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ORIGINAL ARTICLE

The interactive effect of external rewards and self-determined choice on memory

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Abstract

Both external motivational incentives (e.g., monetary reward) and internal motivational incentives (e.g., self-determined choice) have been found to promote memory, but much less is known about how these two types of incentives interact with each other to affect memory. The current study ($N = 108$) examined how performance-dependent monetary rewards affected the role of self-determined choice in memory performance, also known as the choice effect. Using a modified and better controlled version of the choice paradigm and manipulating levels of reward, we demonstrated an interactive effect between monetary reward and self-determined choice on 1-day delayed memory performance. Specifically, the choice effect on memory decreased when we introduced the performance-dependent external rewards. These results are discussed in terms of understanding how external and internal motivators interact to impact learning and memory.

Introduction

Psychologists have investigated various motivational factors that can enhance performance (Elliot, 2008; Martin, 1963; Oudeyer et al., 2016; Pessoa, 2009; Qin et al., 2020; Stephens, 1933; Zhang et al., 2017). For example, the classic operant conditioning theory (Skinner, 1938, 1955) and reinforcement learning theory (Dayan & Niv, 2008; Schultz et al., 1997; Sutton & Barto, 1998) have emphasized external incentives such as rewards, whereas other theories (i.e., self-determination theory) have emphasized internal incentives such as self-determination or perceived agency/sense of agency (being able to make choice/decision about the behaviors or having control over the environment) (Di Domenico & Ryan, 2017; Fujiwara et al., 2013; Jin et al., 2015; Kaplan & Oudeyer, 2007; Leotti & Delgado, 2011; Leotti et al., 2010; Meng & Ma, 2015; Murayama et al., 2015).

In the domain of memory, existing research has supported both perspectives. In terms of external incentives, many studies have found that monetary rewards facilitate explicit memory[1] (Ariel & Castel, 2014; Callan & Schweighofer, 2008; Castel et al., 2013; Madan & Spetch, 2012; Miendlarzewska et al., 2016). External rewards are thought to lead to dopamine release and heightened attention, which in turn fosters plasticity of the hippocampal memory system (Adcock et al., 2006; Cohen et al., 2014, 2016; Elliott et al., 2019; Murty & Adcock, 2014; Shohamy & Adcock, 2010).

In terms of internal incentives, recent research has begun to explore the influence of self-determined choice on memory. These studies showed that when participants make choices about when and what to learn, their memory was enhanced. This choice effect has been found in both adults (Gureckis & Markant, 2012; Markant & Gureckis, 2014; Markant et al., 2014; Voss et al., 2011a, 2011b; Voss et al., 2011a, 2011b) and children (Ruggeri et al., 2019). This choice effect has been attributed to humans' innate desire

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[1] Explicit memory is the conscious memory of a previous experience, whereas implicit memory does not involve consciousness (Rugg et al., 1998; Sheldon & Moscovitch, 2010).

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for autonomy or sense of agency, which can be realized via self-determined choice (Patall et al., 2008). Interestingly, Murty and his colleagues further found that inconsequential choice (i.e., choice unrelated to the content of the memoranda) could promote memory performance (DuBrow et al., 2019; Murty et al., 2015). In these studies, participants were asked to remove one of two occluder screens (two different hiragana characters matched for preference) to remember the revealed object. In the choice condition, participants could decide which occluder to remove, whereas in the fixed condition they were forced to remove the occluder screen on the side of the highlighted text. The memoranda of each trial were predetermined and matched in the two conditions. Results showed that participants had better recognition memory in the choice condition than in the fixed condition, suggesting that motivational factors associated with choice itself had inherent value that could enhance the memory. In addition, neuroimaging studies have indicated that, like external rewards, choice activates the dopaminergic reward regions (Leotti & Delgado, 2011, 2014), which further interact with the hippocampal memory system to produce enhanced memory performance (Murty et al., 2015, 2019).

Much of the previous research has examined the external rewards and self-determined choice separately, so little is known about whether and how they may interact to affect memory. Given that both monetary rewards and choice enhance memory performance via overlapping mechanisms (i.e., the reward system interacts with the memory system), it would be necessary to determine whether they have interactive effects or merely additive effects. Thus far, only three studies have tested the influence of external rewards on the effect of other internal motivators (curiosity and interest) on memory using the trivia question task (Duan et al., 2020; Murayama & Kuhbandner, 2011; Swirsky et al., 2021). Two studies revealed an interactive effect of reward and curiosity/interest on memory (i.e., rewards enhanced memory for low-curiosity/interest items, but not for high-curiosity/interest items) (Murayama & Kuhbandner, 2011; Swirsky et al., 2021) and one showed an additive effect of reward and curiosity (i.e., both rewards and curiosity enhanced memory performance, without an interaction) (Duan et al., 2020). The former two studies used a between-subjects manipulation of reward and included two levels/groups (i.e., two groups performed the task: control and reward groups) while the latter used a within-subjects manipulation of reward and included three levels (i.e., one group performed the task at three reward levels: none, low and high reward).

Outside the domain of memory, self-determination theory has suggested that external rewards undermine intrinsic motivation (i.e., lower self-reported interest, less time spent on task) and consequently impair task performance (Deci, 1971; Deci et al., 1999; Ma et al., 2014; Murayama et al., 2010). One possible mechanism for the undermining effect is the decreased sense of autonomy/agency due to the introduction of external rewards (Deci et al., 1999; Eisenberger et al., 1999; Houlfort et al., 2002). That is, external rewards lead participants to engender an external locus of causality for the task and hence lose a sense of autonomy/agency, which in turn leads to less enjoyment and poorer performance. Based on the undermining effect, we predicted that external rewards would reduce the choice effect on memory, and hence show a significant interaction between external rewards and self-determined choice.

Here, we used a modified and better controlled version of the choice paradigm and manipulated levels of reward to investigate how performance-dependent monetary rewards affected the choice effect on memory.[2] In the previous paradigm, two different Japanese characters were used as the occluders in each trial (DuBrow et al., 2019; Murty et al., 2015). Although the preference of the two Japanese characters in each trial had been rated to be similar, there might still be potential differences between the two occluders (Chen & Risen, 2010; Izuma & Murayama, 2013), affecting the choices and memory. Therefore, in the current study, we used the same occluder (a question mark in a circle) in each trial to eliminate potential differences between the two occluders.

