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Reward-Enhanced Memory in Younger and Older Adults

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Explicitly claims to have predicted no difference, and opted to test this with a p-value

Objectives. We investigated how the anticipation of remote monetary reward modulates intentional episodic memory formation in younger and older adults. On the basis of prior findings of preserved reward–cognition interactions in aging, we predicted that reward anticipation would be associated with enhanced memory in both younger and older adults. On the basis of previous demonstrations of a time-dependent effect of reward anticipation on memory, we expected the memory enhancement to increase with study–test delay.

Method. In Experiment 1, younger and older participants encoded a series of picture stimuli associated with high- or low-reward values. At test (24-hr postencoding), recognition hits resulted in either high or low monetary rewards, whereas false alarms were penalized to discourage guessing. Experiment 2 was similar to Experiment 1, but the study–test delay was manipulated within subjects (immediate vs 24 hr).

Results. In Experiment 1, younger and older adults showed enhanced recognition for high-reward pictures compared with low-reward pictures. Experiment 2 replicated this finding and additionally showed that the effect did not extend to immediate recognition.

Discussion. The current findings provide support for a time-dependent mechanism of reward-based memory enhancement. They also suggest that aging leaves intact the positive influence of reward anticipation on intentional long-term memory formation.

Key Words: Episodic memory—Incentives—Motivation—Older adults—Reward anticipation.

WHY are some experiences remembered, while others are forgotten? One factor that shapes memory is motivation (Shohamy & Adcock, 2010). Laboratory studies with healthy younger adults have shown that motivational states associated with anticipating and obtaining reward (money, points, or other motivationally significant outcomes) can enhance memory. Cues that signal opportunities for future reward are better remembered than neutral cues (Wittmann, Dolan, & Düzel, 2011; Wittmann, Schiltz, Boehler, & Düzel, 2008; Wittmann et al., 2005), an advantage that extends to unrelated information that is presented after the reward-signaling cue (Adcock, Thangavel, Whitfield-Gabrieli, Knutson, & Gabrieli, 2006; Kuhl, Shah, DuBrow, & Wagner, 2010). Thus, the mere anticipation of a reward can enhance memory formation, at least when the availability of reward is manipulated within lists and within subjects, as opposed to between lists or between subjects (Ngaosuvan & Mäntylä, 2005; Nilsson, 1987). Memory is also enhanced by reward outcomes, such that events preceding and following the receipt of a reward are better remembered than events surrounding a neutral or negative outcome (Mather & Schoeke, 2011). Finally, both incidental memory formation (Bialleck et al., 2011; Mather & Schoeke, 2011; Murayama & Kuhbandner, 2011; Wittmann et al., 2005, 2008, 2011) and intentional memory formation (Adcock et al., 2006; Kuhl et al., 2010; Murty, LaBar, Hamilton, & Adcock, 2011) are sensitive to reward, suggesting that reward effects on memory are not limited to a specific set of encoding operations.

The neurobiological mechanisms underlying reward-based enhancement of episodic memory are still under investigation, but converging evidence from animal neurophysiology, neuropharmacology, and human neuroimaging experiments points toward dopaminergic modulation of hippocampally based long-term consolidation processes as a likely candidate (for a review, see Shohamy & Adcock, 2010). Indeed, in a recent behavioral study in humans, reward anticipation during encoding had a greater effect on memory performance on delayed tests of memory than on immediate tests (Murayama & Kuhbandner, 2011; though this finding was seen only for items rated as uninteresting by participants not for items rated as interesting). Similarly, Murayama and Kitagami (2013) found that reward cues enhance delayed but not immediate recognition memory for just-presented items. Although consistent with a reward effect on long-term consolidation, it should be noted that the Reward × Delay interaction on human memory could also be explained by other mechanisms, such as a selective effect of reward on "storage strength" rather than "retrieval strength" (Bjork & Bjork, 1992; see also Kornell, Bjork, & Garcia, 2011).

Little is known about the effects of reward anticipation on episodic memory in older adults. Yet, given the ubiquitous finding of age-related deficits in episodic memory (for reviews, see Light, 2000; Zacks, Hasher, & Li, 2000),

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the question of whether older adults' memory remains sensitive to motivational influences is an important one. For example, it remains to be established what role motivational manipulations could play in memory training in the aging population.

Aging is associated with well-documented decline in dopamine systems (Kaasinen et al., 2000; Wang et al., 1998), and there is a good amount of evidence suggesting that the acquisition of stimulus–reward associations may be impaired in older adults (for reviews, see Eppinger, Hämmerer, & Li, 2011; Mohr, Li, & Heekeren, 2010). At the same time, some studies indicate that the influence of reward feedback on memory may be preserved in older adults (Eppinger & Kray, 2011; Spaniol & Wegier, 2012; Weiler, Bellebaum, & Daum, 2008; see also Mata, Josef, Samanez-Larkin, & Hertwig, 2011). However, most of the existing studies on aging and reward effects on memory have used associative learning paradigms, such as the Iowa Gambling Task (Denburg, Tranel, & Bechara, 2005). In these tasks, stimulus–outcome pairings are acquired gradually, over the course of multiple learning trials. It is thus unclear whether their results generalize to hippocampus-dependent memory for unique episodes.

One piece of evidence that relates to this issue is the literature on value-directed encoding in younger and older adults (Castel, 2007; Castel, Benjamin, Craik, & Watkins, 2002; Castel, Farb, & Craik, 2007; Castel et al., 2011; Castel, Murayama, Friedman, McGillivray, & Link, 2013). In the value-directed remembering paradigm, participants are presented with lists of words in which each word has a specific point value. Participants can earn points by remembering the words, and the goal is to earn as many points as possible. In this task, older adults tend to remember fewer words than younger adults, but they are successful at using a variety of encoding strategies (e.g., selective attention and rehearsal) to prioritize high-value over low-value words (Castel, 2007; Castel et al., 2002, 2007, 2011, 2013). These findings indicate that aging is associated with preserved access to metacognitive skills that enable selective remembering of high-value information, at least when memory is tested after brief delays (i.e., minutes), memory load is relatively low (12–20 words), and incentives are strictly symbolic (points). It is unclear, at this point, whether the age-related equivalence in value-directed encoding would extend to situations involving longer delays, longer lists, and more potent incentives such as monetary rewards.

