Temporal proximity to the elicitation of curiosity is key for enhancing memory for incidental information

Running title: Temporal proximity is key

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Abstract

Curiosity states benefit memory for target information, but also incidental information presented during curiosity states. However, it is not known whether incidental curiosity-enhanced memory depends on when incidental information during curiosity states is encountered. Here, participants incidentally encoded unrelated face images at different time points while they anticipated answers to trivia questions. Across two experiments, we found memory enhancements for unrelated faces presented during high- compared to low-curiosity states, but only when presented shortly after a trivia question. This suggests processes associated with the elicitation of curiosity - but not sustained anticipation or the satisfaction of curiosity - enhance memory for incidental information.

Curiosity has widely been assumed to benefit memory, with theories postulating that curiosity is a motivational state that stimulates information seeking to reduce uncertainty (Berlyne, 1966; Gottlieb & Oudeyer, 2018; Gruber & Ranganath, 2019; Kidd & Hayden, 2015; Litman et al. 2005; Loewenstein, 1994). Research that addresses the relationship between curiosity and learning has typically used a trivia paradigm in which participants are tested on memory for answers to trivia questions that elicit different levels of curiosity (e.g., Kang et al. 2009). These studies demonstrate that memory of trivia answers is higher for questions that elicited high levels of curiosity (referred to from here-on out as curiosity-enhanced memory) (e.g., Fastrich et al. 2018; Gruber et al. 2014; Kang et al. 2009; Marvin & Shohamy, 2016; McGillivray et al. 2015; Wade & Kidd, 2019).

Evidence also demonstrates that curiosity significantly enhances memory for incidental information. For example, Gruber et al. (2014) presented an incidental face image in the middle of the anticipation period between eliciting curiosity (via the presentation of a trivia question) and satisfying curiosity (via the presentation of an answer to a trivia question). Memory for the incidental face image was higher when participants anticipated answers with high compared to low curiosity. Therefore, states of high curiosity not only improve learning for topics that piqued an individual's curiosity, but a high-curiosity state can also improve memory of information beyond the target of a person’s curiosity (for further replications, see Fandakova & Gruber, 2020; Galli et al. 2018; Gruber et al. 2014; Stare et al. 2018). However, it is not clear how memories are enhanced for incidental information during curiosity states.

Neuroimaging research has shown that curiosity states increase activity within the dopaminergic circuit (Duan et al. 2020; Gruber et al. 2014; Kang et al. 2009) and thereby benefit hippocampus-dependent memories for curiosity target and incidental information (see the Prediction, Appraisal, Curiosity, and Exploration (PACE) Framework for a theoretical framework, Gruber & Ranganath, 2019). Importantly, in one fMRI study (Gruber et al. 2014), we showed that the neural dynamics predicting curiosity-related memory enhancements for incidental images were evident when curiosity was elicited (i.e., during the presentation of a trivia question associated with high curiosity). As activation in the dopaminergic circuit increases phasic dopamine release in the hippocampal memory system (Düzel et al., 2010; Kang et al., 2009; Lisman & Grace, 2005; Rossato et al., 2009; Shohamy & Adcock, 2010), we theorise that curiosity-enhanced memory for incidental information will be higher when the incidental information is presented in close proximity to when curiosity is elicited. Alternatively, arousal-biased competition theories stipulate that arousal, potentially elicited via trivia stimuli, suppresses competing non-target mental representations (e.g., such as incidental faces) in favour of goal-relevant stimuli (Mather et al., 2016; Mather & Schoeke, 2011). Arousal-based theories would therefore suggest there would be a decrease in memory for incidental items in close proximity to the elicitation of curiosity where biasing of target information would be greater.

