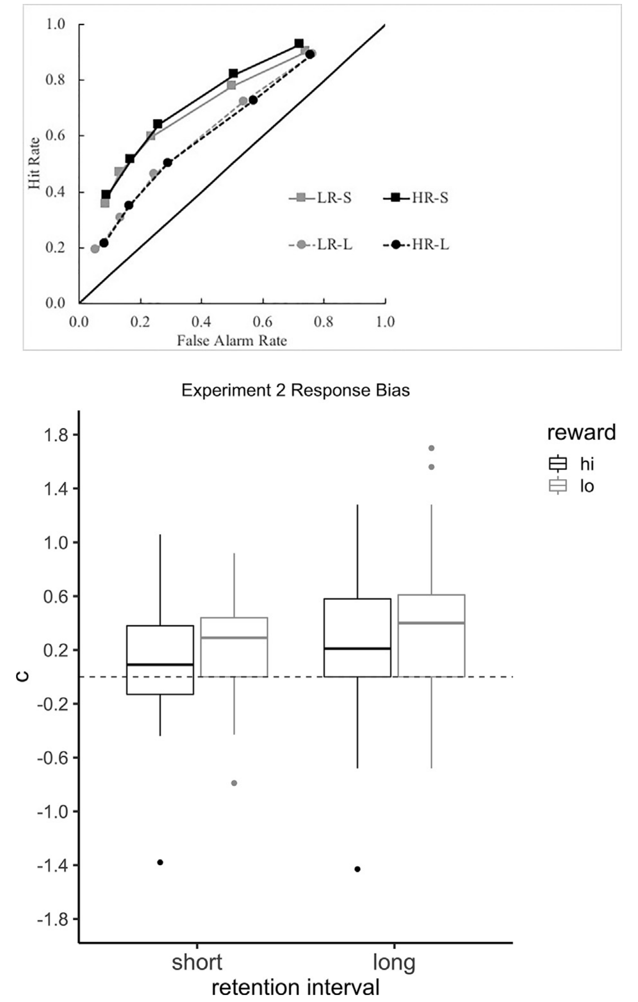


Fig. 3. Recognition data from experiment 2.
Note. Top) A 6-point ROC curve plotting hit and false alarm rate as a function of reward value (high, low), and retention interval (short, long) at each confidence level. Square markers indicate the short delay, and round markers the long delay. High reward trials indicated by the black ink, low reward by the gray ink. Bottom) Box plots of the response bias values (*c*) as a function of 4 task conditions. Hi = high reward; Lo = low reward; c = signal detection parameter criterion. In signal detection, values of *c* above zero reflect a “conservative” criterion indicating a bias for the “new” response, and values of *c* below zero are indicative of a “liberal” criterion indicating a bias toward the “old” response.

3.2.2.3. False alarm rate. There were no significant main effects of reward, $F(1, 36) = 2.49, p = .13, \omega_p^2 = 0.037$, or retention interval, $F(1, 36) = 1.28, p = .27, \omega_p^2 = 0.007$, on false alarm rate, and no interaction, $F(1, 36) = 0.45, p = .51, \omega_p^2 = -0.015$. When responses were restricted to high confidence only, false alarm rates were higher for high ($M = 0.26, SE = 0.02$) compared to low ($M = 0.20, SE = 0.03$) reward items, $F(1, 36) = 6.18, p = .02, \omega_p^2 = 0.120$.

3.2.2.4. Discriminability. There was a main effect of retention interval on *d′*, $F(1, 36) = 33.39, p < .001, \omega_p^2 = 0.460$, such that discriminability was higher at the short ($M = 1.10, SE = 0.13$) compared to the long delay ($M = 0.65, SE = 0.08$). Neither the main effect of reward, $F(1, 36) = 0.43$, $p = .51$, $\omega_p^2 = -0.015$, nor the interaction were significant, $F(1, 36) = 0.25$, $p = .62$, $\omega_p^2 = 0.007$, even when trials were limited to those given a high confidence rating.

3.2.2.5. Response bias. There was a main effect of retention interval, $F(1, 36) = 9.79$, $p = .003$, $\omega_p^2 = 0.188$, such that response bias values were less positive at the short ($M = 0.22$, $SE = 0.05$) than the long ($M = 0.39$, $SE = 0.07$) delay. There was no main effect of reward, $F(1, 36) = 2.50$, $p = .13$, $\omega_p^2 = 0.038$, no significant interaction, $F(1, 36) = 0.32$, $p = .57$, $\omega_p^2 = -0.018$ and this pattern remained even when trials were limited to those given a high confidence rating. One sample *t*-tests indicated that means of the significant main effect of retention interval were significantly greater than zero indicating a greater bias toward the "new" response at short and long delay, $t(29) \geq 4.53$, $p \leq .001$, $r \geq 0.643$. This was also true of the criterion values for high and low reward although there were no significant differences between these two values, $t(36) \geq 3.74$, $p \leq .001$, $r \geq 0.529$. See Fig. 3-Bottom for a graphical depiction of the response bias values at each level of the independent variables.