Only one study to date (Mather & Schoeke, 2011) has investigated the effects of reward on incidental memory formation in younger and older adults. When encoding is incidental, reward effects are unlikely to reflect the use of reward-specific metacognitive strategies and are more likely to result from direct modulation of memory formation processes. Mather and Schoeke (2011) employed a modified monetary incentive delay task (Knutson, Fong, Adams, Varner, & Hommer, 2001), in which each trial started with a cue that indicated whether participants could gain money, lose money, or receive nothing by responding quickly to a visual target. Pictures of everyday objects served as visual targets, and the reward rate was held constant at 67% by virtue of an adaptive algorithm that adjusted target durations to each individual's response speed. At the end of each trial, participants received outcome feedback. The question of interest was how cue-induced reward anticipation, as well as reward outcomes, would affect memory for the target objects. Reward anticipation enhanced recognition memory, though this was seen only for positively valenced target objects. Reward outcomes (i.e., end-of-trial "hit" feedback) were associated with a stronger incidental memory enhancement than reward anticipation. Moreover, the effect did not depend on the valence of the target objects, and it extended to targets encoded in the two trials following the positive feedback. These patterns were similar for younger and older adults, suggesting that aging may leave intact the (nonstrategic) effects of reward anticipation and delivery on episodic memory formation.

Following up on Mather and Schoeke's (2011) study on incidental encoding, as well as the work by Castel and colleagues (Castel, 2007; Castel et al., 2002, 2007, 2011, 2013), the goal of the current study was to examine the effect of reward anticipation on intentional memory formation in younger and older adults. Intentional uses of memory are particularly compromised in normal aging (Craik & McDowd, 1987; Hasher & Zacks, 1979; Jennings & Jacoby, 1993), and thus represent an important target for training and intervention. If reward anticipation can boost intentional learning and long-term retention, this would provide a highly efficient means toward memory enhancement. We were specifically interested in motivational effects on intentional memory when no rewards are received during learning, as is often the case in everyday life.

Anecdotal evidence suggests that temporally remote incentives (e.g., money, grades, social recognition) can energize learning in younger adults, thereby enhancing later memory performance (but see Ngaosuvan & Mäntylä, 2005; Nilsson, 1987). Recent experimental findings (Adcock et al., 2006) confirm that anticipation of delayed rewards can boost memory formation in younger adults. In Adcock and colleagues' (2006) monetary incentive encoding (MIE) paradigm, participants studied 120 pictures of scenes, each of which was preceded by a cue indicating the sum of money ($0.01 or $5.00) that could be earned by correctly identifying the picture on a subsequent recognition test. Immediately after each picture presentation, participants had to complete several trials of a speeded visual motor task ("arrow task") that had an attention-demanding choice component, similar to distractor tasks used in the literature on divided attention and memory (Craik, Govoni, Naveh-Benjamin, & Anderson, 1996). On the recognition test, 24 hr after encoding, participants gained money for recognition hits. Recognition hit rates for high-reward items exceeded those for low-reward items. Of note, performance on the arrow task was not modulated by the reward value of the just-seen picture. Such modulation would have been expected if high-reward pictures elicited more postencoding processing (e.g., rehearsal) than low-reward pictures. Additionally, the neuroimaging data revealed increased connectivity between hippocampus and the dopaminergic midbrain during encoding of subsequently remembered (vs not remembered) high-reward pictures. Converging with the reports of reward-enhanced incidental encoding (Bialleck et al., 2011; Mather & Schoeke, 2011; Murayama & Kuhbandner, 2011; Wittmann et al., 2005, 2008, 2011), Adcock and colleagues' (2006) findings suggest that, in younger adults, reward can modulate memory formation directly, without requiring postencoding rehearsal (cf. Castel, 2007; Castel et al., 2002).

In the first experiment of the current study, we used Adcock and colleagues' (2006) MIE paradigm to establish whether intentional long-term memory is enhanced by the anticipation of remote rewards in older adults. Based on previous findings of age-equivalent reward effects on incidental memory (Mather & Schoeke, 2011), we predicted that age differences in reward-motivated intentional memory enhancement would also be small or nonexistent. Objective measures of memory (recognition hit rates) were critical for testing our hypothesis, but we also collected recognition confidence ratings to explore potential effects of reward on subjective memory strength. In line with the idea that reward anticipation can influence memory without altering attentional deployment during encoding (Adcock et al., 2006), we further predicted that performance on the arrow task that followed each target presentation would show no effect of reward. In the second experiment, we further probed the time course of reward-motivated memory enhancement, by manipulating the interval between study and test.

General Method

Participants

All participants gave written informed consent for the study, which was approved by the ethics committee at Ryerson University. Each experiment included a unique set of participants. Participant characteristics are shown in Table 1. The younger adults were students who received partial course credit or $10.00/hr for their participation. The older adults were community-dwelling individuals who received $10.00/hr. Participants in both groups additionally had the opportunity to win monetary rewards for their performance in the MIE task, but this was not disclosed to participants until they arrived for their first testing sessions. This was done to ensure that the rewards would not constitute an incentive to participate. Participants were screened for major health problems (e.g., history of neurological or psychiatric illness, cancer, cardiovascular disease), had normal or corrected-to-normal vision and hearing, and scored 27 or higher on the Mini-Mental State Examination (Folstein, Folstein, & McHugh, 1975).