In order to further disentangle whether early rather than late processes during curiosity states affect memory for incidental information, we performed two behavioural experiments building on previous work using the trivia paradigm. In Experiment 1, we used a between-subjects design in which the incidental face image was shown either early or late during the anticipation period (i.e., either subsequently after the presentation of the trivia question or immediately preceding the trivia answer). In Experiment 2, we used a within-subjects design and further interrogated the findings of Experiment 1 by spanning the presentation of unrelated face images across the whole anticipation period (i.e., at one of four possible time points). This allowed us to investigate whether a linear relationship existed between the magnitude of curiosity-enhanced memory of incidental information and the time point at which it was presented.

Across two experiments, participants underwent a three-stage paradigm with (1) a screening phase, (2) a study phase, and (3) a surprise recognition test phase for incidental face images. During the screening phase, we obtained an equal number of low- and high-curiosity questions for which participants did not know the answers (for details, see Fig 1A & supplementary material 1.2). In the subsequent study phase (Fig 1B-D), the selected trivia questions were randomly presented followed by an anticipation period that preceded the presentation of the associated trivia answer. During the anticipation phase, a crosshair was presented that was replaced by an image of an emotionally neutral unrelated face.

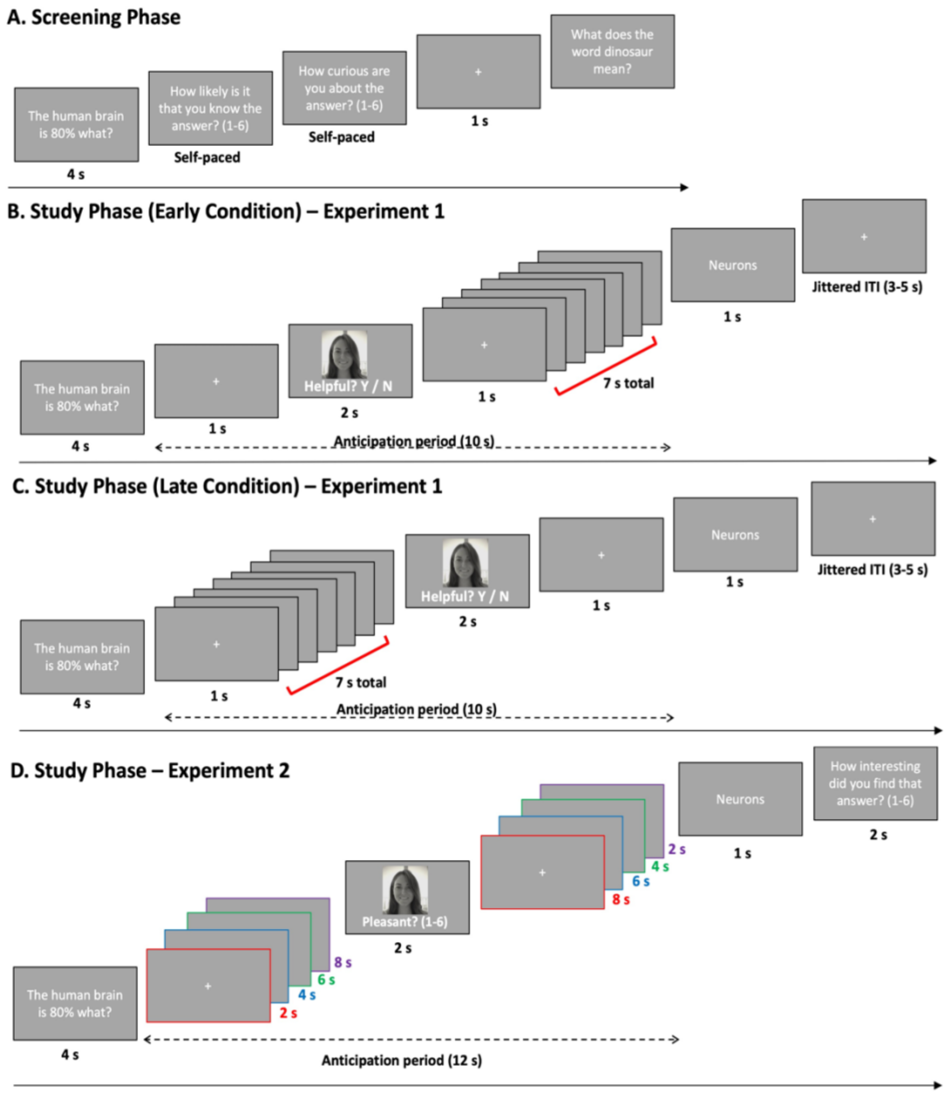

Figure 1. Experimental Design. (A) During the Screening phase, trivia questions were randomly selected from a pool of trivia questions (the trivia stimuli are available online at OSF: https://osf.io/he6t9/). Participants rated their prior knowledge and curiosity for trivia questions on a 6-point scale. In Experiment 1, the screening phase lasted until the

participant selected 56 low-curiosity trials (pressed 1, 2 and 3) and 56 high-curiosity trials (pressed 4, 5 and 6) of which they do not have prior knowledge (112 trials in totals). In Experiment 2, this lasted until 64 low-curiosity trials and 64 high-curiosity trials were selected (128 trials in total). (B-C) Study phase Experiment 1: Participants encoded trivia questions (4 s), followed by a 10 second anticipation period (depicted by the dashed line). Using a between-subjects design, participants were pre-allocated into Early or Late