Participants were randomly assigned to one of three groups (control group, ambiguous reward group, and explicit reward group). All participants performed an inconsequential choice encoding task under two conditions (choice or no choice) and a subsequent recognition memory test at a 24-h delay. The memory test was conducted 24 h later rather than immediately to maximize the effects (the choice and reward effects and most importantly, the expected interactive effect) as previous studies have revealed that consolidation enhances the effect of rewards and choice on memory (Cheng et al., 2020; Murayama & Kitagami, 2014; Murty et al., 2019; Shohamy & Adcock, 2010). We included two reward groups to test whether reward salience would affect how external rewards and choice interact to influence memory. Previous studies have revealed that, compared to non-salient rewards, salient external rewards lead to a more external locus of causality and a stronger reduction of choice effect on intrinsic motivation and math performance (Hendijani & Steel, 2020; Ross, 1975). We predicted that explicit (more salient) rewards would reduce the choice effect more than would ambiguous (less salient) rewards. For the explicit reward group, the computer screen showed the exact amount

[2] Before the main study, we conducted a replication experiment of the behavioral studies by Murty and his colleagues (DuBrow et al., 2019; Murty et al., 2015) to verify the choice effect in the modified paradigm. The method and results are presented in the Supplementary Materials.

of reward during the encoding phase for each correct trial in a subsequent memory test. The ambiguous reward group was informed orally by the experimenter that their eventual subject payment would depend on the memory performance in a subsequent memory test. They were simply told, during the encoding phase of the experiment, the average amount participants would receive, but not the specific amount of reward for each correct trial. Finally, participants in the control group were told they would receive a fixed amount of subject payment (see "Methods" for details).

Method

Participants

A total of 118 participants were recruited in this study. Data from 10 participants were excluded for the following reasons: prior experience[3] with the experimental materials ($n = 1$), failure to understand the task[4] ($n = 4$), failure to complete the experimental procedure ($n = 1$), and failure to save the data due to network issues ($n = 4$). The final sample size was 108, with 36 for each group (control group: 16 males; mean + SD = 21.9 + 4.31 years; ambiguous reward group: 16 males; mean + SD = 21.8 + 2.95 years; explicit reward group: 15 males; mean + SD = 20.8 + 2.03 years). A power analysis using the effect size of the interaction between external and internal motivators in one previous study (Murayama & Kuhbandner, 2011) showed that our sample size was adequate. Specifically, Murayama and Kuhbandner (2011) reported that the interaction effect was $F(1, 42) = 4.97$, generalized eta-squared = 0.04. Because generalized eta-squared cannot be used for power analysis (Lakens, 2013; Olejnik & Algina, 2003), we calculated partial eta-squared based on the above F value and degrees of freedom with the following formula, partial eta-squared = (F_stat × df_num)/ ((F_stat × df_num) + df_denom), where df_num = degree of freedom for the numerator and df_denom = degree of freedom for the denominator. Partial eta-squared = $(4.97 \times 1)/(4.97 \times 1 + 42) = 0.106$. We then conducted a power analysis with GPower using the following parameters: F-test of within-between interaction of repeated measures, effect size f (SPSS specification in the Options) = 0.344 (which was calculated from the partial eta-squared of 0.106), power = 0.8, alpha = 0.05, number of groups = 3, number of measurements = 2, and nonsphericity correction = 1). This power analysis yielded a total sample size of 90, which is smaller than our actual sample size of 108.

All participants had normal or corrected-to-normal vision and reported no history of neurological problems. The study was approved by the Institutional Review Board of the Institute of Psychology, Chinese Academy of Sciences, and all participants provided written informed consent before taking part in the experiment.

Stimuli

Two hundred and forty-six images of living and non-living objects with a medium level of familiarity, arousal, and emotional valence were used as the memory materials for the experiment. These images have been used in a previous study (Cheng et al., 2020). Among these images, six (three living images and three non-living images) were used to attenuate primacy and recency effects and were not included in the subsequent test and analyses. The remaining 240 images were divided into two sets. A total of 120 images (60 living images and 60 non-living images, counterbalanced across conditions) were used as encoding items, and the other 120 images (60 living images and 60 non-living images) were used as filler new items in the recognition test. The assignment of image sets to the encoding task and recognition test was counterbalanced across participants.

Procedure

Due to the COVID-19 pandemic, the experiment was conducted online rather than in the lab. Participants were required to find a quiet room to complete the tasks alone using PsychoPy3 on Pavlovia.org (MacAskill et al., 2022). Participants were randomly assigned to three groups (see Fig. 1). Each participant completed an encoding task and a recognition test. During the choice memory encoding, participants were asked to remove one of the two occluder screens on the left and right sides to remember the image underneath. There were two conditions (choice and fixed conditions, intermixed in trials), with 60 trials in each condition being analyzed. In the test, participants were asked to judge whether the image was old or new. One hundred and twenty previously presented images and 120 filler new images were presented.

For the control group, participants were informed at the start of the experiment that they would receive a fixed and performance-independent amount of money (¥55, about the average amount of payment for the two reward groups based on a pilot study). Each trial in the encoding task began with a cue ("选择 [choice]" or "非选择 [fixed]") for 1.5 s that indicated the condition of current trial, then a fixation was displayed for 1.5 s or 2 s. Next, two question marks were presented as occluders until participants pressed "Left Arrow"

[3] Information about possible prior experience was based on the records of our previous experiments and participants' self-report after the experiment.

[4] Participants were asked whether they understood the task during and after the experiment.