Table 1. Participant Characteristics by Age Group and Experiment

Characteristic	Younger adults	Older adults
Experiment 1		
N	36 (18 females)	37 (18 females)
Age (yr)	23.06 (3.33)	73.03 (7.99)
Age range	18–33	60–88
Education (yr)	16.58 (1.99)	16.00 (2.98)
Vocabulary[a]	17.81 (4.59)	24.28 (3.90)
MMSE	29.36 (1.15)	28.65 (1.09)
Experiment 2		
N	32 (24 females)	32 (24 females)
Age (yr)	21.25 (4.41)	71.13 (5.77)
Age range	18–33	63–89
Education (yr)[b]	14.56 (1.52)	16.81 (2.97)
Vocabulary[c]	15.03 (3.71)	22.91 (4.18)
MMSE	28.78 (1.10)	28.56 (1.01)

Notes. MMSE = Mini-Mental State Examination (Folstein et al., 1975); Vocabulary = raw score (maximum of 33) on the Mill-Hill Vocabulary Scale (Raven, 1982). Standard deviations are shown in parentheses.

[a]Significant age difference, $t(70) = 6.47$, $p < .01$, $\eta^2 = 0.37$. Vocabulary data from one older adult were missing.

[b]Significant age difference, $t(69) = 4.12$, $p < .01$, $\eta^2 = 0.20$.

[c]Significant age difference, $t(69) = 8.52$, $p < .01$, $\eta^2 = 0.51$.

Stimuli and Apparatus

E-Prime (Psychology Software Tools, Inc.) was used for stimulus presentation and response collection on a laptop computer with a 15-in. flat-panel LCD. Viewing distance was approximately 50 cm. All stimuli were presented centrally against a black background. Instructions, cues, and feedback messages appeared in white 18-point Arial font. The number keys (1–4) at the top of the keyboard were used for confidence ratings following "old" judgments.

Experiment 1

Method

Design.—The design included the between-subject factor age group (younger vs older) and the within-subject factor reward (high vs low).

Materials.—The stimuli included 248 color photographs of scenes (124 indoor, 124 outdoor; see Figure 1 for examples), taken from a picture database in CorelDraw. Each stimulus measured 4.8 × 4.8 cm onscreen. None of the stimuli contained people or animals. The materials were divided into four stimulus sets of 60 stimuli (half indoor, half outdoor). The sets contained approximately equal proportions of specific types of indoor scenes (e.g., kitchens, living rooms) and outdoor scenes (e.g., deserts, mountains).

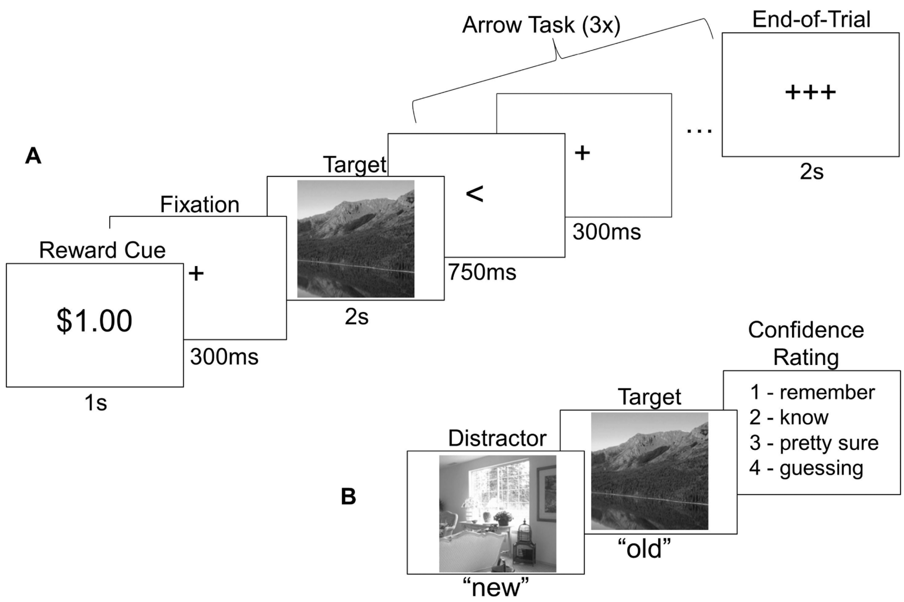

Figure 1. Trial procedure in Experiment 1. (A) Example of a study trial. (B) Example of two test trials. The first trial is a correct rejection, and the second trial is a hit followed by a confidence rating.

Procedure.—At the beginning of Session 1, the experimenter provided detailed task instructions, including an explanation of the reward scheme. The encoding task was thus intentional. A 10-min practice task served to familiarize participants with the requirements of both the study phase and the test phase. The practice task included 20 stimuli that were not used during the experimental trials.

The experiment closely followed the procedures for the monetary encoding task described by Adcock and colleagues (2006). Participants completed 124 study trials, of which the first 4 were treated as primacy buffers and were later excluded. Figure 1A illustrates the timing of the trial sequence. A literal cue informed participants of the reward value (high: \$1.00; low: \$0.01) of the upcoming stimulus. The stimulus itself required no manual response but was immediately followed by a 3-trial choice reaction time task ("arrow task"). On each trial of the arrow task, an arrowhead was presented, with a left-pointing arrowhead cuing a left key-press, and a right-pointing arrowhead cuing a right key-press. The arrow sequences were pseudorandom. The purpose of the arrow task was to bind participant's attention and minimize any effect of the reward cue on strategic rehearsal after the presentation of each stimulus.

The test phase was administered 24 hr after the study phase. After reviewing the instructions for the recognition test, participants completed 248 test trials, presented in random order. The timing of the test trials was self-paced. Following each "old" response, participants were asked to rate their confidence in this decision on a 4-point scale. They were instructed to choose "1" if they remembered the moment that they encountered the picture, "2" if they felt sure that the picture was presented, but had no specific memory, "3" if they were pretty sure but not certain that the picture was old, and "4" if they were just guessing that the picture was old (Adcock et al., 2006).