conditions. (B) For the Early condition an emotionally neutral face (incidental item) is presented after 1 s and (C) for the Late condition an emotionally neutral face is presented after 7 s. Participants rated (yes/ no) whether this particular person would be knowledgeable about the trivia topic and could help them figure out the answer. After the anticipation period, the trivia answer was presented (1 s). The end of a trial is denoted by a white fixation on a grey background (3-5 s jittered inter-trial interval (ITI)). (D) Study phase Experiment 2: Participants are presented with trivia questions (4 s), followed by a 12 s anticipation period (depicted by the dashed line). After a pseudo-random period of time (2, 4, 6 or 8 s) an emotionally neutral face (incidental item) is presented in the anticipation period (2 s), and participants were to rate how pleasant they find the image on a scale from 1 (‘not at all pleasant’) to 6 (‘extremely pleasant’). The anticipation period then continued until a total of 12 seconds had passed since the presentation of the trivia question. The colour boxes are for explanatory purposes only and denote the four timing combinations of when the incidental face could be presented. For example, if a fixation period lasted 4 s before the incidental face image was presented (2 s) the remaining anticipation period lasted 6 s (12 s in total) - highlighted by the blue boxes. After the anticipation period, the trivia answer was presented (2 s). The end of a trial is denoted by a white fixation on a grey background (2-4 s ITI). For both experiments, the study phase was divided into four blocks.

In Experiment 1 (N= 61; see supplementary materials 1.1), the face image was shown either 1 s after question offset (Early condition; Fig 1B) or 7 s after question offset (Late condition; Fig 1C). During the presentation of the face, participants had to give a yes/ no response as to whether this particular person would be knowledgeable about the trivia topic and could help them figure out the answer (cf., Gruber et al., 2014). This encoding judgement was used to ensure that faces were likely to be encoded with a similar level of attention across both curiosity conditions. Following the encoding task, a surprise recognition memory test for the faces was administered. The recognition test occurred approximately 10 min after the end of the study phase. Participants were tested with a six-way recognition judgement to dissociate between recollection- and familiarity-based recognition of incidental face images (see supplementary materials 1.3).

