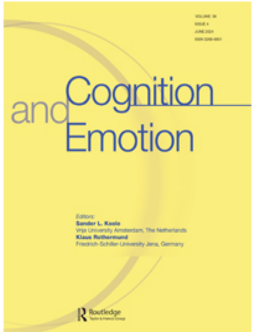

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Reward enhancement of item-location associative memory spreads to similar items within a category

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Reward enhancement of item-location associative memory spreads to similar items within a category

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ABSTRACT
The experience of a reward appears to enhance memory for recent prior events, adaptively making that information more available to guide future decision-making. Here, we tested whether reward enhances memory for associative item-location information and also whether the effect of reward spreads to other categorically-related but unrewarded items. Participants earned either points (Experiment 1) or money (Experiment 2) through a time-estimation reward task, during which stimuli-location pairings around a 2D-ring were shown followed by either high-value or low-value rewards. All stimuli were then tested for location memory or recognition (yes/no), immediately and after a 24-hour delay. Across both experiments (combined analysis), there was a robust improvement in location memory following high-value rewards, even though evidence supporting this effect was reliable in Experiment 2 but not in Experiment 1. The memory-enhancing effect of reward was observed on both the immediate and delayed location-memory tests. Reward-enhanced memory for both directly rewarded stimuli and categorically related stimuli that were not directly rewarded. No reliable effect of reward value on yes/no recognition-memory performance was observed in either experiment. We hypothesise that reward enhances the consolidation of recent experience and conceptually related memories to make these more available for future decisions.

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Reward; memory; item-location; retroactive reward influence; categorically related

Associating an item with a rewarding experience has been reported to improve memory for that item across a wide range of studies (see Miendlarzewska et al., 2016 for a review). This effect is hypothesised to reflect a process of memories being tagged as important after association with reward to enhance the later accessibility of that information for future decision-making. Recent studies in the cognitive neuroscience of memory have shown interactions between the dopaminergic reward system and the medial temporal lobe (MTL) memory system that enhance memory consolidation (Lisman & Grace, 2005; Shohamy & Adcock, 2010). This process can be seen as a method of invoking arousal and emotion tied to a positive outcome, similar to the well-known effects of negative emotional modulation enhancing memory via amygdala modulation of the MTL (McGaugh, 2018) that also tags memories as important based on emotional experience. Both of these phenomena can be viewed as extrinsic events tagging memories as particularly important for future actions, making information about past important events more available for subsequent actions towards reward or away from punishment (Shohamy & Adcock, 2010).

Murayama and Kitagami (2014) showed that a rewarding task immediately following the study of a visual image led to better recognition memory for that stimulus. This supports the hypothesis that the dopaminergic response to the reward enhanced

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consolidation of the memory and importantly controls for motivation or attentional effects of reward because the reward condition was not known at the time of study. Only after viewing the image were participants aware that there would be either a rewarding event or control task but receiving the subsequent reward enhanced memory for the previously seen item. The neurophysiology of this effect is thought to depend on dopaminergic activity from the ventral tegmental area (VTA) on newly-formed memory representations within the MTL. Several studies have reported human neuroimaging findings suggesting a relationship between dopaminergic activity from the VTA and neural activity in the MTL related to memory. Adcock et al. (2006) used functional magnetic resonance (fMRI) to measure the relationship between the VTA and hippocampal activity during a reward-memory paradigm. Reward enhanced memory and corresponded to a link between increased activity in the VTA and the hippocampus for high-reward items. Wittmann et al. (2005) and Wolosin et al. (2012) similarly found enhanced memory associated with reward and increased connectivity between reward regions (VTA/substantia nigra) and the medial temporal lobe.

In addition to reward-enhancing effects on memory measured through recognition memory, Gruber et al. (2016) and Braun et al. (2018) found improvements in associative memory tests that involved item context. Gruber et al. (2016) found that memory for item context improved for highly rewarded items. Braun et al. (2018) found improved spatial location memory in a combined analysis of several experiments for tests given at a 24-hour delay. Both of these memory tests required binding of the item to elements of the encoding context, such as spatial location, which have been hypothesised to particularly depend on the MTL memory system (Eichenbaum et al., 2007). Enhancing memory for these more complex representations suggests that the influence of reward may work through reactivation and strengthening mechanism that enhances related or associated items. Supporting this idea, Patil et al. (2017) found that when the reward was associated with a category of items (tools or animals), recognition memory was enhanced for previously seen but unrewarded members of the rewarded category as well. This surprising result suggests that the influence of dopamine on the MTL affects not just the consolidation of memories that immediately precede the rewarding event, but spreads to related memories and enhances the consolidation of those traces as well. We might hypothesise that the adaptive role of enhancing memories associated with reward would generalise to related items for future planning or decision-making purposes.

The memory-enhancing influence of reward has been found most consistently on recognition tests at a delay after initial study, usually 24 h after the memory encoding and reward events (Braun et al., 2018; Murayama & Kitagami, 2014; Patil et al., 2017). The impact at a delay suggests that the reward effect triggers an enhanced consolidation process, strengthening memory over time, rather than impacting the initial storage of memory as we would expect increased attention or motivation to produce. In these paradigms, a delayed test more sensitively detects different memory strengths between the rewarded and unrewarded memory. Gruber et al. (2016) reported an immediate effect of reward on a memory test that assessed item-context associations, however. The detectable immediate effect in the Gruber et al. (2016) study may have arisen from a greater dependence of associative memory on MTL systems making the reward effect larger immediately or simply that this generally more difficult type of memory test provides greater statistical sensitivity to the enhancement of post-study reward.

Here, we examined the effect of reward on item-location memory and yes/no recognition for both immediate and 24-hour delayed tests across two experiments. To induce a rewarding experience, we employed a time estimation task comparable to that used in the study by Murayama and Kitagami (2014). In Experiment 1, participants earned points for performance, with motivation reinforced by a simulation that the participant was climbing a competitive high-score list. In Experiment 2, the same task was rewarded with a small, direct monetary bonus. In both experiments, study stimuli were drawn from categories of items and high or low reward was associated consistently by category. Only some of the studied items in each category were directly rewarded, allowing us to test whether the experience of reward led to memory enhancement for related items (an indirect reward effect). If our hypothesis is correct, then we would expect to find both increased associative and simple recognition memory for items linked to high reward compared to those linked to low reward. Additionally, we hypothesised that reward enhancement for associative memory may be detectable immediately as well as after a 24-hour delay. Lastly, we expected that the enhancement from greater reward would spread to enhance memory for related items in the same item category even when these were not directly rewarded.

Experiment 1

Participants

Participants were 61 adult volunteers recruited through Amazon's Mechanical Turk (MTurk) online marketplace who completed the experiment online and received $15 in compensation for completing both sessions. Since we did not have an a priori estimate of the size of the effect of reward on our novel spatial memory test, the sample size was chosen to be similar to that used by Braun et al. (2018). The study methods and procedures were approved by the Northwestern University IRB office (protocol #STU00213705).

Participants were recruited exclusively through Amazon's Mechanical Turk (MTurk) online marketplace and traditional demographic information (gender, age, etc.) is not reported as it was not collected from participants in order to maximise their privacy. Studies assessing the demographic characteristics of participants recruited through MTurk reported an average age of 36 years old (Paolacci et al., 2010), a slight majority of respondents were female (51%), with an averageannual reported income of approximately $47,000 (Difallah et al., 2018). Paolacci et al. (2010) noted that the characteristics of MTurk workers were more similar to the general U.S. population than participants recruited from traditional university subject pools. More recently, Moss et al. (2020), reported finding no changes to MTurk participant demographics due to the COVID-19 pandemic. For participation in this study, we selected only MTurk Masters, which is defined as workers who "demonstrate excellence through a wide range of tasks" and maintain a low study rejection rate in order to avoid low-quality respondents (or artificial response "bots"), who are less likely to carefully comply with study requirements and task instructions.