The first eight trials included the four target stimuli that had served as primacy buffers during the study phase, as well as four distractors. These trials were later excluded, leaving 240 trials (60 high-reward targets, 60 low-reward targets, and 120 distractors) in the analysis. Figure 1B illustrates the trial procedure. For each correct "old" response (i.e., recognition hit), participants received either \$1.00 or \$0.01, depending on the reward value of the target. To discourage overly liberal responding, incorrect "old" responses (i.e., false alarms) were penalized with −\$0.50. Participants received no feedback until the end of the test phase, when they received a cash payment of the cumulative rewards earned in the study.

The assignment of specific stimulus sets (see *Materials* section) to high-reward target status, low-reward target status, and distractor status was counterbalanced across participants in each age group, as was the assignment of response keys to "old" and "new" responses (old left vs old right), resulting in eight counterbalancing conditions. Each of these conditions was administered to 4–5 participants in each age group. The order of trials within the study and test phases was individually randomized for each participant.

Results

Arrow task performance.—Performance on the arrow task, during the study phase, was of interest because it provided an indirect measure of reward cue effects on encoding. For example, stimuli that were preceded by high-reward cues (henceforth referred to as "high-reward stimuli") may have attracted more attention or elicited a greater postencoding rehearsal effort compared with low-reward stimuli. If so, performance on the arrows task should be worse following high-reward stimuli than following low-reward stimuli. Using mixed analyses of variance (ANOVAs), we examined the effects of age group (young vs old), order (first vs second vs third arrow presentation within each study trial), and reward (high vs low) on three performance indices: the proportion of failures to respond while the arrow was on the screen, response accuracy, and response time (RT; see Table 2). In each case, only the main effect of reward, as well as interactions of reward with age and trial order, was of interest. We therefore do not report the other effects.

Small but significant effect

Failures to respond. The main effect of reward was significant, $F(1, 142) = 5.21$, $p = .03$, $\eta_p^2 = 0.07$, with a slightly greater proportion of response failures on low-reward trials ($M = 0.11$) than on high-reward trials ($M = 0.10$). This effect was qualified by a significant Age Group × Order × Reward interaction, $F(2, 142) = 3.92$, $p = .02$, $\eta_p^2 = 0.05$. We probed this interaction with separate repeated measures ANOVAs for each age group. For older adults, no effects involving reward were significant, whereas for younger adults, there was a significant main effect of reward, $F(1, 71) = 7.75$, $p < .01$, $\eta_p^2 = 0.18$, as well as a significant Order × Reward interaction, $F(2, 71) = 5.43$, $p < .01$, $\eta_p^2 = 0.13$. Individual t tests showed that reward affected younger adults' failure-to-respond rate for the first arrow only, $t(35) = 2.73$, $p = .01$, $\eta^2 = 0.18$, with a higher failure-to-respond rate on low-reward trials ($M = 0.17$) than on high-reward trials ($M = 0.13$).

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Accuracy. There were no significant effects involving reward.

Median RT. There was a significant main effect of reward on median RT, $F(1, 142) = 8.12$, $p = .01$, $\eta_p^2 = 0.10$. Arrow-task responses following high-reward stimuli ($M = 499$ ms) were slower than those following low-reward stimuli ($M = 496$ ms). Although statistically significant, the RT difference was so small that it was unlikely to represent a psychologically meaningful effect.

Recognition performance.—Hit rates and false alarm rates are shown in Table 2. Because the distractor stimuli were never paired with reward values, they could not be sorted according to reward. Accordingly, only a single false alarm rate was calculated for each participant. Inferential tests of reward on memory were therefore limited to the analysis of hit rates (for similar cases, see Adcock et al., 2006; Mather & Schoeke, 2011). For descriptive purposes, we also report the sensitivity measure d' (Green & Swets, 1966) and the response bias measure c (Macmillan & Creelman, 1990) for high-reward and low-reward conditions, using the same false alarm rates for both conditions. However, inferential tests on d' and c were limited to a comparison of the age groups, collapsing across the reward conditions.

Table 2. Experiment 1 Results

	Younger adults	Older adults
	Arrow task	
Failure-to-respond rate		
LR, Arrow 1	0.17 (0.17)	0.33 (0.21)
LR, Arrow 2	0.03 (0.04)	0.04 (0.06)
LR, Arrow 3	0.03 (0.03)	0.05 (0.09)
HR, Arrow 1	0.13 (0.13)	0.33 (0.22)
HR, Arrow 2	0.02 (0.03)	0.03 (0.05)
HR, Arrow 3	0.02 (0.04)	0.05 (0.08)
Accuracy		
LR, Arrow 1	0.99 (0.02)	0.95 (0.20)
LR, Arrow 2	0.96 (0.03)	0.92 (0.20)
LR, Arrow 3	0.96 (0.04)	0.94 (0.20)
HR, Arrow 1	0.99 (0.02)	0.95 (0.21)
HR, Arrow 2	0.96 (0.04)	0.93 (0.20)
HR, Arrow 3	0.96 (0.04)	0.93 (0.19)
RT (ms)		
LR, Arrow 1	566 (57)	648 (45)
LR, Arrow 2	398 (37)	484 (52)
LR, Arrow 3	393 (39)	484 (55)
HR, Arrow 1	570 (53)	650 (63)
HR, Arrow 2	401 (36)	492 (56)
HR, Arrow 3	395 (39)	486 (57)
	Recognition task	
Hit rate		
LR	0.54 (0.18)	0.61 (0.15)
HR	0.61 (0.16)	0.64 (0.14)
False alarm rate	0.20 (0.12)	0.32 (0.10)
d'		
LR	1.02 (0.45)	0.79 (0.44)
HR	1.23 (0.45)	0.88 (0.39)
C		
LR	0.42 (0.40)	0.08 (0.31)
HR	0.32 (0.37)	0.04 (0.36)
Confidence		
LR	1.99 (0.54)	2.38 (0.55)
HR	1.82 (0.47)	2.36 (0.58)

Notes. HR = high reward; LR = low reward; RT = response time. Confidence ratings were given on a scale of 1–4, with lower ratings indicating higher confidence. Standard deviations are shown in parentheses.