To investigate curiosity-enhanced memory for incidental face images in Experiment 1, we used a two-way mixed-effects ANOVA to test if curiosity (2 levels: high vs. low) was positively associated with better memory performance and whether the time point of face presentation (2 levels between-subjects: early vs. late) interacted with the potential curiosity-enhanced memory for incidental faces (Fig 2). The results indicated a significant interaction between curiosity and the time point of face presentation (F(1,59) = 7.86, p = .007, partial eta squared = .118; Fig 2). Neither the main effect of curiosity (F(1,59) = 1.96, p = .167, partial eta squared = .032) nor the main effect of time point of face presentation (F(1,59) = 0.46, p = .498, partial eta squared = .008) reached significance. Follow-up one-tailed t-tests revealed that, in the early presentation group, recollection estimates for faces were significantly higher for high- compared to low-curiosity trials (t(29) = 2.76, p = .005, Cohen's d = .505, mean difference = 3.87, lower = 1.49, upper = ∞). In contrast, for late presentation, we did not find a significant difference in recollection for faces between the high- and low-curiosity condition (t(30) = -1.08, p = .854, Cohen's d = -0.193, mean difference = -1.29, lower = -3.33, upper = ∞) (for further analyses, see supplementary results 2.1-2.2).

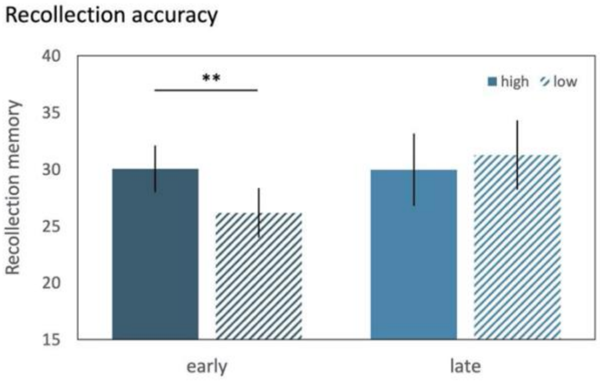

Figure 2. Recollection accuracy for incidental faces for Experiment 1. Proportion of correctly remembered faces for the early and late face presentation groups split by high and low curiosity conditions. Results reveal a significant interaction between curiosity state and time point of face presentation on subsequent memory for incidental faces. Participants remembered more faces when in a high- compared to a low-curiosity state if the face was

presented early in the anticipation period. Recollection accuracy for incidental items were as follows: High curiosity early (mean = 30.04%, SD = 11.22), low curiosity early (mean = 26.17 %, SD = 12.02), high curiosity late (mean = 29.97%, SD = 17.74), and low curiosity late (mean = 31.26%, SD = 16.95), curiosity-enhanced memory (high – low) early (mean = 3.87%, SD = 7.66) and late (mean = -1.29%, SD = 6.68). Standard error is depicted by a vertical black line. ** = significant differences at a threshold of $p < .01$. The findings of Experiment 1 suggest that high- compared to low-curiosity states show enhanced memory for incidental information if it is presented in close proximity to the elicitation of curiosity. These effects were specific to recollection, did not generalise across familiarity-based recognition, and could not be explained by performance on the encoding judgments (see supplementary results 2.1-2.2).

To investigate whether there was a difference in the way the face stimuli were encoded, we investigated whether RTs of the encoding judgment as a potential index of “alertness” during encoding differed between conditions. Therefore, we ran a two-way mixed effects ANOVA on RTs with curiosity (high vs. low) as within-subjects factor and the time point of face presentation (early vs. late) as between-subjects factor (see Table S1 for means (SDs)). Neither the main effects of curiosity (F(1,59) = 3.03, p = .087, partial eta squared = .049), time point of face presentation (F(1,59) = 1.09, p = .300, partial eta squared = .018) nor their interaction (F(1,59) = 3.76, p = .057, partial eta squared = .059) reached significance suggesting that “alertness” potentially did not differ between curiosity and timing of face presentation conditions. However, to further interrogate whether RTs, as a potential index of “alertness”, during encoding had any effects on later memory, we included curiosity-related RT differences during encoding (i.e., high curiosity RTs – low curiosity RTs) as a covariate in a two-way mixed effects ANCOVA with curiosity (high vs. low) and time point of face presentation (early vs. late) as factors on recollection memory. Consistent with the ANOVA findings, the interaction between curiosity and time point of face presentation remained when the difference in RTs during high vs. low curiosity encoding was controlled for (F(1,58) = 8.23, p = .006, partial eta squared = .124). No other main effects or interactions were significant (curiosity: F(1,58) = 2.27, p = .137, partial eta squared = .038; time point of face presentation: F(1,58) = 0.22, p = .644, partial eta squared = .004; curiosity-related RT difference: F(1,58) = 0.63, p = .432, partial eta squared = .011; curiosity * curiosity-related RT difference: F(1,58) = 0.44, p = .509, partial eta squared = .008).