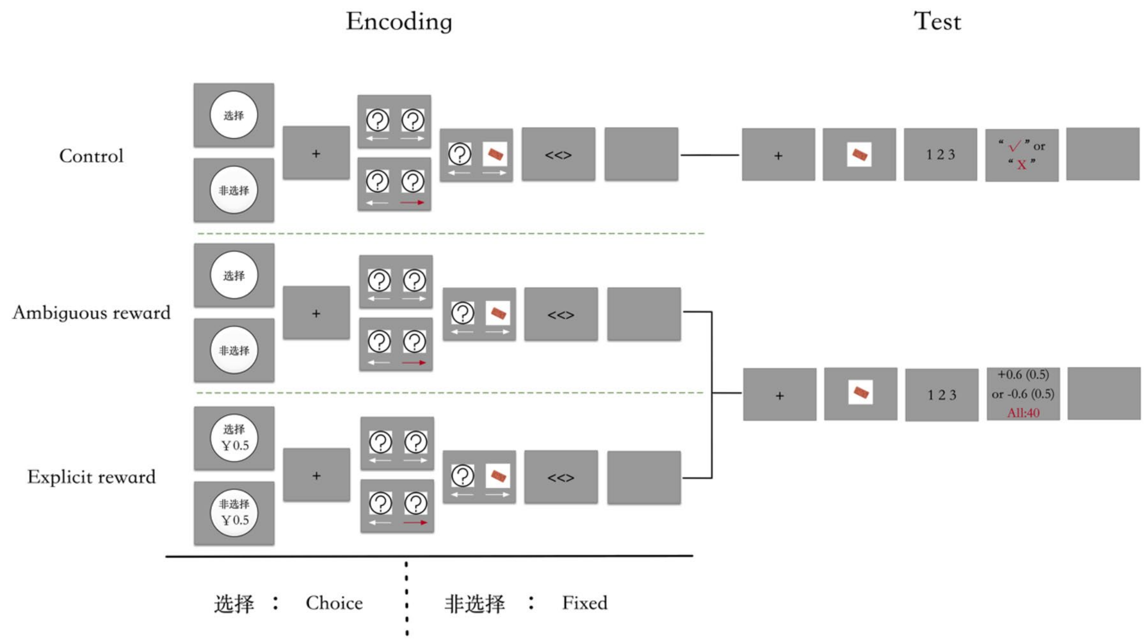

Fig. 1 Schematic depiction of the encoding phase and the recognition test. During the encoding phase, participants were asked to remove the occluder on the left or right side to remember the image underneath. In the choice condition (选择: Choice), participants made their own decision regarding which occluder to remove, whereas in the fixed condition (非选择: Fixed), participants had to remove the predetermined occluder on the side of the red arrow. In the control group, participants were informed that they would receive a fixed amount of subject payment and they received neutral feedback in the test. In the two reward groups, participants were informed that their payment would be dependent on their memory performance and they received performance-dependent rewards in the test. Specifically, in the ambiguous reward group, participants were informed orally, during the encoding phase, of the average reward amount for the experiment (without specific information about the exact amount for each correct response), whereas in the explicit reward group, participants were informed visually of the exact reward amount during each trial

or "Right Arrow" to indicate to remove the occluder on the left or right side or until 5 s elapsed. In the choice condition, participants made their own decision regarding which occluder to remove, whereas in the fixed condition, participants had to remove the predetermined occluder on the side of the red arrow. After the removal of the occluder, participants encoded the image underneath for 2 s. To prevent carryover effects (Anderson et al., 2006), participants performed two flanker tasks in which they judged the direction of the middle arrow of a set of three arrows for 4.8 s (2.4 s for each flanker task) after encoding. The intertrial interval (ITI) was a blank screen for 1.3 s, 1.5 s, or 1.7 s. Finally, with a 24-h delay (approximately), participants returned for the recognition test, in which they were instructed to judge whether the images were OLD by pressing "V" or NEW by pressing "N" within 3 s and to rate their confidence by pressing "1" (very sure), "2" (sure), or "3" (very unsure) within 3 s. After confidence rating, feedback of "√" or "×" was presented for 1.2 s to indicate a correct or an incorrect response for the "OLD" or "NEW" judgment (ITI = 1 s).

For the ambiguous reward group, the procedure was the same as that for the control group with the only exception that, before the encoding task, participants in the ambiguous reward group were orally informed that their subject payment would be related to their performance on a memory test a day later (i.e., "The better you perform on tomorrow's memory test, the larger your payment will be. On average you will get ¥55 for the experiment."). In the recognition test, they were informed that they would be rewarded for each correct recognition (+¥0.6) and penalized for false alarm (– ¥0.6) in addition to the basic payment (¥10). The penalty was used to prevent the participants from using the strategy to respond "OLD" to all images. This particular design (i.e., rewarding correct recognition and penalizing false alarms while ignoring misses and correct rejections) was based on a classic study on performance-dependent rewards and memory (Adcock et al., 2006). It is believed to lead to a neutral payout under maximum expected value in signal detection decision models and to avoid changing the decision criterion (Macmillan & Creelman, 2004). After each trial, participants received feedback on reward/penalty and the cumulative reward they had obtained.

For the explicit reward group, the procedure was the same as that for the ambiguous group except that the specific amount for each correct recognition was provided before the encoding task (i.e., "You will get ¥0.5 for tomorrow's each correct recognition of images presented today. Thus, the better you memorize these images, the larger your

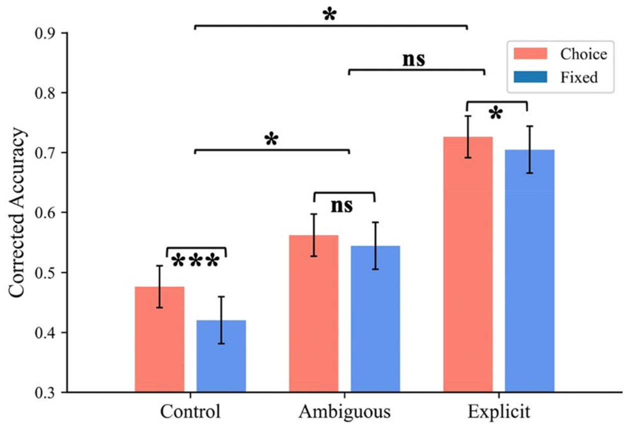

Fig. 2 Mean memory performance (corrected accuracies) for the choice and fixed conditions when participants received the fixed payment (the control group) or when they received performance-dependent rewards (the ambiguous reward group and the explicit reward group). Error bars represent the standard error of the mean across participants. *p < 0.05, ***p < 0.001, *ns* non-significant

payment will be. On average you will get ¥55 for the experiment.") and the reward amount was displayed on the screen for each trial during the encoding phase. Please note that the amount of each reward and penalty was adjusted from ¥0.6 in the ambiguous reward group to ¥0.5 in the explicit reward group. This downward adjustment was necessary to match the final payment for participants in all three groups (about ¥55), because of the better overall memory performance in the explicit reward group than the ambiguous reward group and the control group. The exact amount of adjustment was determined by a pilot study (Fig. 2).