3.2.2.6. Memory confidence. To compare with Experiment 1, we calculated the proportion of 'guess new', 'guess old', and 'sure new', 'sure old' responses for high and low category items. A Reward (high, low) x Memory (old, new) ANOVA on the proportion of guess responses revealed a significant main effect of memory, $F(1, 36) = 28.42$, $p < .001$, $\omega_p^2 = 0.419$, such that participants used the 'guess new' response ($M = 0.24$, $SE = 0.03$) more often than 'guess old' ($M = 0.13$, $SE = 0.01$). This indicates that when participants had low confidence in their response because the memory trace was ambiguous, they endorsed the 'guess new' response more often overall, but this was not influenced by the value of the reward category. There was no significant interaction, $F(1, 36) = 0.59$, $p = .47$, $\omega_p^2 = -0.012$, and no main effect of reward, $F(1, 36) = 0.733$, $p = .39$, $\omega_p^2 = -0.007$. A Reward (high, low) x Memory (old, new) ANOVA on the proportion of sure responses indicated no significant main effects of memory, $F(1, 36) = 0.13$, $p = .72$, or reward $F(1, 36) = 1.16$, $p = .29$. The interaction was also not significant, $F(1, 36) = 1.08$, $p = .31$, $\omega_p^2 = 0.002$. The proportion of 'sure new' ($M = 0.18$, $SE = 0.02$), and 'sure old' ($M = 0.17$, $SE = 0.03$) responses, did not differ as a function of high reward.

3.3. Discussion

In Experiment 1, participants were relatively more liberal, tending toward the "old" response when judging high compared to low reward items. To empirically test whether participants were using the 'old' response more often for high reward category items simply because the penalty for being wrong was less than the possible reward for being correct, in Experiment 2, we manipulated the amount of penalty to be financially equivalent to the reward for a hit. Although participants were generally conservative in their responding, critically, changing the payoff structure so the false alarm penalty matched the amount of the possible reward resulted in no significant effect of reward on response bias, thereby significantly weakening the effect of reward contingencies on participant's decision-making strategies at retrieval seen in Experiment 1. Participant confidence or strength of the memory trace also did not differ as a function of reward value. Consistent with Experiment 1, we replicated higher hit rate and false alarm rates for high compared to low reward items, but in Experiment 2 this was only true when analyses were restricted to high confidence trials only. Further, like Experiment 1, we did not find evidence that high reward influenced memory sensitivity, regardless of whether or not we restricted analyses to high confidence.

Few prior studies have had the ability to examine the effect of reward on memory measures other than hit rate, and even fewer have systematically manipulated the false alarm penalty (but see Han et al., 2010; Sun et al., 2018) to determine how this affects participants' decision-making strategies at retrieval. The results from Experiment 1 suggest that participants were reluctant to use the 'old' response for low-reward category items, potentially because the penalty for an incorrect 'old' response far outweighed the reward for a correct 'old' response. The results from Experiment 2 supported this idea. When the penalty for an incorrect "old" response matched the value of the reward for a correct "old" response, the reluctance to use to low category items significantly decreased and response patterns for high and low category items were more similar.

In both Experiment 1 and 2 (and many prior studies), the 'new' response did not affect participants earnings in any way and therefore served as a 'safe' option to avoid financial penalty. In the current paradigm where the category of the item conveys information about the amount of the reward or penalty for 'old' responses, participants could simply choose at the time of retrieval to make their response based on the reward structure of the task, rather than memory for the item, per se, but this strategy does not fit with the entire pattern of results. In Experiments 1 and 2, when confidence was low potentially because the memory trace was weak or ambiguous, participants used the 'guess new' and 'guess old' responses to the same extent for high and low reward items. This is contrary to what one would expect when the experimental reward-penalty structure makes it more financially beneficial to indicate 'old' even for high reward items with a weak memory trace. Interestingly, in Experiment 1, participants used the high confidence 'old' response more often for high compared to low reward items, but in Experiment 2 we did not find this effect, despite the fact that participants did the exact same encoding task, and in both cases did not learn about the penalty for false alarms until retrieval instructions. This finding provides some evidence that the amount of the penalty at retrieval influences both decision biases, but also perceptions of memory strength or memory quality, which should have been equivalent across these two experiments given the identical encoding conditions.