To determine whether participants gave different ratings on the encoding judgement between curiosity conditions and the time point of face presentation, we ran a two-way mixed effects ANOVA on the proportions rated “helpful” (i.e., “yes” responses) with curiosity (high vs. low) and time point of face presentation (early vs. late) as factors. Helpfulness ratings significantly differed with curiosity states (F(1,59) = 22.05, p < .001, partial eta squared = .272) but not with time point of face presentation (F(1,59) = 0.01, p = .915, partial eta squared = .000). The interaction between curiosity and time point of face presentation was not significant (F(1,59) = 0.08, p = .775, partial eta squared = .001). Potentially surprisingly, faces were rated as significantly more helpful during low- compared to high-curiosity states (see Table S2). Due to this significant difference, the curiosity-related difference in helpfulness ratings (i.e., high – low curiosity) was added as a covariate in a two-way mixed effects ANCOVA on recollection accuracy with curiosity (high vs. low) and timing of face presentation (early vs. late) as factors. Importantly, the interaction between curiosity and time point of face presentation remained when the difference in helpfulness ratings during high vs. low curiosity encoding was controlled for (F(1,58) = 7.86, p = .007, partial eta squared = .119). No other main or interaction effects were significant (curiosity: F(1,58) = 0.84, p = .364, partial eta squared = .014; timing of face presentation: F(1,58) = 0.43, p = .517, partial eta squared = .007; curiosity-related helpfulness rating difference: F(1,58) = 0.49, p = .487, partial eta squared = .008; curiosity * curiosity-related helpfulness rating difference: F(1,58) = 0.27, p = .604 partial eta squared = .005).

In Experiment 2 (N = 32; see supplementary materials 1.1), during the anticipation window an unrelated face replaced the fixation cross after 2, 4, 6 or 8 s (Fig 1D) spanning the entire anticipation period. During the presentation of the face, participants had to rate how pleasant they found the face, from 1 (‘not at all pleasant’) to 6 (‘extremely pleasant’), after which the fixation cross re-appeared for the remainder of the anticipation period (either 8, 6, 4, or 2 s depending on when the face image was presented; see Fig 1D). This decision-making judgement was deemed incidental as it was not semantically related to the trivia question. Finally, in Experiment 2, we implemented a 1-day delayed surprise memory test, as the experiment served as a pilot experiment for a potential future neuroimaging experiment, and as such, we wished to reduce task demands on individuals on the day of scanning. Participants therefore made a 4-point confidence judgement on whether they thought the face was presented during the study phase (see supplementary materials 1.3). The 4-point confidence judgement is consistent with previous studies that showed curiosity-enhanced memory for incidental faces in delayed memory tests (Gruber et al. 2014; Stare et al. 2018).