Results

A 2 (condition: choice vs. fixed) × 3 (group: control vs. ambiguous reward vs. explicit reward) ANOVA was conducted. Corrected accuracy (hit rate minus false alarm rate) was the dependent variable. Results showed a significant main effect of condition, $F(1,105) = 23.50$, $p < 0.001$, $\eta 2 = 0.18$, with higher corrected accuracy in the choice condition than that in the fixed condition. There was also a significant main effect of group, $F(2,105) = 15.18$, $p < 0.001$, $\eta 2 = 0.22$, with higher corrected accuracy in the explicit reward group than that in the ambiguous reward group, $p = 0.04$ (Tukey HSD-corrected), higher corrected accuracy in the explicit reward group than that in the control group, $p < 0.001$ (Tukey HSD-corrected), and marginally higher corrected accuracy in the ambiguous reward group than that in the control group, $p = 0.084$ (Tukey HSD-corrected). Crucially, there was a significant interaction between condition and group, $F(2,105) = 3.49$, $p = 0.034$, $\eta 2 = 0.06$. Simple effect analysis showed a strong choice effect on memory in the control group, mean difference = 0.056 (SD = 0.011), 95% CI [0.033, 0.078], $p < 0.001$. However, the effect was only marginally significant in the explicit reward group, mean difference = 0.018 (SD = 0.011), 95% CI [− 0.005, 0.040], $p = 0.061$, and non-significant in the ambiguous reward group, mean difference = 0.021 (SD = 0.011), 95% CI [− 0.001, 0.044], $p = 0.122$. We further compared the choice effect between the control group and the two reward groups separately, and found significant group-by-condition interactions in both analyses (for the comparison of the control group and the ambiguous reward group, $F(1,70) = 5.02$, $p = 0.028$, $\eta 2 = 0.07$, and for the comparison of the control group and the explicit reward group, $F(1,70) = 4.55$, $p = 0.036$, $\eta 2 = 0.06$). Finally, when comparing the choice effect between the ambiguous reward group and the explicit reward group, the results showed a non-significant group-by-condition interaction, $F(1,70) = 0.07$, $p = 0.796$, $\eta 2 = 0.001$. Taken together, we found that the choice effect on memory was significantly reduced by the presence of external incentives, and the ambiguous and explicit rewards affected the choice effect on memory to a similar extent.

We also performed the above analyses with uncorrected accuracy (hit rate). Results showed a similar pattern as those with corrected accuracy and are presented in the Supplementary Materials. We also performed the ANOVA to analyze group and condition differences in response time (RT) to select the occluders in the encoding phase. Results showed slower RTs to select the occluders in the choice condition than in the fixed condition in all groups. Detailed results are presented in the Supplementary Materials. To exclude the influence of the RTs to select the occluders in the encoding phase, additional ANOVA were performed controlling for the difference in RT between the choice and fixed conditions. Results showed the same pattern as that found without controlling RT (see the Supplementary Materials).

Discussion

Using a modified paradigm of Murty et al.'s (2015) original choice task (see the Supplementary Materials), the current study demonstrated a reliable choice effect, such that self-determined choice enhanced 24-h delayed memory independently of the content of memoranda, encoding time, and external cues (e.g., different occluders). This result is consistent with many previous studies of the choice effect using other tasks such as motor learning (Lewthwaite et al., 2015; Meng & Ma, 2015; Murayama et al., 2015; Patall et al., 2008), and extends the choice effect to episodic memory. It suggests that making choice can satisfy the innate desire for agency, thus has an inherent value that can enhance memory performance as well as other cognitive performance (Murty et al., 2015; Patall et al., 2008).

Most importantly, our study revealed a significant reduction in the beneficial influence of choice on delayed memory when performance-dependent rewards were introduced to the learning context (the two reward groups). This is the first evidence showing that external rewards interact with self-determined choice to impact memory. Although external rewards enhanced memory performance (better performance in reward groups than in control group), they reduced the choice effect, suggesting that the external motivational incentives (monetary rewards) weakened the role of internal motivational incentives (perceived agency) in memory.

Our evidence of the interactive effect of external rewards and self-determined choice on memory was consistent with two previous studies that revealed interactive effects of rewards and other internal motivators (curiosity and interest) on memory (Murayama & Kuhbandner, 2011; Swirsky et al., 2021). These findings extend the traditional undermining effect (when external rewards lead to poorer intrinsic motivation and consequently poorer performance) (Deci et al., 1999) in the following respect. The traditional undermining effect refers to the effect that the removal of external rewards diminishes performance on future tasks, whereas the current study and the two previous related studies (Murayama & Kuhbandner, 2011; Swirsky et al., 2021) showed that external rewards reduced the effect of internal motivators when external rewards were still in place.

It should be noted that one previous study showed a non-significant interaction between external and internal motivational factors (monetary rewards and curiosity) on memory (Duan et al., 2020). Using the trivia question task, Duan et al.'s study first asked participants to rate the curiosity for getting to know the answer of each trivia question (curiosity: low vs. medium vs. high). Then, trivia questions were presented with answers and participants were told that their memory for trivia answers would be tested on the next day and rewarded according to the reward cues associated with them (reward: none vs. low vs. high). That is, as we mentioned in the Introduction, this study used a within-subjects manipulation of reward with three levels (all participants performed the task on none, low, and high reward levels) while the current study and the other two related studies (Murayama & Kuhbandner, 2011; Swirsky et al., 2021) used a between-subjects manipulation of reward with two levels (two groups of participants performed the task and each participant performed on only one reward level). It is possible that, in the study by Duan and colleagues, the three reward levels interfered with one another when administered within participants, so that the internal curiosity effect on each reward level would not differ significantly. In addition, the non-significant impact of reward on the curiosity effect might be due to the multiple reward levels used in that study. Some previous studies have showed that the presence vs. absence of reward, but not the actual amount of reward, affected memory performance, perhaps because the reward prediction error (whether reward is greater or less than expected) did not differ significantly across multiple levels of reward (Bunzeck et al., 2010; Ergo et al., 2020; Rouhani et al., 2018).