What remains unclear, is the psychological effect of the 'new' response having no impact on the financial outcome of the trial and its influence on participant responding. With the exception of one paper (Sun et al., 2018) we are not aware of any motivated recognition studies that have rewarded correct responses, and penalized error responses, regardless of target or lure status, to eliminate the 'new' response as a strategic way to avoid the financial penalty. We manipulate this aspect of the paradigm in Experiment 3.

4. Experiment 3

To specifically test whether participants used the 'new' response strategically to avoid the false alarm penalty, we made two significant changes to the paradigm in Experiment 3. First, correct and error responses, regardless of target/lure status were rewarded or penalized. This change required participants to rely on their memory during recognition, rather than making a strategic judgment at the time of retrieval based on information about the reward value inherent in the category of the stimulus. This made the old/new recognition decision more akin to prior studies that paired individual stimuli to a reward value at the time of encoding and therefore old/new decisions had to be made based on memory for the item (Adcock et al., 2006; (Bowen et al., 2020); Mather & Schoeke, 2011; Spaniol et al., 2014). Second, we asked participants to reflect on the strength of their memory both as a prospective judgment of learning at encoding, and a metamemory judgment at retrieval in the form of a third response option (in addition to old/new). This third option allowed participants to decline to respond (Brown et al., 2019). Declining to respond—in other words, the option to 'skip' the trial—guaranteed them a small reward.

We pre-registered our study ideas, hypotheses and analyses on the Open Science Framework (https://osf.io/p26qy/). We had several predictions: 1) judgments of learning at encoding will be higher for high reward category items compared to low-reward category items; 2) low-reward items would have weaker memory traces and would make up a higher proportion of trials participants chose to use the 'skip' option; 3) on trials initially given a 'skip' response, memory accuracy (hit rate minus false alarm rate) would be lower for low reward compared to high reward items; 4) hit rates would be higher for high reward category items compared to low reward on non-skip trials. There were two possibilities concerning the effects of the penalty for incorrect decisions. It is possible the results from Experiment 2 would replicate, because the penalty for incorrect decisions matched the reward for correct decisions; however, the inclusion of monetary rewards and punishments for any correct or incorrect response, regardless of target or lure status, could result in a different pattern.

4.1. Methods

4.1.1. Participants

Data collection for this project commenced at Boston College on June 20th 2019. A second data collection site—Southern Methodist University—was added on October 18th 2019.

The recruitment methods, exclusionary criteria, and payment were the same as Experiment 1 and 2. Participants were paid $12/h if tested at Boston College and $5/half hour if tested in Southern Methodist University (based on different IRB protocols). Participants additionally earned performance-based rewards and were paid in cash at the end of each session. Using G*Power, we calculated and pre-registered (DOI: 10.17605/OSF.IO/P26QY) a sample size estimate of $N = 41$ ($n = 18$ collected at Southern Methodist University) based on an effects size from a similar experiment focused on the effects of high and low reward and retention interval on hit rate (Spaniol et al., 2014; $\eta_p^2 = 0.13$) and $1\text{-}\beta = 0.95$. A total of 50 participants were tested, but four were excluded from analyses for a BDI score above our cutoff of 13, two for failing to participate in the second session, and three because of experimenter error. With the exception of the Digit Symbol, questionnaire data were collected online using REDCap (https://projectredcap.org/software/). Participant characteristics and scores on the questionnaires are reported in Table 1.

4.1.2. Paradigm

At encoding, participants viewed indoor and outdoor scenes and were told their memory for half the images would be tested that day during session 1 and the other half the following day during session 2. While viewing the images, they were asked to make a judgment of learning, indicating on a scale of 1 (sure forget) to 6 (sure remember), of how well they think they will remember the item on the subsequent memory test. Participants were informed during encoding instructions that images from one category were worth a high reward of $0.24, and the other category worth a low reward of $0.09, if correctly recognized on the memory test. The assignment of indoor and outdoor scenes to high and low reward category was counterbalanced across participants. During retrieval, participants were given more explicit instructions regarding the reward contingencies. They were given three response choices, 'old', 'new' or 'skip'. If 'old' or 'new' decision was correct, they would earn either $0.24 for the high reward category images, and $0.09 for low reward category images. However, if their 'old' or 'new' decision was incorrect, they would be penalized with a monetary loss of -$0.24 for the high reward category images, and a loss of -$0.09 for low reward category images. After their old/new decision, participants were prompted to make a confidence judgment of 1 (not confident) to 6 (totally confident), but were told this would not affect their earnings. If they were unsure about whether the image was old or new, they could choose the 'skip' option, which would result in a lower, but guaranteed reward of $0.08 for the high reward category images, or $0.03 for the low reward category images. If participants chose this 'skip' option, they were next prompted to make an old/new decision followed by a confidence judgment, but neither of these affected their financial outcome.

4.2. Results

In line with the two previous studies described above, we analyzed the data collapsed across confidence judgments.