Following up the findings of Experiment 1, in Experiment 2 we used a linear regression model to determine whether curiosity-enhanced memory of incidental information linearly decreased at larger intervals from the elicitation of curiosity. This model indeed revealed a significant effect of time point on curiosity-enhanced memory ($F(1,126) = 9.91$, $p = .002$, $R^2 =.073$; Fig 3A). Next, to determine at which time point the curiosity-enhanced memory effect was significant, we conducted four follow-up one-tailed t-tests investigating when recognition memory for faces was higher in high- compared to low-curiosity conditions (i.e., at 2, 4, 6 and 8 s). This analysis revealed a significant difference at both 2 s ($t(31)= 3.06$, $p = .002$, confidence intervals (5.28, 26.35), mean difference = 15.8), and 4 s ($t(31)= 1.73$, $p = .045$, confidence intervals (-0.98, 11.91), mean difference = 5.5), but no significant difference at 6 s and 8 s ($p = .380$ and $p = .471$, respectively) (Fig 3B).

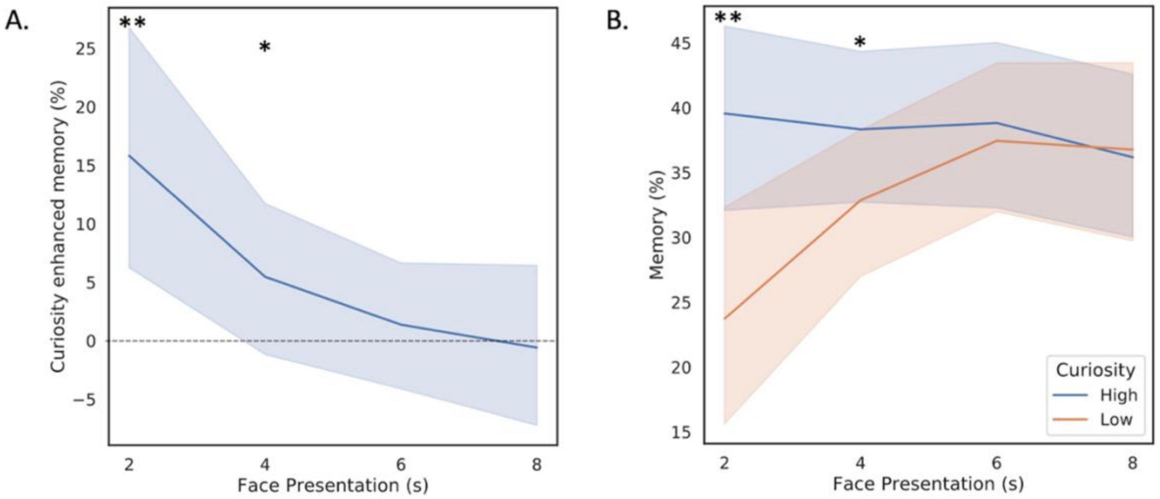

Figure 3. Recognition memory for incidental faces for Experiment 2. (A) Curiosity-enhanced memory (high – low) at each presentation time point. (B) Percentage of correctly recognised faces at each presentation time point, split by high- and low-curiosity conditions. Participants recognised significantly more faces when in a high-curiosity trial if the face was presented early in the anticipation window (at both 2 and 4 s). ** and * = significant differences at a threshold of p < .01 and p <.05 respectively. 95% confidence intervals are depicted by the shaded area. Recognition memory for incidental items were as followed: Curiosity-enhanced memory (high – low) (2s: mean = 15.80 %, SD = 29.21; 4s: mean = 5.54 %, SD = 17.89; 6s: mean = 1.33%, SD = 16.26; 8s: mean = -0.62 %, SD = 20.24). For each time point the recognition memory scores were as followed: 2s (high curiosity: mean = 39.58 %, SD = 21.37; low curiosity: mean = 23.70 %, SD = 29.83), 4s (high curiosity: mean = 38.81%, SD = 17.38; low curiosity: mean = 32.92 %, SD = 18.28), 6s (high curiosity: mean = 38.78 %, SD = 19.70; low curiosity: mean = 37.53 %, SD = 17.93) and 8s (high curiosity: mean = 36.18 %, SD = 19.66; low curiosity: mean = 36.76 %, SD = 22.01). Extrapolating from this data we found that, consistent with Experiment 1, incidental curiosity-enhanced memory is largest when presented in close proximity to the elicitation of curiosity (i.e., 2 s after the presentation of a trivia question), but its magnitude linearly decreased with increasing time interval from the elicitation of curiosity.