Contrary to our hypothesis that explicit (more salient) rewards would reduce the choice effect more than would ambiguous (less salient) rewards, we did not find a difference in the choice effect on memory between the two reward groups. Instead, we found the same reductions of the choice effect in both reward groups compared to the control group. Unlike our study, a previous study found that salient rewards offset the choice effect on math performance, whereas non-salient rewards even led to an increased choice effect (Hendijani & Steel, 2020). Two differences between the two studies might have contributed to this inconsistency. First, Hendijani and Steel's study manipulated rewards and choice during the math test, whereas the current study administered the memory test 24 h after the manipulation of rewards and choice during the encoding phase. Some previous studies have revealed that less salient rewards (i.e., incidental rewards or irrelevant rewards) impact the delayed memory but not the immediate memory (Cheng et al., 2020; Murayama & Kitagami, 2014), suggesting that the less salient or ambiguous rewards' effect is dependent on memory consolidation (Murayama & Kitagami, 2014). Consequently, it is possible that the interaction effect between rewards and choice may also appear only after memory consolidation. Second, the current study used a smaller amount of reward for each trial in the explicit reward group (¥0.5) than that in the ambiguous group (¥0.6) to match the overall reward across the three groups. The smaller amount of reward in the explicit reward group might have reduced the effect of rewards in this group (although it was still significant, as we detected better overall performance in the explicit reward group than in either the control group or the ambiguous reward group). Future study should explore these possible explanations.

What potential mechanisms are involved in the interactive effect of external rewards and self-determined choice on memory? Here, we proposed three interpretations of the interactive effect. First, the combined positive effects of both external rewards and internal self-determined choice might reach a certain limit thus rewards showed less effectiveness. As aforementioned, the external and internal incentives involve overlapping mechanisms (the reward dopaminergic system). Thus it is possible the combination of these two incentives activated the reward system or triggered the dopamine release to a ceiling that could not lead to a further increase in performance (Mobbs et al., 2009; Aarts et al., 2014) or may even backfire. Indeed, one recent study revealed that too-high external reward would even impair memory performance (Cheng et al., 2020). Recent models of neuromodulatory effects on memory have also suggested that increases in arousal can result in decreased states of exploration/intrinsic motivation, which can have a negative impact on memory (Clewett & Murty, 2019). This scenario is akin to the Yerkes-Dodson Law about arousal/motivation and performance (Dodson, 1915). Future computational models and experimental research may be able to determine how the brain integrates the "values" of external rewards and internal sense of agency and to see whether the Yerkes–Dodson Law applies here.

Second, it is possible that rewards reduced the inherent value of the choice and hence its effect on performance. Consistent with this explanation, previous neuroimaging study using the traditional undermining effect paradigm has revealed decreased activity in the valuation system (i.e., the striatum and the prefrontal areas) in the reward group as compared to the control group after the reward was no longer provided (Murayama et al., 2010). It suggests that external rewards may directly modify the reward value of choice and hence its effect on memory.

Third, the interactive effect might reflect a boost in memory from the monetary reward but this boost was stronger when there was no choice than when there was a choice. Previous studies have revealed that money could evoke participants' feeling of strength or efficacy (Bandura, 1977; Rodgers et al., 2008) that counteracted the impairing effect of the negative situation or emotion on performance (Boucher, 2012; Zhou et al., 2009). For example, money improved the performance in the ego-depletion (negative) situation, but not in the non-depletion (not negative) situation (Boucher & Kofos, 2012). In the current study, the deprivation of the opportunities to choose in the fixed condition might have led to negative feelings (stressful, helpless) and impaired performance due to the automatic arousal and stress hormones release (Leotti et al., 2010), but the effect was buffered by monetary rewards. In contrast, the choice condition was a less negative situation and hence was not buffered as much by the monetary rewards.

The current study revealed two types of motivators, the external and internal motivators, which interact with each other to affect memory performance. It is worth mentioning that other domains of cognition have also involved two competing or integrative processes. For example, in the domain of attention, some studies have suggested the endogenous and exogenous attention use the same system and compete with each other for its control (Berger et al., 2005; Godijn & Theeuwes, 2002). In the sensory domain, studies have suggested that multisensory inputs can integrate (i.e., visual–auditory integration) for more efficient processing (Lupyan & Ward, 2013; Williams et al., 2004).

One major limitation of the current study is that it could not pinpoint the specific phase or phases (encoding, consolidation, or retrieval) during which external rewards and choice interacted to affect memory. We manipulated choice and reward during the encoding phase, but the test was conducted 24 h later. We expected that our results were dependent on memory consolidation during sleep based on previous literature as mentioned earlier, but could not determine what effects we would have found if we had used an immediate memory test or a delayed memory test while subjects had been deprived of sleep. Another limitation of the study was that the groups received different types of feedback during the recognition test. The control group received neutral feedback, whereas the reward groups received monetary feedback. This difference in feedback might have led to differences in motivation or effort, which might have contributed to the interactive effect (i.e., motivation or effort induced by monetary feedback was more beneficial for items in the fixed condition). Future studies should use designs that can manipulate the reward (and choice) in different memory phases, collect sleep measures, and use similar feedback for different groups.

In conclusion, the current study showed an interactive effect of external rewards and self-determined choice on memory, such that the choice effect on memory is reduced by the introduction of performance-dependent monetary rewards. Future study should investigate whether other types of internal motivators (i.e., sense of competence) and external motivators (i.e., social reward) also have interactive effects on memory.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00426-023-01807-x.

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Author contributions MZ and TJ designed and conceived the study. JX, YL and ZD performed the experiments and analyzed the data. MZ, CC and VPM wrote the manuscript.

Data availability Open practices: The datasets generated and analyzed during the current study are available in the OSF repository, https://osf.io/tz52n/?view_only=9b195eb780f543f0bf9675b71e9ad571.