Materials

A total of 264 object images were used from the Olivalab open-access image database (Konkle et al., 2010; stimuli retrieved from http://olivalab.mit.edu/MM/objectCategories.html, examples of stimuli shown in Figure 1; entire stimuli set can be seen at https://osf.io/zv4ah/). These images were organised as 22 lists, with each list consisting of 12 visually similar items from the same category. The list categories used were: balls, benches, birds, bowls, butterflies, cats, crowns, dogs, dolls, gloves, hats, helmets, mugs, phones, rings, robots, sippy cups, socks, tape dispensers, teddy bears, toy trains, and trash cans. Each participant saw item images from a randomly selected set of 10 of the lists, of which five were randomly assigned to be high-reward and five were randomly assigned to be low-reward. Within a list, eight of the 12 items were used for study and four were used as foils on the recognition memory test.

Procedure

The presentation of stimuli, response collection, and response feedback were implemented online via web browsers (Javascript and HTML5). Prior to accepting the task on the Amazon Mechanical Turk marketplace and providing their informed consent, participants were given an overview of the study and told that they would need to complete two sessions over two days for credit. Participants were told that their goal was to earn as many points as possible to get to the top position on a participant leaderboard (simulated). Additionally, to ensure compliance with the reward task, participants were informed that they would need to earn at least 60% of the possible points (36,744 out of a total of 61,240 points) to receive credit for the study. The simulated leaderboard tracked their progress and showed them their position on the leaderboard via an avatar image selected by participants at the start of the experiment. To motivate their success, their position consistently improved if they continued to meet the reward task requirement. The leaderboard consisted of 10 stimulated positions, with the top position equal to approximately 60% of the total number of possible points that could be earned in the experiment. Additionally, each position below that was incremented by approximately 60% of the total number of points that a participant could earn in one trial. Therefore, it was simulated that participants would achieve consistent improvement in their leaderboard position throughout the study. Participants were told that each position on the leaderboard was a prior participant's total points earned. Participants were debriefed on the leaderboard manipulation at the end of the study.

After completing a demonstration of the study and reward phases of the experiment, participants began the main part of the experiment. The main part of

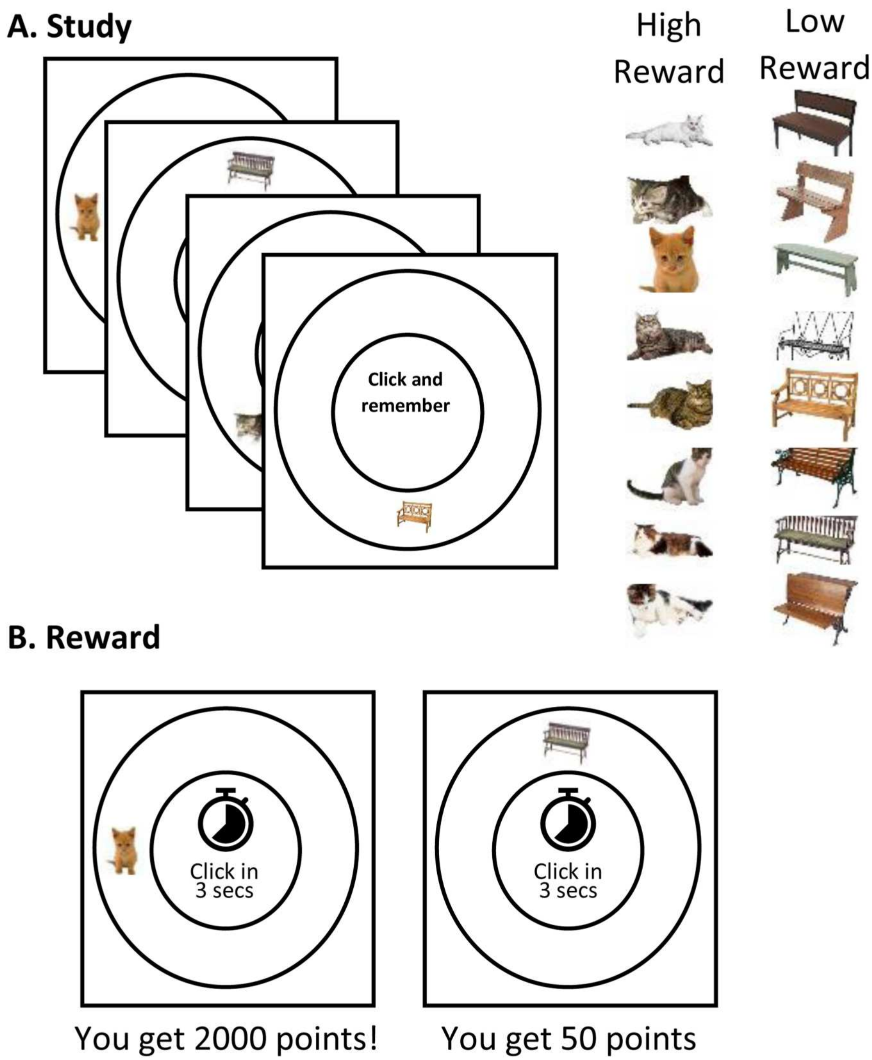

Figure 1. Study and reward phases of the experiment protocol. In the study phase, participants saw two intermixed lists of eight related images (16 total) presented at random spatial locations to remember. Then participants completed a reward phase that asked them to perform a time-estimation task in which half the stimuli from the preceding study phase were shown (8 total, 4 high reward and 4 low reward). In the shown example, four of the cats would be reshown in the study location during the time-estimation task and an accurate response received a high-reward level. The bench images were the low-reward stimuli that were associated with a lower reward for accurate time-estimation responses. Five rounds of list pairs were shown (10 lists, 80 total object-location pairings) before the subsequent test phase.

the experiment started with the study phase, in which participants completed five rounds of stimulus presentation in which they attempted to learn the locations of 16 stimuli (80 total). For each round, each image was displayed in one of 16 possible positions around a circular ring (see Figure 1). The study phase was self-paced so each image could be seen for as long as participants preferred but a minimum display time of 3 s for each image-location association was implemented to prevent participants from clicking through without seeing them. In each round, images came from two different lists (8 images from each list, each associated with a unique location on the ring) in a randomly intermixed order. Participants acknowledged seeing the location of each image by clicking on its location, earning 10 points per image.

After seeing the 16 images for each study cycle, participants entered the reward phase, during which they completed a time-estimation reward task for eight of the images seen during the study phase. For each image, the image was shown in its studied location and the participants were instructed to make a mouse-click response exactly three seconds after the appearance of a centrally presented cue, the word "Start". If their response was within 500 ms (2500–3500 ms response time), then they earned points towards their leaderboard position. One of the image categories (half of the images) was assigned to a low-reward condition for which each accurate response earned 50 points. The other category was assigned to a high-reward condition for which each response earned between 750 and 2000 points (750, 1000, 1250, and 2000), a much more substantial reward than was available in any other part of the procedure. During this reward phase, each image was seen again for a minimum of two seconds up to the response cut-off time of 7 s. After the response cutoff, participants were shown verbal feedback on the accuracy of their time-estimation mouse click or non-response (positive feedback: "Superb!", "Well Done!" etc. negative feedback: "Too slow" or "Too fast"; all feedback was shown alongside the text "You (could have) earned (item value) points!"). During this feedback time of 2 s, the image in the studied location also stayed on screen. Therefore, depending on the participant's response time, the minimal amount of time each image was shown again during the reward phase was 4 s, ranging up to a maximum duration of 9 s.