4.2.1. Judgment of learning at encoding

An average judgment of learning rating was calculated for high ($M = 3.35$, $SE = 0.15$) and low ($M = 3.39$, $SE = 0.19$) category items. In contrast to our prediction, there was no significant difference, $t(40) = 0.14$, $p = .89$, $r = 0.022$.

4.2.2. Recognition performance for 'skip' trials

4.2.2.1. Proportion of 'skip' trials. The proportion of trials given the 'skip' response did not significantly differ for high ($M = 0.27$, $SE = 0.03$) and low ($M = 0.28$, $SE = 0.03$) reward category items, $t(40) = 0.43$, $p = .67$, $r = 0.068$.

4.2.2.2. Accuracy of 'skip' trials. Hit and false alarm rates were calculated for trials initially given a 'skip' response. This analysis includes only 33 participants because not all participants had 'skip' data in every condition. Further, the data were collapsed across retention interval to increase the number of trials included in the analysis. A paired samples *t*-test indicated a significant difference in corrected memory accuracy (hit rate minus false alarm rate), $t(32) = 2.01$, $p = .05$, $r = 0.334$, but in contrast to our predictions, accuracy was lower for high ($M = 0.09$, $SE = 0.04$) compared to low value ($M = 0.18$, $SE = 0.03$) category items. To be consistent with other analyses, memory sensitivity (d') was also calculated and revealed the same pattern as the corrected recognition, $t(32) = 2.176$, $p = .04$, $r = 0.359$, that sensitivity was higher for low reward items ($M = 0.59$, $SE = 0.10$) compared to high reward ($M = 0.24$, $SE = 0.11$).

4.2.3. Recognition performance

Excluding the trials given an initial 'skip' response, hit rates, false alarm rates, discriminability measure d', and response bias measure c, were calculated and are reported in Table 2. Inferential tests (i.e., repeated-measures ANOVA) of within-subject factors of reward (high vs. low), and retention interval (short vs. long) on each of these dependent variables are reported below.

4.2.3.1. Hit rate. A main effect of retention interval, $F(1, 40) = 9.96$, $p = .003$, $\omega_p^2 = 0.176$, indicated that hit rates were higher after a short ($M = 0.77$, $SE = 0.03$) compared to a long delay ($M = 0.69$, $SE = 0.03$). Neither the main effect of reward, $F(1, 40) = 0.11$, $p = .74$, $\omega_p^2 = -0.022$, nor the interaction were significant, $F(1, 40) = 0.002$, $p = .97$, $\omega_p^2 = -0.024$. When responses were restricted to high confidence only (excluding trials given a response of 3 or 4), the patterns remained the same.

4.2.3.2. False alarm rate. A main effect of retention interval, $F(1, 40) = 8.80$, $p = .005$, $\omega_p^2 = 0.003$, indicated that false alarm rates were higher at the long ($M = 0.26$, $SE = 0.03$) compared to the short delay ($M = 0.20$, $SE = 0.02$). Neither the main effect of reward, $F(1, 40) = 1.11$, $p = .30$, $\omega_p^2 = 0.003$, nor the interaction were significant, $F(1, 40) = 0.94$, $p = .34$, $\omega_p^2 = -0.005$. When responses were restricted to high confidence only, the patterns remained the same.

4.2.3.3. Discriminability. There was a main effect of retention interval on d', $F(1, 40) = 20.04$, $p < .001$, $\omega_p^2 = 0.312$, such that memory discriminability was higher at the short ($M = 1.84$, $SE = 0.13$) compared to the long delay ($M = 1.38$, $SE = 0.11$), but neither the main effect of reward, $F(1, 40) = 0.43$, $p = .51$, $\omega_p^2 = -0.0143$, nor the interaction were significant, $F(1, 40) = 0.97$, $p = .33$, $\omega_p^2 = -0.001$.