References

Aarts, E., Wallace, D.L., Dang, L.C., Jagust, W.J., Cools, R., D'Esposito, M. (2014). Dopamine and the cognitive downside of a promised bonus. *Psychological Science, 25*, 1003–1009. https://doi.org/10.1177/0956797613517240

Adcock, R. A., Thangavel, A., Whitfield-Gabrieli, S., Knutson, B., & Gabrieli, J. D. (2006). Reward-motivated learning: Mesolimbic activation precedes memory formation. *Neuron, 50*(3), 507–517. https://doi.org/10.1016/j.neuron.2006.03.036

Anderson, A.K., Wais, P.E., Gabrieli, J.D.E. (2006). Emotion enhances remembrance of neutral events past. *Proceedings of the National Academy of Sciences, 103*, 1599–1604. https://doi.org/10.1073/pnas.0506308103

Ariel, R., & Castel, A. D. (2014). Eyes wide open: Enhanced pupil dilation when selectively studying important information. *Experimental Brain Research, 232*(1), 337–344. https://doi.org/10.1007/s00221-013-3744-5

Bandura, A. (1977). Self-efficacy: Toward a unifying theory of behavioral change. *Psychological Review, 84*(2), 191–215. https://doi.org/10.1037//0033-295x.84.2.191

Berger, A., Henik, A., & Rafal, R. (2005). Competition between endogenous and exogenous orienting of visual attention. *Journal of Experimental Psychology: General, 134*(2), 207–221. https://doi.org/10.1037/0096-3445.134.2.207

Boucher, H. C., & Kofos, M. N. (2012). The idea of money counteracts ego depletion effects. *Journal of Experimental Social Psychology, 48*(4), 804–810. https://doi.org/10.1016/j.jesp.2012.02.003

Bunzeck, N., Dayan, P., Dolan, R. J., & Duzel, E. (2010). A common mechanism for adaptive scaling of reward and novelty. *Human Brain Mapping, 31*(9), 1380–1394. https://doi.org/10.1002/hbm.20939

Callan, D. E., & Schweighofer, N. (2008). Positive and negative modulation of word learning by reward anticipation. *Human Brain Mapping, 29*(2), 237–249. https://doi.org/10.1002/hbm.20383

Castel, A. D., Murayama, K., Friedman, M. C., McGillivray, S., & Link, I. (2013). Selecting valuable information to remember: Age-related differences and similarities in self-regulated learning. *Psychology and Aging, 28*(1), 232–242. https://doi.org/10.1037/a0030678

Chen, M. K., & Risen, J. L. (2010). How choice affects and reflects preferences: Revisiting the free-choice paradigm. *Journal of Personality and Social Psychology, 99*(4), 573–594. https://doi.org/10.1037/a0020217

Cheng, S., Jiang, T., Xue, J., Wang, S., Chen, C., & Zhang, M. (2020). The influence of rewards on incidental memory: More does not mean better. *Learning and Memory, 27*(11), 462–466. https://doi.org/10.1101/lm.051722.120

Clewett, D., & Murty, V. P. (2019). Echoes of emotions past: How neuromodulators determine what we recollect. *eNeuro*. https://doi.org/10.1523/ENEURO.0108-18.2019

Cohen, M. S., Rissman, J., Suthana, N. A., Castel, A. D., & Knowlton, B. J. (2014). Value-based modulation of memory encoding involves strategic engagement of fronto-temporal semantic processing regions. *Cognitive, Affective, & Behavioral Neuroscience, 14*(2), 578–592. https://doi.org/10.3758/s13415-014-0275-x

Cohen, M. S., Rissman, J., Suthana, N. A., Castel, A. D., & Knowlton, B. J. (2016). Effects of aging on value-directed modulation of semantic network activity during verbal learning. *NeuroImage, 125*, 1046–1062. https://doi.org/10.1016/j.neuroimage.2015.07.079

Dayan, P., & Niv, Y. (2008). Reinforcement learning: The good, the bad and the ugly. *Current Opinion in Neurobiology, 18*(2), 185–196. https://doi.org/10.1016/j.conb.2008.08.003

Deci, E. L. (1971). Effects of externally mediated rewards on intrinsic motivation. *Journal of Personality and Social Psychology, 18*(1), 105–115.

Deci, E. L., Koestner, R., & Ryan, R. M. (1999). A meta-analytic review of experiments examining the effects of extrinsic rewards on intrinsic motivation. *Psychological Bulletin, 125*(6), 627–668.

Di Domenico, S. I., & Ryan, R. M. (2017). The emerging neuroscience of intrinsic motivation: A new frontier in self-determination research. *Frontiers in Human Neuroscience, 11*, 145. https://doi.org/10.3389/fnhum.2017.00145

Duan, H., Fernandez, G., van Dongen, E., & Kohn, N. (2020). The effect of intrinsic and extrinsic motivation on memory formation: Insight from behavioral and imaging study. *Brain Structure & Function, 225*(5), 1561–1574. https://doi.org/10.1007/s00429-020-02074-x

DuBrow, S., Eberts, E. A., & Murty, V. P. (2019). A common mechanism underlying choice's influence on preference and memory. *Psychonomic Bulletin & Review*. https://doi.org/10.3758/s13423-019-01650-5

Eisenberger, R., Pierce, W. D., & Cameron, J. (1999). Effects of reward on intrinsic motivation–negative, neutral and positive: Comment on. *Psychological Bulletin, 125*(6), 677–691. discussion 692–700.

Elliot, A. J. (2008). *Handbook of avoidance and approach motivation*. Psychology.

Elliott, B. L., Blais, C., McClure, S. M., & Brewer, G. A. (2019). Neural correlates underlying the effect of reward value on recognition memory. *NeuroImage*. https://doi.org/10.1016/j.neuroimage.2019.116296

Ergo, K., De Loof, E., & Verguts, T. (2020). Reward prediction error and declarative memory. *Trends in Cognitive Sciences, 24*(5), 388–397. https://doi.org/10.1016/j.tics.2020.02.009

Fujiwara, J., Usui, N., Park, S. Q., Williams, T., Iijima, T., Taira, M., et al. (2013). Value of freedom to choose encoded by the human brain. *Journal of Neurophysiology, 110*(8), 1915–1929. https://doi.org/10.1152/jn.01057.2012

Godijn, R., & Theeuwes, J. (2002). Programming of endogenous and exogenous saccades: Evidence for a competitive integration model. *Journal of Experimental Psychology: Human Perception and Performance, 28*(5), 1039–1054. https://doi.org/10.1037//0096-1523.28.5.1039

Gureckis, T. M., & Markant, D. B. (2012). Self-directed learning: A cognitive and computational perspective. *Perspectives on Psychological Science, 7*(5), 464–481. https://doi.org/10.1177/1745691612454304

Helen, C., & Boucher, M. N. K. (2012). The idea of money counteracts ego depletion effects. *Journal of Experimental Social Psychology, 48*, 804–810.