The study and reward phase were then repeated for each pair of lists to help strengthen participants' memory for the image locations. Afterwards, a new set of 16 stimuli from two different image lists were presented. Thus, a total of 10 study/reward rounds occurred: five distinct stimulus sets, each composed of high-reward and low-reward image lists, with each set presented twice. At the end of the third study list and the end of the repetition of the fourth study list, participants were informed if they were accumulating enough points to meet the performance requirements for inclusion in the study (and compensation).

After completing the study and reward phases of the experiment, participants completed both the location and recognition tasks, in that order, for the studied stimuli (see Figure 2). Half of the studied images were shown during the location test and half were shown in an image-recognition test. For the location test, each image was shown in two locations around the ring, one of which matched the study position, while the second (foil) location was randomly selected from among all locations that were at least 3 positions (of 16 possible, minimum of 67.5°) away from the study position. Participants were instructed to click on the image that was in the original studied location. For the recognition test, the images were shown in the centre of the screen with a 4-point response scale reflecting their confidence for whether they thought they had seen the image at all during the study phase (Definitely No, Maybe No, Maybe Yes, and Definitely Yes). Half of the images were from the study phase and half were images from the same image categories but had not been seen previously. For both tests, participants were informed that they would earn 10 points for making each response, but if the response was correct, they would earn an additional 10 points. Feedback for points earned was immediately provided after test responses, and on the location memory test, the correct location of each item was also immediately shown. We provided participants with feedback because preliminary data had shown that participants' memory scores after the 24-hour delay were close to the floor. The experimental session ended after completing both memory tests. Participants then returned for an additional memory test 24 h (± 6 h) later. The same location and recognition tests were given in the second session, although the order of stimulus presentation, as well as foil locations, was re-randomised.

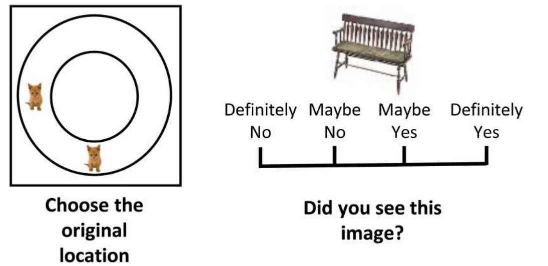

Figure 2. Test phase. First, 40 of the studied images (half) were shown in the circular array together with another copy of the image at an inaccurate (foil) location. Participants indicated where they thought the image had been shown originally in the study phase. Then, participants were given a yes/no recognition memory test using a 4-point scale to indicate confidence for the remaining 40 studied stimuli. The tests were given immediately after the completion of all the study and reward list presentations and then again after a 24-hour delay.

Thus, for each of the 10 image lists, 4 rewarded images were seen in the study phase and the reward phase and 4 unrewarded images that were seen during the study phase but not the reward phase (see Figure 1). On the location test, two rewarded and two unrewarded images were tested from each list, and similarly, during the recognition test, two-rewarded and two-unrewarded old images from each list were presented along with four previously unseen foils. Item recognition confidence ratings, based on participants' four-point confidence scale responses, were also collected.

Results

All analyses were conducted in R, version 4.0.2. Of the 61 participants, nine individuals opted out of the experiment prior to or after starting the demonstration trial and did not continue to the main experiment. An additional four participants did not return for the second test session and were excluded. The remaining participants completed the second session an average of 22.8 (SD = 2.0) hours later (range 18.29–27.5). One additional participant was excluded for mis-entering their worker identification number, leading to receiving the first session twice. Two others were excluded because they did not earn the minimum amount of reward (15.7% or 9,650 points and 51.3% or 31,430 points of total reward earned respectively) stipulated in the instructions for meeting the inclusion criteria. The final number of participants included in the data analyses was 45.

Reward earned

The average number of points earned for all phases was 52,314 (85.4% of the possible perfect score, 61,240 points) (SD = 5,676 points, 9.3%). Participants were slightly better in accuracy on the time estimation task, $t(44) = 2.03$, $p = .049$, Cohen's $d = 0.16$, $BF = 1.05$, for the high-reward condition 84.6% (SE = 1.5%) compared to the low-reward condition 82.9% (SE = 1.6%).

Location memory

Participants' performance on the item-location memory test was reliably better than chance overall ($M = 64.6\%$, SE = 2.2%, chance = 50%), $t(44) = 6.50$, $p < .001$. Accuracy on the location test was not affected by the distance between the target and foil location ($M = 65.0\%$ correct SE = 2.6% for the closest two locations versus $M = 64.3\%$, SE = 2.4% for the furthest, $t < 1.0$). Across reward conditions and delay, differences in location memory performance were analysed as a $2 \times 2 \times 2$ repeated-measures ANOVA with factors for reward value (High versus Low), inclusion in the reward phase (Direct versus Indirect), and test time (Immediate versus 24-hour delay). Bayes factors were estimated for all main effects. As expected, performance was better on the immediate memory test given at the end of the study session, 66.7% correct (SE = 2.4%), compared with the 24-hour delayed test with 62.5% correct (SE = 2.3%), $F(1,44) = 8.59$, $p = .005$, $\eta p^2 = 0.16$, $BF = 4.96$. Location memory for the High-reward category stimuli was an average of 66.2% correct (SE = 2.2%) compared with 62.9% (SE = 2.6%) for the Low-reward category, in the predicted direction, but not at a statistically reliable level, $F(1,44) = 3.24$, $p = .079$, $\eta p^2 = 0.07$, $BF = 1.20$ (see Figure 3A). Whether the reward was directly or indirectly associated with the study item did not affect location memory ($M = 64.3\%$ correct, SE = 2.4% for Direct versus $M = 64.8\%$, SE = 2.3% for Indirect), $F(1,44) = 0.12$, $p = .731$, $\eta p^2 < 0.01$, $BF = 0.12$. There was a reliable interaction of test time and direct/indirect reward, $F(1,44) = 7.27$, $p < .009$, $\eta p^2 = 0.14$, reflecting a greater decrease in memory after the test delay for items directly rewarded (regardless of reward value) than for items not directly rewarded. No other interactions were reliable.

Recognition memory

Recognition memory performance was scored as corrected recognition, the hit rate (correctly choosing definitely old or maybe old for previously seen stimuli) minus false alarm rate (choosing definitely old or maybe old for novel stimuli). Average corrected recognition ($M = 32.6\%$, SE = 4.2%) was reliably higher than chance (0%) across all conditions combined, $t(44) = 7.79$, $p < .001$. Corrected recognition was analysed via the same $2 \times 2 \times 2$ repeated-measures ANOVA factors as for location memory above. Bayes factors were included with all main effects. Memory performance was better for the immediate test, 41.2% (SE = 4.4%) compared with 24.1% (SE = 4.2%) for the 24-hour delayed test, $F(1,44) = 72.08$, $p < .001$, $\eta p^2 = 0.62$, $BF > 100$. Recognition was slightly better for items directly rewarded, 34.6% (SE = 4.3%), than for items not directly rewarded, 30.7% (SE = 4.3%), $F(1,44) = 4.12$, $p = .049$, $\eta p^2 = 0.09$, $BF = 0.64$. However, memory performance was not better for items associated with high-reward value, 31.8% (SE = 4.2%), than for items associated with low-reward value, 33.5% (SE = 4.4%), $F(1,44) < 1$, $\eta p^2 = 0.01$, $BF = 0.17$. No interactions among the main effects were reliable (see Figure 3B).