Hit rates. A mixed ANOVA with factors age group (young vs old) and reward (high vs low) yielded a significant effect of reward, $F(1, 71) = 19.43$, $p < .01$, $\eta_p^2 = 0.22$. On average, hit rates were higher for high-reward targets ($M = 0.63$) than for low-reward targets ($M = 0.57$). The Age Group × Reward interaction failed to reach significance, $F(1, 71) = 2.98$, $p = .09$, $\eta_p^2 = 0.04$, even though the power to detect a medium-sized interaction was high ($1 - \beta = 0.99$; Erdfelder, Faul, Lang, & Buchner, 2007). Separate t tests for each age group confirmed that the reward effect was significant for both younger adults, $t(35) = 3.73$, $p < .01$, $\eta^2 = 0.28$, and older adults, $t(36) = 2.33$, $p = .03$, $\eta^2 = 0.13$.

False alarm rate. The false alarm rate was significantly higher for older adults than for younger adults, $t(35) = 5.11$, $p < .01$, $\eta^2 = 0.43$.

Signal detection indices. Across the reward conditions, d' was significantly higher for younger adults ($M = 1.13$) than for older adults ($M = 0.84$), $t(71) = 3.05$, $p < .01$, $\eta^2 = 0.21$, whereas response bias was significantly more liberal for older adults ($M = 0.30$) than for younger adults ($M = 0.37$), $t(71) = 3.84$, $p < .01$, $\eta^2 = 0.29$.

Recognition confidence.—Following each "old" response on the recognition test, participants were asked to rate their confidence on a scale of 1–4, with low values indicating high confidence and high values indicating low confidence (see Figure 1; see also Adcock et al., 2006). On the basis of evidence that these types of judgments reflect a continuous memory strength variable (Wixted & Mickes, 2010), we calculated average confidence ratings for recognition hits (Table 2). It should be noted that a large literature associates remember/know judgments with recollection and familiarity, respectively (Tulving, 1985; Yonelinas, 2002). However, this strong assumption was not warranted in the current experiments. In our task (see also Adcock et al., 2006), participants were explicitly encouraged to base ratings on their recognition confidence, and received only minimal instruction regarding the formal distinction between remember and know states. Although the issue of different retrieval processes was not central to the aims of the current study, it would be interesting to examine, in future research, whether reward has a differential impact on familiarity and recollection. This could be accomplished, for example, with a remember/know procedure in which the two remember/know responses are not confounded with recognition confidence (see Wixted & Mickes, 2010). A mixed ANOVA on mean confidence ratings for recognition hits, with factors age group and reward, produced significant effects of age group, $F(1, 71) = 14.29$, $p < .01$, $\eta_p^2 = 0.17$ (younger adults: $M = 1.91$; older adults: $M = 2.37$), reward, $F(1, 71) = 10.26$, $p < .01$, $\eta_p^2 = 0.13$ (high: $M = 2.09$, low: $M = 2.18$), and Age Group × Reward, $F(1, 71) = 6.80$, $p = .01$, $\eta_p^2 = 0.09$. Follow-up *t* tests showed that younger adults were more confident in recognition hits to high-reward targets than in hits to low-reward targets, $t(35) = 3.56$, $p < .01$, $\eta^2 = 0.27$. For older adults, confidence in recognition hits did not differ as a function of reward, $t(36) = 0.51$, $p = .62$, $\eta^2 = 0.01$.

Discussion

Both younger and older adults in Experiment 1 demonstrated reward-enhanced recognition memory. As predicted, high-reward stimuli were more often correctly identified than low-reward stimuli, in both age groups. This replicates Adcock and colleagues' (2006) finding that intentional memory formation is boosted by the anticipation of uncertain remote rewards and parallels Mather and Schoeke's (2011) report of age-equivalent reward effects on incidental memory formation with immediate rewards.

Experiment 1 left several questions unanswered. First, the reward effect on recognition hit rates was modest, particularly in the older group, who also showed no reward-related boost in recognition confidence. Second, examination of the arrow-task responses, which offered an indirect measure of the attention devoted to high-reward and low-reward stimuli during encoding, yielded mixed results. In line with Adcock and colleagues' (2006) findings, we had hypothesized that reward would not affect arrow-task performance. However, in Experiment 1, younger adults failed to respond to the first arrow slightly more often after low-reward stimuli than after high-reward stimuli. There was also a very small, age-independent effect of reward on arrow RT. In summary, although we observed a modest reward-based enhancement of memory in both age groups, the experiment was inconclusive regarding the mechanism underlying this effect.

Experiment 2

The goals of Experiment 2 were twofold. First, we sought to replicate the finding of reward-enhanced intentional memory formation in younger and older adults. Second, we wanted to test whether the reward effect on memory, observed in both younger and older adults, would interact with the study–test delay (Murayama & Kuhbandner, 2011; see also Shohamy & Adcock, 2010). Reward × Delay interactions on memory have been widely interpreted as evidence for an effect of reward on long-term memory consolidation (Murayama & Kuhbandner, 2011; Shohamy & Adcock, 2010). Alternatively, it is possible that the reward effect in Experiment 1 resulted from differential study time allocation or selective rehearsal (Castel, 2007; Castel et al., 2002). To differentiate between these hypotheses, Experiment 2 thus featured a within-subjects manipulation of the retention interval. If reward anticipation modulates memory consolidation, its effect on memory should increase after a delay, when consolidation processes have had a chance to unfold (Hamann, 2001; McGaugh, 2000). No reward effect, or a smaller effect, should be seen on an immediate memory test. Similar time-dependent effects have been reported previously in the young–adult literature, both for reward effects on memory (Murayama & Kuhbandner, 2011) and for emotion effects on memory (Sharot, Delgado, & Phelps, 2004; Sharot & Yonelinas, 2008). In contrast, according to the reward-modulated encoding account, similar reward effects would be predicted on both immediate and delayed memory tests.