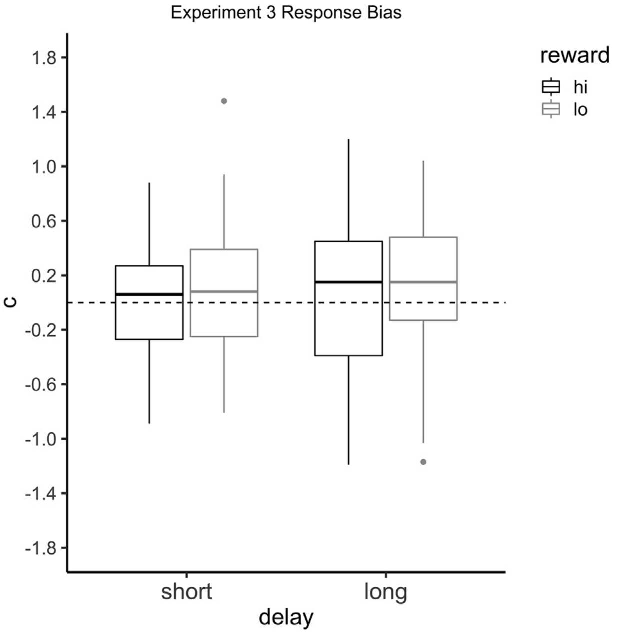


Fig. 4. Recognition data from experiment 3.
Note. Box plots of the response bias values (*c*) as a function of 4 task conditions. Hi = high reward; Lo = low reward; c = signal detection parameter criterion. In signal detection, values of *c* above zero reflect a “conservative” criterion indicating a bias for the “new” response, and values of *c* below zero are indicative of a “liberal” criterion indicating a bias toward the “old” response.

4.2.3.4. Response bias. There were no main effects of retention interval, $F(1, 40) = 0.78$, $p = .38$, $\omega_p^2 = -0.005$, or reward, $F(1, 40) = 0.24$, $p = .63$, $\omega_p^2 = -0.018$, and the interaction was also not significant, $F(1, 40) = 0.57$, $p = .46$, $\omega_p^2 = -0.010$. Refer to Fig. 4 for a graph depicting of the response bias values at each level of the independent variable. Follow-up one sample *t*-tests indicated that none of the four means entered into this interaction were significantly different from zero indicating no overall bias toward an old or new response, $t(40) \leq 1.30$, $p \geq .21$, $r \geq 0.201$, for any of the conditions.

To compare response bias values across all three experiments, we ran a 2 (Reward: high, low) x 2 (Retention Interval: short, long) x 3 (Experiment: 1, 2, 3) mixed-ANOVA, with reward and retention interval as within-subjects and experiment as a between-subjects factor. This analysis revealed a main effect of reward, $F(1, 105) = 8.41$, $p = .005$, $\omega_p^2 = 0.065$, such that values of *c* were less positive (i.e., more liberal) for high ($M = 0.20$, $SE = 0.04$) compared to low reward items ($M = 0.32$, $SE = 0.04$), a main effect of retention interval, $F(1, 105) = 14.39$, $p < .001$, $\omega_p^2 = 0.111$, such that values of *c* were less positive at the short ($M = 0.19$, $SE = 0.03$) compared to long ($M = 0.32$, $SE = 0.04$) delay. There was also a significant main effect of experiment, $F(2, 105) = 7.56$, $p = .001$, $\omega_p^2 = 0.108$. Follow-up independent samples *t*-tests indicated that values were significantly more positive for Experiment 1 ($M = 0.39$, $SE = 0.07$) and Experiment 2 ($M = 0.31$, $SE = 0.06$) compared to Experiment 3 ($M = 0.08$, $SE = 0.06$), $t(69) \geq 2.76$, $p \leq .007$, $\eta^2 = 0.16$, but means in Experiments 1 and 2 did not differ from each other, $t(65) = 1.03$, $p = .31$, $\eta^2 = 0.02$. Critically, a one-sample *t*-test indicated that the means for Experiment 1, $t(65) = 6.45$, $p < .001$, $r = 0.777$, and Experiment 2, $t(36) = 5.66$, $p < .001$, $r = 0.686$ were significantly greater than zero. The mean for Experiment 3 did not differ from zero, $t(40) = 1.22$, $p = .23$, $r = 0.189$. This indicates that the overall conservative response bias in this paradigm was reduced from Experiment 1 to 2 after the experimental changes to the amount of the false alarm penalty, but this was not a statistically different reduction. In Experiment 3 when all responses were rewarded or penalized, response bias was eliminated. None of the interactions from the ANOVA were significant, $F(1, 105) \leq 2.20$, $p \geq .12$, $\omega_p^2 \leq 0.022$. See Table 2 for the means of all the conditions and each experiment.

4.3. Discussion

The goal of this experiment was to better understand participant strategy during the motivated recognition tasks, particularly regarding the use of the ‘new’ response. In Experiment 1 and 2, and prior work detailed in the general introduction (e.g., Adcock et al., 2006; (Bowen et al., 2020); Spaniol et al., 2014) the ‘new’ response did not impact the financial outcome of the trial, thus serving as a safe option to avoid a potential penalty for a false alarm. Results from Experiment 1 and 2 indicated that the amount of the false alarm penalty influenced participant responding, but it was unclear whether the ‘new’ response was leading participants to rely less on their memory and make a recognition decision based on the particular reward-penalty and response structure of the experimental design. In the current experiment, the amount of false alarm penalty was manipulated to match the amount of the reward to high and low reward category items as it was in Experiment 2, but all correct responses (both hits and correct rejections) were rewarded, and all incorrect responses (both false alarms and misses) were penalized. Instead of using the ‘new’ response to eliminate the possibility of a financial penalty, we opted for participants to rely on the strength of their memory (i.e., meta-memory) and use ‘skip’ trials for a small, but guaranteed reward when they were unsure about the old/new decision and did not want to risk the penalty for an incorrect response.