Hendijani, R., & Steel, P. (2020). Motivational congruence effect: How reward salience and choice influence motivation and performance. *Cogent Business & Management, 7*(1), 1791444.

Houlfort, N., Koestner, R., Joussemet, M., Nantel-Vivier, A., & Lekes, N. (2002). The impact of performance-contingent rewards on perceived autonomy and competence. *Motivation and Emotion, 26*(4), 279–295.

Izuma, K., & Murayama, K. (2013). Choice-induced preference change in the free-choice paradigm: A critical methodological review. *Frontiers in Psychology, 4*, 41. https://doi.org/10.3389/fpsyg.2013.00041

Jin, J., Yu, L., & Ma, Q. (2015). Neural basis of intrinsic motivation: Evidence from event-related potentials. *Computational Intelligence and Neuroscience, 2015*, 698725. https://doi.org/10.1155/2015/698725

Kaplan, F., & Oudeyer, P. Y. (2007). In search of the neural circuits of intrinsic motivation. *Frontiers in Neuroscience, 1*(1), 225–236. https://doi.org/10.3389/neuro.01.1.1.017.2007

Lakens, D. (2013). Calculating and reporting effect sizes to facilitate cumulative science: A practical primer for t-tests and ANOVAs. *Frontiers in Psychology, 4*, 863. https://doi.org/10.3389/fpsyg.2013.00863

Leotti, L. A., & Delgado, M. R. (2011). The inherent reward of choice. *Psychological Science, 22*(10), 1310–1318. https://doi.org/10.1177/0956797611417005

Leotti, L. A., & Delgado, M. R. (2014). The value of exercising control over monetary gains and losses. *Psychological Science, 25*(2), 596–604. https://doi.org/10.1177/0956797613514589

Leotti, L. A., Iyengar, S. S., & Ochsner, K. N. (2010). Born to choose: The origins and value of the need for control. *Trends in Cognitive Sciences, 14*(10), 457–463. https://doi.org/10.1016/j.tics.2010.08.001

Lewthwaite, R., Chiviacowsky, S., Drews, R., & Wulf, G. (2015). Choose to move: The motivational impact of autonomy support on motor learning. *Psychonomic Bulletin & Review, 22*(5), 1383–1388. https://doi.org/10.3758/s13423-015-0814-7

Lupyan, G., & Ward, E. J. (2013). Language can boost otherwise unseen objects into visual awareness. *Proceedings of the National Academy of Sciences of the United States of America, 110*(35), 14196–14201. https://doi.org/10.1073/pnas.1303312110

Ma, Q., Jin, J., Meng, L., & Shen, Q. (2014). The dark side of monetary incentive: How does extrinsic reward crowd out intrinsic motivation. *NeuroReport, 25*(3), 194–198. https://doi.org/10.1097/WNR.0000000000000113

MacAskill, M., Hirst, R., & Peirce, J. (2022). Building Experiments in PsychoPy. *Building Experiments in PsychoPy*, 1–100.

Macmillan, N., & Creelman, C. D. (2004). *Detection theory: A user's guide*. Psychology Press.

Madan, C. R., & Spetch, M. L. (2012). Is the enhancement of memory due to reward driven by value or salience? *Acta Pathologica, Microbiologica, Et Immunologica Scandinavica, 139*(2), 343–349. https://doi.org/10.1016/j.actpsy.2011.12.010

Markant, D. B., DuBrow, S., Davachi, L., & Gureckis, T. M. (2014). Deconstructing the effect of self-directed study on episodic memory. *Memory & Cognition, 42*(8), 1211–1224. https://doi.org/10.3758/s13421-014-0435-9

Markant, D. B., & Gureckis, T. M. (2014). Is it better to select or to receive? Learning via active and passive hypothesis testing. *Journal of Experimental Psychology: General, 143*(1), 94–122. https://doi.org/10.1037/a0032108

Martin, B. (1963). Reward and punishment associated with the same goal response: A factor in the learning of motives. *Psychological Bulletin, 60*, 441–451. https://doi.org/10.1037/h0045000

Meng, L., & Ma, Q. (2015). Live as we choose: The role of autonomy support in facilitating intrinsic motivation. *International Journal of Psychophysiology, 98*(3 Pt 1), 441–447. https://doi.org/10.1016/j.ijpsycho.2015.08.009

Miendlarzewska, E. A., Bavelier, D., & Schwartz, S. (2016). Influence of reward motivation on human declarative memory. *Neuroscience and Biobehavioral Reviews, 61*, 156–176. https://doi.org/10.1016/j.neubiorev.2015.11.015

Mobbs, D., Hassabis, D., Seymour, B., Marchant, J.L., Weiskopf, N., Dolan, R.J., Frith, C.D. (2009). Choking on the money: reward-based performance decrements are associated with midbrain activity. *Psychological Science, 20*, 955–962. https://doi.org/10.1111/j.1467-9280.2009.02399.x

Murayama, K., Matsumoto, M., Izuma, K., & Matsumoto, K. (2010). Neural basis of the undermining effect of monetary reward on intrinsic motivation. *Proceedings of the National Academy of Sciences of the United States of America, 107*(49), 20911–20916. https://doi.org/10.1073/pnas.1013305107

Murayama, K., & Kuhbandner, C. (2011). Money enhances memory consolidation—But only for boring material. *Cognition, 119*(1), 120–124. https://doi.org/10.1016/j.cognition.2011.01.001

Murayama, K., & Kitagami, S. (2014). Consolidation power of extrinsic rewards: Reward cues enhance long-term memory for irrelevant past events. *Journal of Experimental Psychology: General, 143*(1), 15–20. https://doi.org/10.1037/a0031992