Method

Experiment 2 used the same procedures as Experiment 1, but additionally featured a within-subject manipulation of test delay. Half of the recognition test (30 high-reward targets, 30 low-reward targets, 60 distractors) was administered immediately following the study phase (“short delay”), whereas the other half was administered 24 hr later (“long delay”). The assignment of specific stimuli to the immediate and delayed test phases was counterbalanced across participants in each age group. During the study phase, short-delay targets and long-delay targets were randomly intermixed, and participants did not know which items they would be tested on at the short delay, and which at the long delay. Participants received their cumulative rewards for both sessions at the end of the second session.

Results

Arrow task performance.—We again conducted mixed ANOVAs of age group (young vs old), order (first vs second vs third arrow), and reward (high vs low) on failures to respond, accuracy, and RT on the arrow task (Table 3). There was no effect of reward, nor any interactions of reward with the other factors, for any of the measures.

Recognition performance.—Hit rates and false alarm rates, as well as d' and c indices, are shown in Table 3.

Hit rates. A mixed ANOVA with factors age group (young vs old), delay (short vs long), and reward (high vs low) yielded a significant effect of delay, $F(1, 62) = 71.37$, $p < .01$, $\eta^2_p = 0.54$. Hit rates were higher in the short-delay condition ($M = 0.76$) than in the long-delay condition ($M = 0.64$). The reward effect was also significant, $F(1, 62) = 10.17$, $p < .01$, $\eta^2_p = 0.14$. Hit rates were higher for high-reward targets ($M = 0.71$) than for low-reward targets ($M = 0.69$). These effects were qualified by a Delay × Reward interaction, $F(1, 62) = 4.22$, $p = .04$, $\eta^2_p = 0.06$. We probed this interaction with separate mixed ANOVAs for hit rates at the short and long delays, with factors age group and reward. At the short delay, there was no significant effect of reward, $F(1, 62) < 1.0$. At the long delay, there was a significant effect of reward, $F(1, 62) = 12.67$, $p < .01$, $\eta^2_p = 0.17$. None of the interactions involving age was significant, $F(1, 62) \leq .35$, $p \geq .56$, $\eta^2_p \leq 0.01$. Given their relevance to the hypotheses, we nevertheless tested the simple main effects of reward in the long-delay condition separately in each age group. The effect was significant for both younger adults, $t(31) = 2.42$, $p = .02$, $\eta^2 = 0.14$, and older adults, $t(31) = 2.65$, $p = .01$, $\eta^2 = 0.16$.

False alarm rate. A mixed ANOVA with factors age group and delay yielded a significant effect of age group, $F(1, 62) = 9.98$, $p < .01$, $\eta^2_p = 0.14$, with a higher mean false alarm rate in older adults ($M = 0.31$) than in younger adults ($M = 0.22$). The effect of delay was also significant, $F(1, 62) = 16.86$, $p < .01$, $\eta^2_p = 0.21$, with a higher mean false alarm rate at the long delay ($M = 0.28$) than at the short delay ($M = 0.24$).

Table 3. Experiment 2 Results

	Younger adults		Older adults	
	Arrow task			
Failure-to-respond rate				
LR, Arrow 1	0.11 (0.08)		0.30 (0.23)	
LR, Arrow 2	0.02 (0.04)		0.05 (0.06)	
LR, Arrow 3	0.02 (0.04)		0.04 (0.07)	
HR, Arrow 1	0.10 (0.07)		0.32 (0.24)	
HR, Arrow 2	0.02 (0.04)		0.05 (0.06)	
HR, Arrow 3	0.02 (0.03)		0.05 (0.07)	
Accuracy				
LR, Arrow 1	0.99 (0.01)		0.98 (0.05)	
LR, Arrow 2	0.98 (0.03)		0.96 (0.05)	
LR, Arrow 3	0.99 (0.02)		0.97 (0.05)	
HR, Arrow 1	0.99 (0.02)		0.99 (0.02)	
HR, Arrow 2	0.98 (0.03)		0.95 (0.08)	
HR, Arrow 3	0.99 (0.02)		0.96 (0.05)	
RT (ms)				
LR, Arrow 1	564 (47)		642 (41)	
LR, Arrow 2	397 (43)		490 (39)	
LR, Arrow 3	394 (45)		482 (47)	
HR, Arrow 1	563 (48)		640 (40)	
HR, Arrow 2	400 (45)		492 (42)	
HR, Arrow 3	400 (36)		480 (41)	
	Recognition task			
	Short delay	Long delay	Short delay	Long delay
Hit rate				
LR	0.76 (0.17)	0.61 (0.22)	0.75 (0.12)	0.62 (0.16)
HR	0.77 (0.14)	0.66 (0.20)	0.76 (0.12)	0.66 (0.15)
False alarm rate	0.20 (0.10)	0.24 (0.14)	0.28 (0.11)	0.33 (0.12)
d'				
LR	1.71 (0.59)	1.10 (0.58)	1.36 (0.50)	0.80 (0.43)
HR	1.74 (0.48)	1.25 (0.56)	1.37 (0.44)	0.94 (0.47)
C				
LR	0.05 (0.41)	0.24 (0.50)	−0.07 (.29)	0.07 (0.36)
HR	0.04 (0.39)	0.16 (0.46)	−0.07 (.31)	−0.01 (0.34)
Confidence				
LR	1.82 (0.46)	2.17 (0.42)	1.62 (0.50)	2.09 (0.60)
HR	1.75 (0.43)	2.15 (0.45)	1.62 (0.50)	2.05 (0.56)

Notes. HR = high reward; LR = low reward; RT = response time. Confidence ratings were given on a scale of 1–4, with lower ratings indicating higher confidence. Standard deviations are shown in parentheses.