To determine whether pleasantness judgement differed across curiosity states or memory performance we ran a 2 (curiosity; high, low) x 2 (memory; hits, misses) repeated measures ANOVA on participants pleasantness ratings. This analysis revealed that pleasantness ratings did not significantly differ across memory (F(1,31) = 1.43, p = .23) or curiosity effects (F(1,31) = 1.93, p = .17). See Table S2 for mean pleasantness ratings.

Next, to determine whether this effect was due to participants being more “alert” during high curiosity trials we investigated whether response times (RT) to incidental face stimuli differed across time point, condition and memory performance (see Table S1 for mean RTs). A 2 (condition; high curiosity, low curiosity) x 2 (memory; hits, misses) x 4 (timepoint; 2 s, 4 s, 6 s and 8 s) repeated-measures ANOVA was conducted revealing no significant difference in RT score across time point (F(3,48) = 1.58, p = .21), condition (F(1,16) = 0.34, p = .57), memory (F(1,16) = 1.07, p = .32), nor the interactions between these.

Finally, for consistency with our previous analysis and to determine whether our linear regression effect was due to (i) participants being more “alert” during high-curiosity trials (as inferred by RTs) or (ii) participants’ degree of pleasantness rating for the faces (as inferred by encoding judgement), we included two additional independent variables to our previous linear regression model. A multiple regression was therefore run to predict curiosity-enhanced memory performance from time point, curiosity-related RT differences (high – low curiosity) and curiosity-related pleasantness rating (high – low curiosity). These variables significantly predicted curiosity-enhanced memory (F(3,126) = 4.14, p = .008, R^2 = .069). Importantly, only time point added significantly to the model prediction (*p* = .002), whereas curiosity-related RT differences (*p* = .280) and curiosity-related differences pleasantness rating (*p* = .209) did not. Collectively, this indicates that only the time point of face presentation significantly predicted curiosity-enhanced memory even when controlling for RT and pleasantness ratings.

Taken together the current work yields several important contributions to our understanding of how curiosity affects memory for incidental information. First, this work provides further evidence that suggests that high-curiosity states relative to low-curiosity states can improve memory of information beyond the target of a person’s curiosity. Our results suggest that the constraints of this effect are determined by the temporal proximity of incidental information to the elicitation of curiosity. Second, across both experiments we found early curiosity effects on incidental memory were independent of the nature of the incidental encoding judgement (i.e., how knowledgeable or pleasant participants rated the face). In addition, reaction times for encoding judgments as a potential measure of “alertness” did not predict curiosity-enhanced memory across experiments.

Recent theories on curiosity (e.g., Gruber & Ranganath, 2019; Murayama, 2019; Sharon & Sustein, 2020) highlight the importance of dopaminergic brain regions in supporting curiosity and curiosity-related memory enhancements. Although we cannot make strong conclusions about whether our findings are a result of increased release of dopamine, there is reason to believe dopamine may play an important role as our results align with predictions from fMRI findings regarding regions innervated by dopamine including the hippocampus, which suggest that the curiosity-related neural activity is somewhat limited in duration, and potentially fitting with a time-course of clearance of curiosity-triggered dopamine release via re-uptake across seconds (Düzel et al., 2010; Gruber et al., 2014; Shohmay & Adcock, 2010). As fMRI signals in the dopaminergic midbrain have been shown to positively correlate with dopamine release (Knutson & Gibbs, 2007; Schott et al. 2008), this pattern of dopaminergic involvement suggests dopamine might be released during the elicitation of curiosity which benefits hippocampus-dependent memories for incidental information presented in close succession to this release. Speculatively, this provides a plausible neuromodulatory explanation as to why faces presented at larger intervals from the elicitation of curiosity did not benefit from participants heightened state of curiosity. This finding is also consistent with research in the field of reward, that indicates dopaminergic activity scales with high perceived reward, and this predicts incidental memory (Murty & Adcock, 2014; Stanek et al. 2019; Tobler, Fiorillo & Schultz, 2005).