A parallel analysis scoring recognition memory as average confidence ratings (0–3; higher is more confident that the item was seen previously) for just the old items showed that memory confidence was

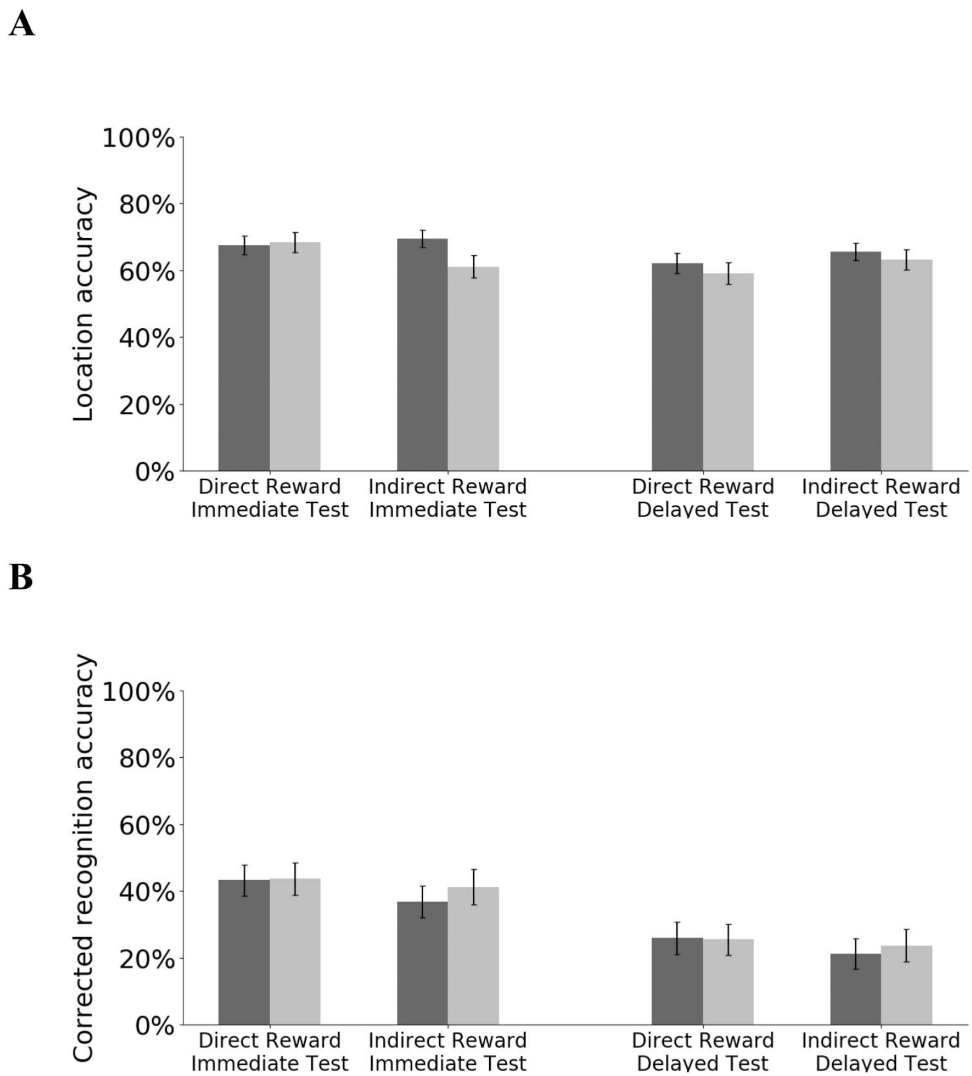

Figure 3. Experiment 1 memory test performance. Reward value indicates the amount of reward associated with an item. Direct items were explicitly associated with reward during that phase while indirect items were from the same reward category but were not presented during the reward phase. (A) Item-location memory (2AFC) was above chance and better on the immediate test than the 24-hour delayed test (2AFC test; 50% is chance performance). Location memory for high-reward items was slightly, but not reliably, better than low-reward items. Also, (B) item recognition memory was above chance on both days (corrected recognition, Hits minus False Alarm rate) but showed no evidence of being affected by reward value.

better for the immediate test, 2.13 (SE = 0.06) compared with 1.92 (SE = 0.05) for the 24-hour delayed test, $F(1,44) = 27.74$, $p < .001$, $\eta p^2 = 0.39$, $BF > 100$. Confidence ratings were reliably better for items directly rewarded, 2.08 (SE = 0.05), than for those indirectly rewarded, 1.97 (SE = 0.05), $F(1,44) = 8.18$, $p = .006$, $\eta p^2 = 0.16$, $BF = 30.30$. However, memory confidence was not better for items associated with high-reward value, 2.01 (SE = 0.05), than for items associated with low-reward value, 2.04 (SE = 0.05), $F(1,44) < 1$, $\eta p^2 = 0.02$, $BF = 0.18$. No interactions among the main effects were reliable.

Discussion

As expected, participants' item-location memory, item recognition, and confidence in item recognition were greater immediately than after a delay. Additionally, items directly associated with reward (regardless of the reward value) were more likely to be accurately recognised, and were recognised with higher confidence, than items indirectly associated with reward. However, item recognition memory was not higher for categories associated with high reward vs. low reward. This finding was not predicted and differs from prior literature (e.g. Patil et al., 2017). Lastly, contrary to our hypothesis, we did not find a reliable difference in memory for the location of items associated with high-reward than low-reward on either immediate or 24-hour delayed tests.

Although the effect of reward on memory was not statistically significant for either location or recognition memory in Experiment 1, for the item-location test, the effect size was moderate ($\eta p^2 = 0.07$) and the Bayes Factor analysis did not provide evidence in favour of the null hypothesis ($BF = 1.20$). By contrast, on the recognition memory test, the Bayes Factor did provide evidence in favour of the null ($BF = 0.17$) suggesting that we did not replicate prior findings of reward enhancement on recognition memory, even after a 24-hour delay (Murayama & Kitagami, 2014; Patil et al., 2017).

In Experiment 2, we replicated the design of Experiment 1 but attempted to increase the saliency of the reward manipulation by providing monetary compensation tied directly to performance on the time estimation task. By enhancing the impact of the reward, we sought to strengthen the beneficial effect of reward on memory and again measure if the enhancement occurred for location and/or recognition tests at both the immediate and delayed time points.

In addition, in Experiment 1, the high- and low-reward trials were intermixed in order, raising the possibility of carry-over effects from the high-reward trials potentially influencing subsequent low-reward trials and reducing the overall difference between these conditions. In Experiment 2, we blocked the presentation of reward types together with the high-reward trials presented first and added a short break before the low-reward trials to minimise the potential carryover effects. Because each list was presented twice and 10 lists were presented in total across the study and reward phases, the order of these trials would not substantively affect primacy or recency effects related to the memory tests given later.

Experiment 2

Participants

Participants were 65 adults recruited through Amazon's Mechanical Turk (MTurk) online marketplace who completed the experiment online and received \$10 in compensation for completing both sessions, with the opportunity to earn up to an additional \$5 in bonus money based on the amount of reward earned in the experiment. The study methods and procedures were approved by the Northwestern University IRB office (protocol #STU00213705).

Materials

The materials were the same as in Experiment 1.