Signal detection indices. A mixed ANOVA on d' with factors age group and delay, collapsed across the reward conditions, yielded a significant effect of age group, $F(1, 62) = 9.01$, $p < .01$, $\eta^2_p = 0.13$, with a higher d' in younger adults ($M = 1.45$) than in older adults ($M = 1.12$). The effect of delay was also significant, $F(1, 62) = 136.61$, $p < .01$, $\eta^2_p = 0.69$, with a higher d' at the short delay ($M = 1.55$) than at the long delay ($M = 1.02$). The Age Group × Delay interaction was nonsignificant, $F(1, 62) < 1$. The same ANOVA on the response bias measure c yielded a significant effect of delay, $F(1, 62) = 13.99$, $p < .01$, $\eta^2_p = 0.18$, with more liberal responding at the short delay ($M = −0.01$) than at the long delay ($M = 0.12$). Neither the main effect of age group, $F(1, 62) = 2.60$, $p = .11$, $\eta^2_p = 0.04$, nor the Age Group × Delay interaction, $F(1, 62) < 1$, was significant.

Recognition confidence.—A mixed ANOVA on mean confidence ratings for recognition hits, with factors age group, delay, and reward, produced only a significant effect of delay, $F(1, 62) = 137.15$, $p < .01$, $\eta_p^2 = 0.69$. Confidence was higher at the short delay ($M = 1.70$) than at the long delay ($M = 2.12$).

Discussion

Predicted equal effects

There were two critical findings in Experiment 2. First, both age groups showed equivalent reward-related improvements in recognition memory at the long test delay. This finding replicates the result of Experiment 1 and suggests that reward-based modulation of episodic memory remains intact in older adults. Second, neither age group showed an effect of reward on memory at the short delay. This dissociation is consistent with the consolidation hypothesis (Adcock et al., 2006; Murayama & Kuhbandner, 2011; see also Shohamy & Adcock, 2010), though it may also be accounted for by differential effects of reward anticipation on different types of memory strength (Bjork & Bjork, 1992; Kornell et al., 2011; see *General Discussion* section). An alternative hypothesis, whereby participants devote more attention or additional rehearsal to high-reward stimuli at encoding (Castel, 2007; Castel et al., 2002), cannot easily account for the Delay × Reward interaction in Experiment. Consistent with idea that the reward-based modulation of memory processes does not involve attentional modulation during encoding, there was no effect of reward anticipation on arrow-task performance, in either age group. Finally, the recognition confidence data gave no indication that reward anticipation during encoding affected the subjective quality of episodic memory at retrieval.

General Discussion

This study was the first to examine the effects of delayed financial rewards on intentional episodic memory formation in younger and older adults. In two experiments using the MIE task (Adcock et al., 2006; Kuhl et al., 2010), younger and older participants studied pictures of scenes that were designated as either low reward ($0.01) or high reward ($1.00). The rewards could be obtained only by remembering the scenes on a later recognition test. Participants remembered more high-reward than low-reward pictures when memory was tested 24 hr after the study phase (Experiments 1 and 2), but not when it was tested immediately following the study phase (Experiment 2). Both age groups showed the same pattern of reward effects on recognition hit rates. Recognition confidence was not sensitive to reward, except in younger adults in Experiment 1. Across the two experiments, younger adults in Experiment 1 also showed the largest reward effect on the recognition hit rate ($\eta^2 = 0.28$); a sizable reward effect may be necessary for subjective awareness.

Overall, the current findings supported our hypothesis, according to which the influence of reward anticipation on intentional episodic memory formation is preserved into old age. They also extend previous findings on aging, reward, and incidental memory (Mather & Schoeke, 2011), and on the time-dependent effect of reward on memory (Murayama & Kuhbandner, 2011).

Contrary to our finding of no effect of reward anticipation on immediate recognition, Mather and Schoeke (2011) reported a slight boost of immediate recognition in both younger and older adults. However, this boost was observed for positive stimuli only (e.g., a picture of dessert) and did not extend to neutral items; only rewarding outcomes enhanced recognition memory regardless of item valence. In the current study, participants studied pictures of indoor and outdoor scenes that contained no people or animals; it is safe to assume that these pictures were emotionally neutral. The null effect of reward on immediate recognition in Experiment 2 was thus consistent with Mather and Schoeke's (2011) findings.

How do the current results differ from demonstrations of intact value-directed encoding in older adults (Castel, 2007; Castel et al., 2002, 2011, 2013). Unlike in the value-directed encoding paradigm, strategic encoding is relatively difficult in the MIE task. The length of the study list (124 stimuli), the inclusion of a fast-paced, attention-demanding poststimulus distractor task ("arrow task"), the use of pictorial stimuli with high semantic overlap (i.e., indoor and outdoor scenes), and the long retention interval (24 hr) all placed limits on the extent to which postencoding rehearsal was likely to be engaged. Rehearsal-based explanations are difficult to rule out entirely in an intentional memory paradigm. For example, it is possible, if not particularly plausible, that participants mentally rehearsed some of the 62 high-reward scene stimuli during the 24-hr retention interval. However, the current findings are more parsimoniously explained in terms of reward-enhanced, hippocampus-dependent memory consolidation (Adcock et al., 2006; Murayama & Kitagami, 2013; Murayama & Kuhbandner, 2011). This is particularly true in light of the sizable literature documenting reward influences on neurobiological processes involved in episodic memory (see Shohamy & Adcock, 2010, for review).