Murayama, K., Matsumoto, M., Izuma, K., Sugiura, A., Ryan, R. M., Deci, E. L., & Matsumoto, K. (2015). How self-determined choice facilitates performance: A key role of the ventromedial prefrontal cortex. *Cerebral Cortex, 25*(5), 1241–1251. https://doi.org/10.1093/cercor/bht317

Murty, V. P., & Adcock, R. A. (2014). Enriched encoding: Reward motivation organizes cortical networks for hippocampal detection of unexpected events. *Cerebral Cortex, 24*(8), 2160–2168. https://doi.org/10.1093/cercor/bht063

Murty, V. P., DuBrow, S., & Davachi, L. (2015). The simple act of choosing influences declarative memory. *Journal of Neuroscience, 35*(16), 6255–6264. https://doi.org/10.1523/JNEUROSCI.4181-14.2015

Murty, V. P., DuBrow, S., & Davachi, L. (2019). Decision-making increases episodic memory via postencoding consolidation. *Journal of Cognitive Neuroscience, 31*(9), 1308–1317. https://doi.org/10.1162/jocn_a_01321

Olejnik, S., & Algina, J. (2003). Generalized eta and omega squared statistics: Measures of effect size for some common research designs. *Psychological Methods, 8*(4), 434–447. https://doi.org/10.1037/1082-989X.8.4.434

Oudeyer, P. Y., Gottlieb, J., & Lopes, M. (2016). Intrinsic motivation, curiosity, and learning: Theory and applications in educational technologies. *Progress in Brain Research, 229*, 257–284. https://doi.org/10.1016/bs.pbr.2016.05.005

Patall, E. A., Cooper, H., & Robinson, J. C. (2008). The effects of choice on intrinsic motivation and related outcomes: A meta-analysis of research findings. *Psychological Bulletin, 134*(2), 270–300. https://doi.org/10.1037/0033-2909.134.2.270

Pessoa, L. (2009). How do emotion and motivation direct executive control? *Trends in Cognitive Sciences, 13*(4), 160–166. https://doi.org/10.1016/j.tics.2009.01.006

Qin, N., Xue, J., Chen, C., & Zhang, M. (2020). The bright and dark sides of performance-dependent monetary rewards: Evidence from visual perception tasks. *Cognitive Science, 44*(3), e12825. https://doi.org/10.1111/cogs.12825

Rodgers, W. M., Conner, M., & Murray, T. C. (2008). Distinguishing among perceived control, perceived difficulty, and self-efficacy as determinants of intentions and behaviours. *British Journal of Social Psychology, 47*(Pt 4), 607–630. https://doi.org/10.1348/014466607X248903

Ross, M. (1975). Salience of reward and intrinsic motivation. *Journal of Personality and Social Psychology, 32*(2), 245.

Rouhani, N., Norman, K. A., & Niv, Y. (2018). Dissociable effects of surprising rewards on learning and memory. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 44*(9), 1430–1443. https://doi.org/10.1037/xlm0000518

Rugg, M. D., Mark, R. E., Walla, P., Schloerscheidt, A. M., Birch, C. S., & Allan, K. (1998). Dissociation of the neural correlates of implicit and explicit memory. *Nature, 392*(6676), 595–598. https://doi.org/10.1038/33396

Ruggeri, A., Markant, D. B., Gureckis, T. M., Bretzke, M., & Xu, F. (2019). Memory enhancements from active control of learning emerge across development. *Cognition, 186*, 82–94. https://doi.org/10.1016/j.cognition.2019.01.010

Schultz, W., Dayan, P., & Montague, P. R. (1997). A neural substrate of prediction and reward. *Science, 275*(5306), 1593–1599. http://www.ncbi.nlm.nih.gov/pubmed/9054347, http://science.sciencemag.org/content/sci/275/5306/1593.full.pdf

Sheldon, S., & Moscovitch, M. (2010). Consciousness and the relation between implicit and explicit memory. *New Horizons in the Neuroscience of Consciousness, 79*, 83.

Shohamy, D., & Adcock, R. A. (2010). Dopamine and adaptive memory. *Trends in Cognitive Sciences, 14*(10), 464–472. https://doi.org/10.1016/j.tics.2010.08.002

Skinner, B. F. (1938). *The behavior of organisms: An experimental analysis*. Appleton-Century-Crofts.

Skinner, B. F. (1955). The control of human behavior. *Transactions of the New York Academy of Sciences, 17*(7), 547–551.

Stephens, J. M. (1933). Punishment and reward in learning. *Science, 78*(2012), 60. https://doi.org/10.1126/science.78.2012.60

Sutton, R. S., & Barto, A. G. (1998). *Reinforcement learning: An introduction*. Massachusetts: MIT Press.

Swirsky, L. T., Shulman, A., & Spaniol, J. (2021). The interaction of curiosity and reward on long-term memory in younger and older adults. *Psychology and Aging, 36*(5), 584–603. https://doi.org/10.1037/pag0000623

Voss, J. L., Galvan, A., & Gonsalves, B. D. (2011a). Cortical regions recruited for complex active-learning strategies and action planning exhibit rapid reactivation during memory retrieval. *Neuropsychologia, 49*(14), 3956–3966. https://doi.org/10.1016/j.neuropsychologia.2011.10.012

Voss, J. L., Gonsalves, B. D., Federmeier, K. D., Tranel, D., & Cohen, N. J. (2011b). Hippocampal brain-network coordination during volitional exploratory behavior enhances learning. *Nature Neuroscience, 14*(1), 115–120. https://doi.org/10.1038/nn.2693

Williams, J. H., Massaro, D. W., Peel, N. J., Bosseler, A., & Suddendorf, T. (2004). Visual-auditory integration during speech imitation in autism. *Research in Developmental Disabilities, 25*(6), 559–575. https://doi.org/10.1016/j.ridd.2004.01.008

Zhang, M., Tu, J., Dong, B., Chen, C., & Bao, M. (2017). Preliminary evidence for a role of the personality trait in visual perceptual learning. *Neurobiology of Learning and Memory, 139*, 22–27. https://doi.org/10.1016/j.nlm.2016.12.009

Zhou, X., Vohs, K. D., & Baumeister, R. F. (2009). The symbolic power of money: Reminders of money alter social distress and physical pain. *Psychological Science, 20*(6), 700–706. https://doi.org/10.1111/j.1467-9280.2009.02353.x