Procedure

The presentation of stimuli, response collection, and response feedback were implemented online via web browsers (Javascript and HTML5). Procedures were the same as in Experiment 1 except as follows. In the time estimation task, accurate responses to images in the Low-reward condition earned 1 cent and accurate responses to images in the High-reward condition earned between 5 and 20 cents (with possible values of 5, 8, 10, or 20 cents). Additionally, instead of High-reward and Low-reward items being intermixed for the time-estimation task as in Experiment 1, all items in the High-reward condition were presented before all items in the Low-reward condition, with a 15-second break in between. This procedure change was implemented to further dissociate the High- and Low-reward conditions, decreasing the likelihood of a reward effect carry-over for a subsequent or preceding item in a separate reward condition. Finally, unlike in Experiment 1, reward was not provided during the memory test; on-screen feedback was still provided, however, identifying the correct item location after each item-location test response.

For this experiment, an exclusion criterion was imposed such that if a participant could not complete the time-estimation task for any of the three practice items by their fifth attempt, their participation was discontinued, and they were not allowed to continue to the main experiment. This exclusion criterion was set because of the increased attention in Amazon's Mechanical Turk online marketplace that the offer of bonus money seemed to create, which changed the type of participants engaging in the experiment.

Results

All analyses were conducted in R, version 4.0.2. Of the original sample of 65 participants enrolled, 10 were found to have completed Experiment 1 previously and were excluded from analysis here. An additional 22 participants did not complete the first session of the experiment either by failing to complete the time estimation demonstration trials to criterion ($n = 21$) or quitting soon after ($n = 1$). One participant was excluded for not earning the minimum amount of reward and three did not return for the second session after completing the first session. The average time delay between the two sessions was 22.6 (SD = 1.8; range [18.6–26.8]) hours. A total of 29 participants were included in the following analyses.

Reward earned

The average amount of bonus money earned was \$4.27 (SD = \$0.47, maximum = \$5). Participants accurately completed the time estimation task on 84.5% of trials (SE = 2.0%) in the High-reward condition and 82.4% of trials (SE = 2.1%) in the low-reward condition; however, these values did not reliably differ, $t(28) = 1.28$, $p = .21$, Cohen's $d = 0.18$, $BF = 0.42$.

Location memory

As in Experiment 1, overall item-location memory was greater than chance ($M = 70.9\%$, SE = 2.7%; chance = 50%), $t(28) = 7.71$, $p < .001$. Accuracy on the location test was again unaffected by the distance between the original position and the foil location ($M = 71.2\%$ correct, SE = 2.2%, for the closest two locations, versus $M = 70.9\%$, SE = 2.4%, for the furthest, $t < 1.0$). Differences in location memory performance (see Figure 4A) were again analysed as a 2 × 2× 2 repeated-measures ANOVA with factors for reward value (High versus Low), inclusion in the reward phase (Direct versus Indirect), and test time (Immediate versus 24-hour delay). Bayes factors were included with all main effects. As we originally hypothesised, item-location memory was significantly better for stimuli from High-reward categories, 74.0% (SE = 2.6%), than for stimuli from Low-reward categories 67.9% (SE = 3.1%), $F(1,28) = 14.56$, $p < .001$, $\eta p^2 = 0.34$, $BF = 26.63$. Performance was also better on the immediate test 73.7% (SE = 2.9%) than on the 24-hour delayed test 68.2% (SE = 2.7%), $F(1,28) = 14.29$, $p < .001$, $\eta p^2 = 0.34$, $BF = 11.41$. Being directly associated with reward did not increase memory for item-location pairs, ($M = 71.5\%$, SE = 2.8%) compared with indirectly-rewarded item-location pairs ($M = 70.3\%$, SE = 3.0%), $F(1,28) < 1$, $\eta p^2 = 0.01$, $BF = 0.17$. No interactions among the main effects were reliable.

Recognition memory

Average corrected recognition ($M = 45.0\%$, SE = 5.1%) across all conditions again exceeded chance performance (0%), $t(28) = 8.81$, $p < .001$. Differences in recognition across reward conditions were assessed with a 2 × 2 × 2 repeated-measures ANOVA of recognition memory accuracy (corrected recognition; hit rate minus false alarm rate) with the same factors as in the location memory analysis above. Bayes factors were included with all main effects. Memory performance was better for the immediate test, 54.1% (SE = 5.4%) compared with 35.9% (SE = 5.1%) for the 24-hour delayed test, $F(1,28) = 70.88$, $p < .001$, $\eta p^2 = 0.72$, $BF > 100$. Recognition was not reliably different for items directly rewarded, 46.7% (SE = 5.0%) than for items indirectly rewarded 43.3% (SE = 5.4%), $F(1,28) = 2.62$, $p = .117$, $\eta p^2 = 0.09$, $BF = 0.39$. Recognition memory was also not reliably different for items associated with high-reward value ($M = 45.0\%$, SE = 5.1%) versus items associated with low-reward value ($M = 45.0\%$, SE = 5.4%), $F(1,28) < 1$, $\eta p^2 < 0.01$, $BF = 0.14$. No interactions among the main effects were reliable (see Figure 4B).

The confidence ratings (0–3) given for old items were also analysed with the same 2 × 2 × 2 ANOVA. Confidence ratings were higher for the immediate test, 2.37 (SE = 0.06) compared with 2.17 (SE = 0.07) for the 24-hour delayed test, $F(1,28) = 23.27$, $p < .001$, $\eta p^2 = 0.45$, $BF > 100$. Confidence ratings were not reliably better for items directly rewarded, $F(1,28) = 1.96$, $p = .172$, $\eta p^2 = 0.07$, $BF = 0.47$ and were not higher for items associated with high-reward value, ($M = 2.28$, SE = 0.06), compared with low-reward value ($M = 2.27$, SE = 0.07), $F(1,28) < 1$, $\eta p^2 < 0.01$, $BF = 0.14$. No interactions among the main effects were reliable.

Discussion

In Experiment 2, we observed a reliable effect of reward condition with better location memory for the study items from categories subsequently associated with a high-reward value on the time-estimation task. This finding is conceptually similar to prior findings (Gruber et al., 2016) of reward enhancing memory, suggesting that dopaminergic release associated with reward enhances memory for item-context consolidation. However, unlike prior reports