Our first hypothesis was that at encoding, participants would judge their ability to remember the high reward category items better than low reward category items, but this was not the case. There were no significant differences in average judgments of learning for the high compared to low reward category items, suggesting that if low reward items are encoded less strongly than high reward items, this is not perceptible or at least reported by participants. Second, related to this previous hypothesis, we predicted that participants would choose the ‘skip’ option more for low reward items because they would have a weaker memory trace, but we did not find support for this either, and in contrast to our third prediction, corrected recognition and memory sensitivity was higher for low reward items compared to high reward for items initially given the ‘skip’ response. Finally, we examined the hit rate, false alarm rate, memory sensitivity and response bias for items not given the ‘skip’ response. Contrary to our hypotheses, we did not find that participants memory sensitivity was better for the high reward category items, but we did replicate our findings from Experiment 2 of no differences in response bias for high versus low, when the amount of the false alarm penalty matched the potential reward. The pattern did not change when we examined just high confidence trials and excluded those given a subsequent rating of 3 or 4.

Despite no evidence that participants had better memory for high compared to low reward items generally, when looking more closely at the trials initially given a ‘skip’ response, subsequent old/new responses were more accurate (hit rate minus false alarm rate) for the low reward items. While we had not hypothesized this outcome, it can be considered broadly consistent with the reward-based criterion shift we reported in Experiment 1 and the hypothesis that the high reward category elicits mnemonic memory signals that are too strong to suppress. Even though the proportion of trials that participants used the ‘skip’ option did not differ for high compared to low reward trials, the strength of the memory for these items was different when they used this option. For high reward items, the quality of the memory was subjectively weak and they were subsequently less accurate than low reward items to which they were subsequently more accurate. Although more nuanced than hypothesized, it is possible that if the underlying mnemonic signals are less strong for low reward items, this leads to a conservative criterion to avoid a penalty, even though participants are ultimately more accurate for those stimuli when they choose to ‘skip’ the trial. We had hypothesized stronger evidence of the criterion shift (e.g., in response bias measures, or differences in the proportion of trials given the skip option), but these findings provide additional evidence for our conclusions from Experiments 1 and 2, that various aspects of the experimental design in motivated recognition studies influence high and low reward items differently, both in the strength and subjective aspects of the memory, and may lead to differential decisional biases thought to be separate from memory.

5. General discussion

In three experiments, we systematically manipulated different aspects of a common reward and memory paradigm to investigate how reward motivation modulates the cognitive mechanisms that underlie memory processes, specifically discriminability and response bias. In the first experiment we replicated prior findings (Adcock et al., 2006; (Bowen et al., 2020) Bowen & Kensinger, 2017;Spaniol et al., 2014,), higher hit rates for high compared to low reward items but high reward was also associated with higher false alarm rates, and a more liberal response bias compared to the low reward category. Participants showed a stronger bias toward the "old" response for high reward items not better memory discriminability suggesting that reward effects on hit rate are not necessarily driven by memory processes, such as a stronger memory trace, but by decisional biases, in a paradigm where both may be operating. Reward effects on response bias were reduced in Experiment 2, however, when the amount of the penalty for incorrect responding to new items was equivalent to the amount of the reward for correct responses to old items. Finally, in Experiment 3, rewarding and penalizing participant responses, regardless of target or lure status, eliminated response bias completely, and provided additional support for the idea that reward influences subjective memory judgments—there were no differences in the proportion of skip trials for low and high reward categories items, but participants were ultimately more accurate for low reward trials they chose to skip compared to high reward. Taken together, the results indicate that reward may not necessarily lead to better memory discriminability, that participants do not always explicitly encode the high reward information differently in this type of paradigm, but that reward can influence decisional biases at the time of retrieval depending on the reward-related experimental conditions.