Perhaps surprisingly, Experiment 2 showed that during high-curiosity trials, memory for incidental faces is consistent across all four time points, whereas in low-curiosity trials memory for incidental faces improves at later presentation times (see Fig 3B, supplementary results 4.1). Our results are therefore inconsistent with arousal-biased theories (e.g., Mather et al., 2016), which predict that arousal, potentially elicited by high curiosity, would supress attention of irrelevant information (e.g., incidental faces). Instead, our results are consistent with recent literature in the field of reward that showed that during early during reward anticipation, memory formation was improved by increased expected reward value (akin to high curiosity) potentially due to a phasic dopamine response, whereas late during reward anticipation, memory formation was enhanced by reward uncertainty reflected by a sustained, ramping of anticipatory dopamine release (Stanek et al., 2019). Notably, the findings by Stanek and colleagues might provide a plausible neuromodulatory explanation as to why memory for incidental faces was comparable in high-curiosity trials at all timepoints as it was supported by potentially both (i) phasic dopamine bursts in the early presentation and (ii) sustained anticipatory dopamine ramping in the later presentations. In contrast, low curiosity memory for incidental information would only be facilitated by the later sustained anticipatory dopamine release driven by uncertainty about the correct answer. Our earlier neuroimaging findings showed that individual differences in activation of dopaminergic areas and the hippocampus elicited by curiosity (i.e., during trivia questions) predicted the magnitude of curiosity-enhanced memory for incidental faces (Gruber et al., 2014). Our current findings complement these earlier results suggesting that curiosity-elicited activity in these areas might only enhance memory for incidental faces in close temporal proximity. Despite our findings aligning with previous literature that highlights dopaminergic involvement our interpretations are speculative, therefore the neural investigation of curiosity-triggered modulation of incidental memory require further investigation.

Another important finding was that curiosity-enhanced memory for incidental face information was also robustly seen across two different types of incidental encoding judgements and was not influenced by encoding judgement performance. In Experiment 1, participants determined ‘whether the particular person would be knowledgeable about the trivia topic’. Using the same incidental encoding judgement as in previous trivia studies (Fandakova & Gruber, 2020; Galli et al. 2018; Gruber et al. 2014; Stare et al. 2018), we replicated and extended the previous findings in showing that incidental curiosity-enhanced memory is specific to the temporal proximity to curiosity elicitation. Although the faces are incidental in the sense that they did not provide any meaningful information relating to the trivia, one could argue that the faces are task-relevant due to the nature of the decision-making judgement. Importantly, curiosity-enhanced memory for incidental faces were still evident with an encoding judgement that is not semantically associated with the trivia stimuli (i.e., rating the pleasantness of the incidental face image in Experiment 2). Taken together, these findings suggest high-curiosity states can improve memory of information beyond the target of a person’s curiosity, even when that information is completely incidental to the topics that piqued an individual's curiosity.

In conclusion, our findings provide a better understanding into how curiosity enhances memory for incidental information, suggesting that the elicitation of curiosity is key. However, future studies should examine the role of curiosity on incidental memory for a broader range of stimuli and with different approaches to elicit curiosity. The impact of such work could be applicable to a wide range of areas and would need to be tested in the real world (for example, in news or education). This may be particularly pertinent given the current pandemic in which the need to disseminate rapidly updating policies and educate the public on disease and health, has never been more apparent. As such, understanding when to present critical information that should be remembered is pivotal. Our results indicate it is important that the to-be-enhanced incidental information is presented as early as possible when curiosity is sparked.

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