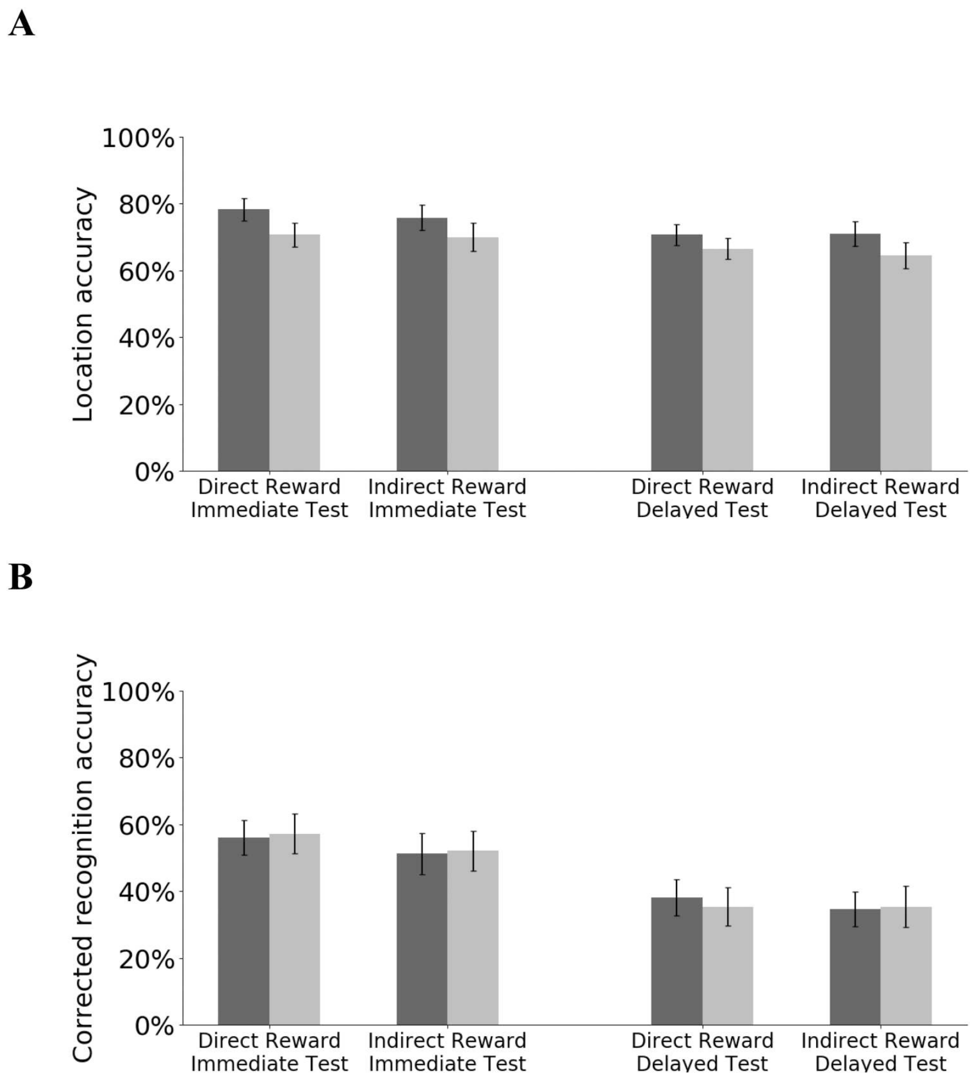

Figure 4 . Experiment 2 memory performance. High- and low-reward value reflects the monetary gains obtained by participants for the time-estimation task that included stimuli from the study phase. Direct represents items that were explicitly associated with reward; Indirect represents items that were implicitly associated with reward by being from the same category as rewarded items. (A) Item location memory (2AFC; chance = 50%) was more accurate for items associated with high reward and better on the immediate test compared with a 24-hour delay. (B) Item recognition (corrected recognition; chance = 0%) was higher for the immediate than delayed test but not better for items associated with higher levels of reward.

we did not observe enhancement by reward on the recognition memory test (Braun et al., 2018) and we did not find a greater effect of reward on the delayed memory test than on an immediate test (Murayama & Kitagami, 2014; Patil et al., 2017). We found expected results of greater item-location memory, item recognition, and recognition confidence at a short delay relative to a long delay, as also found in Experiment 1. We did not find a difference in location memory, recognition, or recognition confidence based on whether an item was directly rewarded or indirectly rewarded, unlike in Experiment 1, where recognition memory and confidence were higher for directly rewarded items.

While the effect of reward was reliable in Experiment 2 but not in Experiment 1, the overall pattern of results was very similar across the two experiments. The difference in the reliability of the result at standard alpha levels might suggest that the methodological differences between the experiments (monetary reward;

blocking High- and Low-reward trials to minimise carry-over effects) led to different outcomes. To assess if the different methodological approaches led to reliably different performance, we performed a combined analysis across Experiments 1 and 2 that included a factor of experiment in addition to the design variables. This analysis will evaluate whether the effect of reward was consistent across experiments or differed across methodologies. In addition, this combined analysis has greater sensitivity to analyses where we have observed null effects (i.e. the lack of an effect of reward on recognition memory; the lack of a selective effect on the 24-hr delayed test) that differ from the prior published literature.

Combined analyses

Reward earned

To evaluate whether the ability to earn monetary reward increased motivation to accurately complete the time estimation task, a 2 × 2 mixed-measures ANOVA on the percentage of reward trials with correct responses with factors for the experiment (Experiment 1 versus Experiment 2) and reward value earned (High versus Low) was carried out. Bayes factors were included with all main effects. We found that the total proportion of trials on which rewards were earned did not differ across experiments ($M = 83.4\%$, SE = 1.5% for monetary rewards; $M = 83.7\%$, SE = 1.1% for point rewards), $F(1,72) < 1$, $\eta p^2 < 0.01$, $BF = 0.42$. There was some evidence across both experiments that participants were more accurate in completing the time-estimation task for trials in the High-reward condition ($M = 84.5\%$, SE = 1.2%), than for trials in the Low-reward condition ($M = 82.7\%$, SE = 1.2%), $F(1,72) = 5.13$, $p = .026$, $\eta p^2 = 0.07$, $BF = 1.74$. The interaction among these factors was not reliable, $F(1,72) < 1$, $\eta p^2 < 0.01$.

Location memory

Location memory performance across experiments was analysed as a 2 × 2 × 2 × 2 mixed-measures ANOVA with a between-participants factor for the experiment (Experiment 1 versus Experiment 2), and within-participants factors for reward value (High versus Low), inclusion in the reward phase (Direct versus Indirect), and test time (Immediate versus 24-hour delay). Bayes factors were included with all main effects. This combined analysis showed a robust effect of high reward ($M = 69.3\%$, SE = 1.7%) vs. low reward (64.9%, SE = 2.0%) on location memory across experiments, $F(1,72) = 12.80$, $p < .001$, $\eta p^2 = 0.15$, $BF > 100$. There was no interaction observed between the effects of reward and experiment ($F(1,72) = 1.12$, $p = .293$, $\eta p^2 = 0.02$) suggesting that effects are comparable across the two slightly different methodologies even as the standard significance threshold was exceeded in one experiment but not the other. Item location memory performance was consistently better on the immediate memory test given at the end of the study session, 69.4% correct (SE = 1.9%), compared with the 24-hour delayed test with 64.7% correct (SE = 1.9%), $F(1,72) = 20.78$, $p < .001$, $\eta p^2 = 0.22$, $BF > 100$. This combined analysis across experiments showed no reliable difference in overall item-location memory between Experiment 2, 70.9% (SE = 2.7%), and 64.6% (SE = 2.2%) in Experiment 1, $F(1,72) = 3.22$, $p = .077$, $\eta p^2 = 0.04$, $BF = 0.96$. Directly associating the item with a reward did not reliably increase memory for the item location, 67.2% correct (SE = 1.9%) compared with 67.0% correct (SE = 1.8%) for items indirectly rewarded, $F(1,72) = 0.09$, $p = .768$, $\eta p^2 < 0.01$, $BF = 0.09$. Other interactions among these factors were not reliable.

The surprising lack of a difference in the effect of direct and indirect reward in the omnibus ANOVA was further examined with analyses separately examining the directly and indirectly awarded trials. For just the indirectly awarded trials, participant post-test performance was significantly greater for high reward ($M = 69.9\%$, SE = 1.9%) than for low-reward trials ($M = 64.1\%$, SE = 2.2%), $F(1,72) = 10.62$, $p < .01$. There was no significant difference of reward type (Experiment 1 – Points: $M = 64.8\%$, SE = 2.3%; Experiment 2 – Money: $M = 70.3\%$, SE = 3.0%), $F(1,72) = 2.15$, $p = .146$, or an interaction between variables, $F(1,72) < 1$, $p = .832$. The effect of reward item-location associations directly linked to high reward and low reward was only marginal in this analysis ($M = 68.6\%$, SE = 2.0%, and $M = 65.7\%$, SE = 2.1% for high and low reward, respectively), $F(1,72) = 3.96$, $p = .050$. There was also a marginal effect that participants who learned item-location associations with monetary reward performance ($M = 71.6\%$, SE = 2.8%) performed marginally better than those who learned with point-value rewards ($M = 64.3\%$, SE = 2.4%), $F(1,72) = 3.74$, $p = .057$. The interaction of these variables was not significant, $F(1,72) = 1.84$, $p = .179$. The separated analysis reinforces the finding that there was a robust indirect effect of reward on item-location memory across the semantically related stimulus categories.