5.1. Novelty of the current paradigm

The novel experimental paradigms utilized in the current set of studies provided the ability to ask different research questions that have rarely been explored in the reward-motivated memory literature. One of these questions was whether reward influences memory discriminability and/or response bias. Prior work (e.g., Adcock et al., 2006; (Bowen et al., 2020); Bowen & Kensinger, 2017; Mather & Schoeke, 2011; Shigemune et al., 2010; Wittmann et al., 2005) has been limited to probing reward effects on hit rates only, because reward value has been randomly assigned to each individual stimulus and as a result, only a single false alarm rate could be calculated. The exception to this is a study probing cued-recall using associative pairs of stimuli where a corrected recognition analysis revealed greater memory for high compared to low reward pairs (Wolosin et al., 2012). In the current studies, assigning reward value to entire categories of items allowed us to calculate a separate hit rate and false alarm rate at each level of the independent variable, which is necessary for an accurate estimate of discriminability and response bias. Memory discriminability in signal detection terms refers to the ability to discriminate signal from noise, or in the case of a recognition test, old from new items, whereas response bias refers to the preference to choose one response over another for a particular class of items. Like the findings from Han et al. (2010), consistently across the three experiments, we found no evidence that high reward led to better memory discriminability. In other words, high reward did not lead one to better distinguish between previously encountered scenes compared to novel scenes, but in Experiment 1, high reward category items did elicit a more liberal response bias as participants were more biased toward the 'old' response, compared to low reward category items. A significant consideration in this set of studies was to not only manipulate the amount of the reward for correct responses, but to also test how the amount of the penalty for an incorrect decision influences responding. In Experiment 2, when penalties for committing a false alarm aligned with the reward value of category, the difference in response bias between high and low category items reported in Experiment 1 was significantly reduced. To understand participant strategy when the category of the image signaled whether it was high or low reward, in Experiment 3 we rewarded correct responses, and penalized incorrect responses, regardless of target or distractor status. Unlike the findings from Experiments 1 and 2, the results from Experiment 3 indicated no difference between hit and false alarm rates for the reward categories and the impact of reward category on response bias was eliminated. Common methods used in this literature can give rise to reward effects on bias (Experiment 1), that can be reduced (Experiment 2) or eliminated (Experiment 3) if the payoff matrix is adjusted appropriately and monetary outcomes are assigned to each response type (i.e., hit, miss, correct rejection, false alarm). The results from all experiments additionally demonstrate that the amount of the false alarm penalty can change participant responding at the time of recognition, despite encoding instructions devoid of information about penalties for incorrect responses at retrieval. Although this is one of the first studies to calculate and analyze these signal detection indices with respect to reward-motivated memory (cf. Han et al., 2010), the question of whether affective processes can modulate these other memory measures has been posed in the related field of emotional-memory (Bowen, Spaniol, Patel, & Voss, 2016; Dougal & Rotello, 2007; Grider & Malmberg, 2008; Kapucu, Rotello, Ready, & Seidl, 2008; Thapar & Rouder, 2009; Windmann & Kutas, 2001). It seems that when the value of the false alarm penalty falls between the two reward values, this influences judgments about memory quality, as well as response bias patterns, and it does so differently for high and low reward category items. When the penalty matches the reward value, this leads to fewer differences in perceived memory strength and response bias for high compared to low reward category items and when all responses are assigned a monetary value, this can eliminate response bias.

A second benefit of assigning reward at the level of the category is that it taps into a different type of memory that has been largely ignored in this field. Although in real-world scenarios we may attach value to single members of a category and may easily recall them later, it may not be *necessary* to experience and remember the motivational relevance of each individual stimulus we encounter. Our memory systems can accumulate information across many experiences to generate a general preference (i.e., reinforcement learning), and extend learned stimulus-reward associations to other unknown stimuli of the same category (Dunsmoor et al., 2015; Patil et al., 2017). We are able to extend our limited experience and make inferences about related information when encountering new stimuli (Dunsmoor et al., 2015; Jang et al., 2019; Patil et al., 2017; Zeithamova, Dominick, & Preston, 2012). Specific memories for individual items within a category may exist that are higher in motivational salience than the rest of the category, but when encountering a new stimulus, one likely reflects on the category of that stimulus as a whole, rather than experience with individual items. For example, while we can likely recall specific books that we particularly enjoyed or disliked, when choosing a new book to read, we probably rely on the value attached to the broader category –such as genre (mystery vs. autobiography) – generated by a combination of many past experiences, rather than on memories for specific books we have read.

In the current studies, we only examined two levels of reward for correct responses to target stimuli, and additionally in Experiment 2 and 3, two levels of penalty for incorrect responses to lure stimuli.

Future research should investigate different levels and combinations of reward and penalty to elucidate the nuances of these contingencies. Further, in all three experiments, participants only learned about penalties for incorrect responses after encoding at the time of retrieval. An interesting next step in this line of work could focus on how penalties affect memory processes more specifically by including this information during encoding instructions as this may lead participants to encode details of each stimulus to a greater degree.

5.2. Challenges of the current paradigm

The paradigm employed in the current set of studies offered many opportunities to broaden our understanding of motivation-memory interaction, but it does deviate from traditional paradigms discussed in the introduction (e.g., Adcock et al., 2006; Bowen et al., 2020; Bowen & Kensinger, 2017; Castel, 2007; Cohen et al., 2016; Geddes et al., 2018; Mather & Schoeke, 2011; Spaniol et al., 2014) thereby making direct comparisons between the published literature and the current findings a challenge.