An interesting alternative to the consolidation account is the possibility, briefly mentioned in the *Introduction* section, that reward cues selectively boost encoding processes that increase the "storage strength" (i.e., long-term availability) of items, but not their "retrieval strength" (i.e., short-term accessibility; Bjork & Bjork, 1992; Kornell et al., 2011; we thank an anonymous reviewer for pointing out this possibility). In this case, items paired with high and low rewards at encoding would be equally likely to exceed a recognition threshold on an immediate recognition test, but on a delayed test, there would be a recognition advantage for high-reward items (see Figure 1, Kornell et al., 2011, for an illustration of this type of interaction). The results of the current experiments, and indeed of other behavioral studies of reward and memory in humans, cannot distinguish between the consolidation and differential strength perspectives; this remains a challenge for future research.

Regarding the practical significance of the current findings, the reward effects on delayed recognition were in the medium range (Experiment 1: $\eta_p^2 = 0.22$; Experiment 2: $\eta_p^2 = 0.17$; see Cohen, 1988). Although these effects are similar to others reported in the experimental literature on reward and memory (Adcock et al., 2006; Callan & Schweighofer, 2008; Kuhl et al., 2010; Mather & Schoeke, 2011; Murayama & Kitagami, 2013; Murayama & Kuhbandner, 2011; Wittmann et al., 2005), their practical significance in applied settings such as memory training may be limited. More research is needed to explore how the magnitude of motivational effects on episodic memory can be increased. Moderators of this effect may include the temporal relationship between rewards and encoding events (Gable & Harmon-Jones, 2010; Mather & Schoeke, 2011), the emotional valence of the study material (Mather & Schoeke, 2011; Wittmann et al., 2008), curiosity and intrinsic motivation (Hess, Emery, & Neupert, 2012; Kang et al., 2009; Murayama & Kuhbandner, 2011), as well as individual difference variables such as anxiety (Murty et al., 2011) and reward sensitivity (Jimura, Locke, & Braver, 2010).

The current study had several potential limitations that should be addressed in future research. The first limitation concerned the memory measures that were employed. The critical analyses involved the uncorrected recognition hit rates for low-reward and high-reward stimuli (see also Adcock et al., 2006; Mather & Schoeke, 2011). Researchers typically use false alarm rates to correct for guessing, but this was not possible here because the experimental design did not produce separate false alarm rates for high-reward and low-reward conditions. However, guessing is not a plausible explanation for the reward effect on hit rates given that participants were not informed of the reward value of the stimuli at test. Differential responding to low-reward and high-reward targets thus had to reflect reward-based differences in memory representations or processes.

Related to the previous point, false alarm rates were higher for older adults than for younger adults, in both experiments. Possible explanations may include an age-related shift from recollection-based to familiarity-based retrieval (Prull, Dawes, Martin, Rosenberg, & Light, 2006) or a liberal response bias in older adults (Mather & Schoeke, 2011). Indeed, examination of the signal detection measures revealed more liberal response settings in older than in younger adults, although this difference was statistically significant in Experiment 1 only. The current study was not designed to address these issues, but it is nevertheless striking that false alarm rates were the only source of age differences in the recognition responses, in both experiments. In future research, it would be useful to examine more closely how reward manipulations affect specific memory and decision processes in younger and older adults.

The second limitation concerned the interpretation of the arrow task that required speeded two-choice decisions immediately following the presentation of each target stimulus. Arrow-task performance showed little (Experiment 1) or no effect (Experiment 2) of the reward value of the just-seen picture. This outcome suggests that postencoding rehearsal was unlikely to have played a major role in reward-based modulation of memory outcomes. However, we cannot rule out the possibility that reward modulated encoding strategies during the stimulus presentation (and indeed, this limitation further adds to the qualification made above regarding the possibility of an encoding-based reward effect). For example, high-reward cues may have energized participants' search for distinctive visual elements that would aid subsequent recognition. This hypothesis could be tested with online measures of encoding processes, such as eye movements (Hollingworth & Henderson, 2002; Shih, Meadmore, & Liversedge, 2012).

A final limitation of the study was the fact that reward anticipation was manipulated with monetary incentives, as is common practice in the literature (Adcock et al., 2006; Mather & Schoeke, 2011; Murayama & Kitagami, 2013; Murayama & Kuhbandner, 2011). It is possible that these incentives were experienced differently by younger adults, most of whom were undergraduate students, and older adults, most of whom were retirees. For example, the subjective utility of a $1.00 reward may be higher for a university student than for a retiree. However, group differences in reward valuation are unlikely to have played a critical role in the current study. First, the reward manipulation affected memory performance in both age groups, with no behavioral evidence that younger or older adults were indifferent to the monetary amounts at stake. Second, prior behavioral and neuroimaging findings suggest that the influence of reward on memory formation shows context-dependent "adaptive scaling" (Bunzeck, Dayan, Dolan, & Düzel, 2010) rather than sensitivity to absolute reward magnitudes. Nevertheless, it would be worthwhile, in future studies, to assess and statistically control for potential group differences in reward valuation, socioeconomic status (Samanez-Larkin et al., 2007), or reward sensitivity (Jimura et al., 2010). It would also be interesting to compare the influence of monetary and nonmonetary (e.g., socioemotional) rewards on memory in younger and older adults, particularly in light of life-span theories that posit increased salience of socioemotional goals during aging (Carstensen, Isaacowitz, & Charles, 1999).

In conclusion, the current study documents age-related stability in the effect of delayed rewards on episodic memory consolidation. This finding may have important implications for the development of memory training programs for older adults, and it highlights the need for additional research into motivation–cognition interactions in aging.

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