The combined analysis also provided an opportunity to assess the differential effects of reward on the delayed tests by comparing forgetting rates across reward conditions in both studies. To evaluate this, we conducted a linear mixed-effects model analysis with the dependent variable of change score between the immediate and delayed tests. The fixed effects consisted of the experiment (Experiment 1 versus Experiment 2), inclusion in the reward phase (Direct versus Indirect), and reward value (High versus Low). Interactions between the fixed effects were included in the model. We also included participant as a random effect. There was no significant difference in forgetting between Experiment 1 ($M = -4.2\%$, SE = 1.4%) and Experiment 2 ($M = -5.5\%$, SE = 1.5%), $F(1,72) = 0.40$, $p = .527$. Forgetting did not reliably differ between items that were directly ($M = -6.6\%$, SE = 1.2%) and indirectly rewarded ($M = -3.1\%$, SE = 1.6%), $F(1,72) = 3.09$, $p = .083$. The difference in forgetting between items associated with high ($M = -5.4\%$, SE = 1.7%) and low-reward value ($M = -4.2\%$, SE = 1.2%) was not reliable, $F(1,72) = 0.27$, $p = .605$. No interactions among these factors were reliable. Forgetting rates appeared to be similar across experiments and reward conditions with no evidence of greater forgetting for the low-reward conditions.

Recognition memory

A mixed-effects ANOVA of corrected recognition memory in the same structure as the analysis above was also conducted. Bayes factors were included with all main effects. There was no reliable difference in item recognition between Experiment 2, 45.0% (SE = 5.1%) and Experiment 1, 32.6% (SE = 4.2%), though there was a trend towards a difference, $F(1,72) = 3.47$, $p = .067$, $\eta p^2 = 0.05$, $BF = 1.23$. Recognition was better on the immediate test, 46.3% (SE = 3.5%) compared to 28.7% (SE = 3.3%) on the 24-hour delayed test, $F(1,72) = 133.79$, $p < .001$, $\eta p^2 = 0.65$, $BF > 100$. Recognition was better for items directly rewarded, 39.3% (SE = 3.3%) than for items indirectly rewarded 35.7% (SE = 3.4%), $F(1,72) = 6.22$, $p = .015$, $\eta p^2 = 0.08$, $BF = 1.37$. The combined analysis still did not yield any evidence for high reward 37.0% (SE = 3.3%) enhancing recognition memory over low reward, 38.0% (SE = 3.5%) in these paradigms, $F(1,72) < 1$, $\eta p^2 < 0.01$, $BF = 0.17$. No interactions among these factors were reliable.

Differences in forgetting on the recognition memory test across the two tests were assessed with a linear mixed-effects model analysis with the dependent variable of change in corrected recognition between the immediate and delayed tests. The fixed effects consisted of the experiment (Experiment 1 versus Experiment 2), inclusion in the reward phase (Direct versus Indirect), and reward value (High versus Low). Interactions between the fixed effects were included in the model. We also included participant as a random effect. There was no significant difference in forgetting between Experiment 1 ($M = -17.2\%$, SE = 2.0%) and Experiment 2 ($M = -18.3\%$, SE = 2.2%), $F(1,72) = 0.13$, $p = .718$. Forgetting did not reliably differ between items that were directly ($M = -18.8\%$, SE = 1.7%) and indirectly rewarded ($M = -16.6\%$, SE = 1.8%%), $F(1,72) = 1.33$, $p = .253$. There was also no difference in forgetting between items associated with high- ($M = -16.8\%$, SE = 1.8%) and low-reward value ($M = -18.4\%$, SE = 2.3%), $F(1,72) = 0.35$, $p = .553$. No interactions among these factors were reliable. As with item-location memory, no evidence was observed for differences in forgetting rate based on the reward condition in the study.

Analysis of confidence ratings (0–3) for recognition of old items showed a similar pattern as the corrected recognition analysis. Greater memory confidence was observed in Experiment 2, 2.27 (SE = 0.06) versus 2.03 (SE = 0.04) in Experiment 1, $F(1,72) = 9.31$, $p < .01$, $\eta p^2 = 0.11$, $BF = 11.69$. Average confidence ratings were greater on the immediate test, 2.22 (SE = 0.38) compared with 2.02 (SE = 0.37) for the 24-hour delayed test, $F(1,72) = 46.98$, $p < .001$, $\eta p^2 = 0.39$, $BF > 100$. Memory confidence was greater for items directly rewarded, 2.17 (SE = 0.35) than for items indirectly rewarded 2.08 (SE = 0.40), $F(1,72) = 8.30$, $p = .005$, $\eta p^2 = 0.10$, $BF = 68.53$. Reward value did not have a reliable effect on memory confidence: High-reward condition, 2.11 (SE = 0.04), versus Low-reward condition, 2.13 (SE = 0.04), $F(1,72) = 0.23$, $p = .633$, $\eta p^2 < 0.01$, $BF = 0.12$. Interactions among these factors were not reliable.

General discussion

Across two experiments, memory for item location was enhanced by post-study reward, adding to a growing array of findings showing that post-encoding associations with reward can enhance recent memories. Participants more accurately remembered the location associated with the initial presentation of an image when either that item or other items in the same semantic category were subsequently associated with high-reward value. This effect held whether the reward was instantiated as money or points. Although the effect of reward in Experiment 1 was too small to be reliable, the effect was robustly observed in Experiment 2 and the combined analysis of data from both experiments showed a highly reliable effect with no significant differences in reward effect between the studies. The enhancing effect of reward on memory for the studied location of an object was observed to occur for item location on both immediate and 24-hour delayed tests.

In prior research examining the effects of reward on memory for object locations, Braun et al. (2018) found improved performance but only at a 24-hour delay. However, Gruber et al. (2016) reported an increase in associative memory for object study context on an immediate memory test, similar to our findings. The difference in the pattern of effects is likely due to methodological differences across experiments. Braun et al. (2018) manipulated the reward association by temporal distance between the study item and the reward event, whereas we directly associated the reward with some items in each category, comparable to the manipulation of reward as a function of background context used by Gruber et al. (2016). It is possible that a more direct association between item context and reward led to a stronger reward effect which could be detected after a shorter time delay.

The spread of the reward effect to categorically related items has been reported previously by Patil et al. (2017), although they did not observe this effect on an immediate test, only a delayed test. We found this effect to be present in both the immediate and delayed tests and again the difference may highlight important methodological considerations. Patil et al. (2017) used an old/new recognition memory test, which we found here to be less sensitive to reward effects (see below). Our findings may support the idea that the reward-enhancing effect boosts memory consolidation through a mechanism that spreads to related items from the same category. We speculate that the item-location test may be a more sensitive measure of this effect, allowing us to see an enhancement of consolidation even on an immediate test because of the greater associative nature of this test compared to simple yes/no recognition. This increase in associative memory could require greater involvement of parts of the brain that are heavily affected by reward. However, it is possible that our results demonstrate that reward can enhance associative memory without having to target consolidation, or it could suggest that reward causes consolidation to occur faster.