First, in prior studies, each trial began with a high or low reward value cue that signaled how much the subsequent image was worth on the memory test whereas in the current studies participants were informed only once during encoding instructions that one of the categories was worth a high reward and the other a low reward. Although we were able to replicate prior findings of higher hit rates for high reward compared to low reward stimuli, it is possible that the reason we did not find any evidence of reward effects on memory discriminability, but strong effects on decisional processes at retrieval, is because the reward cue at the beginning of each encoding trial is necessary to create a strong state of reward anticipation. Indeed, neuroimaging has revealed that there is greater activation in the reward network and other brain regions during the presentation of high compared to low value reward cues (Adcock et al., 2006; Geddes et al., 2018; Knutson et al., 2000; Spaniol, Bowen, Wegier, & Grady, 2015; Wolosin et al., 2012) and that this activation predicts subsequent memory performance (Adcock et al., 2006). As mentioned, in these paradigms with random assignment of rewards to individual items, the only measure of memory performance is hit rate, so there is no way to determine whether reward cues influence memory discriminability as a measure of memory performance. Wolosin et al. (2012) were able to examine hit and false alarm rates at each level of reward utilizing an associative memory task and cued-recall for the stimulus pairs. This is a different type of design and a different type of memory task than used here. A challenge for future research is to create a paradigm that utilizes high and low reward cues at the beginning of each trial, while also having individual lure stimuli that vary by the levels of the reward value.

A second challenge is prior studies with random assignment of reward value to individual stimuli had no inherent mapping of reward to stimulus category. In other words, at retrieval there was nothing about the stimulus itself that could cue participants to its reward value, so one must rely on memory signals in order to make a recognition decision. In the current set of studies, as long as participants remembered which category was high and which category was low reward, one could rely on the properties of the stimulus to make a decision about whether it was worth the risk to say old or new, without relying on memory at all. Perhaps this is an explanation for why we found no evidence of reward effects on memory discriminability, but reliable effects of reward on response bias. Results from all three experiments suggest that processes at the time of retrieval were playing a large role in our results, and when penalties for incorrect responses were manipulated in Experiment 2 and 3, the reward effects on response bias were reduced or eliminated. Stronger reward anticipation signals from the presentation of reward cues at encoding may modulate memory processes, but in situations where the category itself can be informative of reward information, perhaps this has a stronger influence on decisional biases at retrieval.

Experiment 3 was included to elucidate participant strategy underlying the conservative response criterion observed in Experiment 1 and 2, and to test the consequences of removing the ‘new’ response as a safe option that did not affect participant earnings, forcing participants to rely more on their memory. Overall, there were many null findings for the measures of memory. Null results should be interpreted with caution, but we did calculate an a priori power analysis for Experiment 3 to detect an effect in memory discriminability based on effect sizes from related work, but did not find any evidence that high and low reward information was affecting any of the memory measures. There were potentially too many changes to the paradigm to effectively compare the results from Experiment 3 to Experiments 1 and 2. For example, it may have been too cognitively taxing to have the ‘skip’ option during retrieval and an interesting next step might be to remove the skip option altogether, examine memory with only an old/new response, but keep the structure of rewarding correct and penalizing incorrect responses, regardless of target/distractor status. It is additionally possible that the judgment of learning encoding task was subjectively rewarding and superceded the task-based reward anticipation at encoding, or that the task was too demanding to properly encode the stimuli, compared to the indoor/outdoor judgment used in Experiments 1 and 2, but it is not possible to tease this apart in the current data.

Despite the possibility that the task was too difficult, overall memory discriminability values were well above chance; however, the current design may have been masking true reward effects. While criterion shifts are statistically independent of discriminability, they may be correlated empirically across individuals. A study that better orthogonalizes high and low reward for memory, and high and low decision values, and that has higher statistical power to detect individual differences, could examine whether stronger criterion shifts are associated with reduced discriminability effects within individuals. If they are negatively correlated, decision effects may be masking memory effects.

5.3. Conclusion

An adaptive memory system should prioritize motivationally relevant information, and allow that knowledge to be generalized from individual items to whole categories, but retrieval is a reconstructive process. This set of studies suggests that retrieval of motivationally relevant information is susceptible to decisional biases thought to be independent of memory processes. In particular, across three experiments, reward did not lead to better memory discriminability, but instead influenced decision biases that were modulated by the reward structure of the retrieval task. How reward influences processes that occur after encoding, as well as how the reward structure itself influences recognition memory have largely been ignored in the literature (see Dunsmoor et al., 2015; Mather & Schoeke, 2011; Patil et al., 2017 for exceptions), but the present study reveals the importance of considering these factors when designing experimental paradigms aimed at understanding motivation-cognition interactions.

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