Although we found reward-enhanced location memory, we did not find any reliable effect of reward on decreasing the forgetting rate of item location memory or item recognition. Therefore, it is possible that initial memory is boosted by reward and this effect persists after a delay. However, we cannot rule out that the forgetting rate could be affected by reward after either a longer delay or more repetitions. We did not find any evidence for greater memory for item locations directly associated with reward compared to those indirectly associated with reward. We did, however, find weak evidence that item recognition is greater for stimuli directly versus indirectly rewarded, regardless of the value of the reward. Patil et al. (2017) found better recognition memory for items presented in the reward phase than for items not presented in the reward phase. The disparity between our results and theirs, in which they found an increased effect of reward on memory with direct compared to indirect association while we did not, could have been due to differences in the presentation timing between items associated directly and indirectly with reward. In the study by Patil et al., participants studied items not directly associated with reward at a separate and earlier time than they studied items directly associated with reward. In our study, participants studied items that were directly and indirectly associated with reward at the same time.

We did not observe an effect of reward magnitude on item recognition on either immediate or delayed recognition tests, unlike previous reports in the literature (Murayama & Kitagami, 2014; Patil et al., 2017). Neither the old/new response nor confidence measures used here during the recognition test exhibited any influence of reward, even though participants showed the expected greater recognition accuracy and confidence as a function of other factors. That is, recognition memory was slightly enhanced for all items directly rewarded regardless of reward value, indicating a typical improvement in memory for additional exposures, and recognition memory was overall worse at a delay, reflecting typical forgetting effects. It is not entirely clear why our reward paradigm did not enhance performance on a recognition memory test, even at a 24-hour delay. Some previous studies of reward enhancement have reported effects sensitive to specific study item characteristics (Murayama & Kuhbandner, 2011). The methodology used here of intermixed, repeated lists of high- and low-rewarded stimuli presented at specific locations on screen may have affected the dynamics of the reward-enhancement process on memory consolidation to produce less of an effect on recognition memory. One simple explanation of the difference in results is that the more difficult object-location test is more sensitive to a smaller reward effect on memory, which would explain why we observed the effect on that test and not on recognition. Another possibility is that the associative object-location test relies more directly on hippocampal-dependent memory representations (e.g. Eichenbaum et al., 2007; Squire et al., 2007) and was therefore more sensitive to dopaminergic mechanisms through projections into this region. Elliott et al. (2022) reported findings on item and associative memory in regard to individual differences in structural connectivity with the midbrain, supporting this hypothesis that associative memory is more sensitive than item memory to emotion-related memory enhancements. Our data do not provide a way to discriminate between these two hypotheses, but we raise the question as an area of potential future investigation into how and when rewarding experiences improve memory for recent events.

Our findings across two experiments broadly support the hypothesis that reward enhances memory similar to the well-established effects of punishment strengthening memory (McGaugh, 2018). Both phenomena reflect adaptive influences of emotion on memory, but they are hypothesised to differ in neural basis (amygdala versus VTA/ventral striatum) and neurobiological mechanisms (noradrenergic versus dopaminergic). These mechanisms might be expected to operate differently as the emotional signals are likely used differently (e.g. Clewett & Murty, 2019). Positive experiences should allow "adaptive memory" to support decision-making processes towards effective goal selection or reward seeking (Shohamy & Adcock, 2010), instead of avoiding threat stimuli. These more complex decision-making processes may be a reason why we observed that the value of reward generalises to related material, not just directly rewarded objects (as also seen in Patil et al., 2017). Our findings of reward-enhancing item-location memory support theories on the neurobiological processes underlying improved memory through associative binding. Researchers have reported evidence of item-location associative memory tasks being completed through working memory (Chunharas et al., 2022), even in an individual with hippocampal deficits (Allen et al., 2014). However, Allen et al. (2014) found that associative memories in an individual with hippocampal deficits did not persist after a delay. Additionally, a review by Yonelinas (2013) describes evidence of the critical role of the hippocampus in both long-term memory associations and even in working memory for more complex associations. Based on neuroimaging data (Gruber et al., 2016; Lisman & Grace, 2005; Shohamy & Adcock, 2010), it is theorised that dopamine, elicited by reward, interacts with the hippocampus to strengthen the memory binding process during consolidation. Our results seem to support this theory.

A limitation of this study is the perceptual similarity between items of the same category. Due to this within-category similarity, we cannot determine whether semantic category knowledge or spreading of perceptual representations were responsible for reward enhancement spreading to improve location memory for items not directly associated with high reward. Future studies could help to clarify this mechanistic question. Another limitation of this study is the high number of participants excluded. Our high exclusion rate was in part a result of this being an entirely online study. Many individuals withdrew from the study prior to completion due to poor internet connection and/or not being interested/able to complete the demonstration trial. Additionally, many individuals were excluded because they participated in a previous version of this experiment. Therefore, despite the high rate of exclusion, most exclusions wereunrelated to performance in the experiments and would not be expected to bias our results. An additional limitation is that differences between reward conditions may have been more noticeable in prior studies (e.g. attention focused on differences in star colours – Patil et al., 2017; or coin colour – Braun et al., 2018), which could have contributed to our lack of reward effect on item recognition. For follow-up studies, researchers may consider adding a condition in which some categories of items are not rewarded at all, in addition to having low-and high-reward item categories. Including this additional category could further quantify the benefits of high/low reward over no reward on memory. Follow-up work should also further adjust the presentation timing of the categorically related but unrewarded items. It is unclear if this spreading effect of reward on associative memory would still occur if the presentation/study of the related but unrewarded items occurred at an earlier time, as in Patil et al.'s (2017) study. Identifying characteristics of the memory-enhancing effect of reward reflects an exciting new direction in memory research to better understand how memories of past events are used to adaptively guide future behaviour.

For Experiment 2, we changed the reward paradigm from a mixed-list to a pure-list design as a method to reduce carry-over reward effects. However, researchers have reported that items more associated with emotion, such as those linked to a higher reward value, can motivate greater attention resources in either a mixed or pure-list design (Talmi et al., 2007). Therefore, based on the methodology utilised in this study, we cannot rule out that this reward effect was influenced by increased attention to items directly associated with high reward. However, our finding of a similar reward effect for items indirectly associated with high reward, which were shown fewer times than those directly associated, suggests that this effect is not driven solely by increased attention. Additionally, our use of intentional encoding instead of incidental encoding, such as used in the study by Patil et al. (2017), could have influenced the strength of the reward effect found in this study. Participants were aware of a memory test after the experiments. Therefore, they could have intentionally rehearsed their memory for the items and thus improved their memory. However, this possibility does not account for why memory was only better for items associated with high reward rather than all items indiscriminately.

The evidence found in this study supports the theory that reward impacts associative memories more strongly because of their heavy reliance on the MTL and shared semantic and perceptual features, allowing us to better predict the timing and strength in which reward will influence memory. In a real-world scenario, teachers using rewards to boost their students' memories for an upcoming exam could use these results to help determine which experiences associated with rewards would likely be more sensitive to the effect of reward. Additionally, educators could plan for rewards to indirectly influence their student's associative memories, if they can influence the students to view those memories as belonging to the same perceptual/semantic category as the items being directly rewarded.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

The data and materials for all experiments are available at the Open Science Framework, https://osf.io/zv4ah/. None of the experiments were pre-registered in advance, although the two experiments are largely replications of each other.

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