How curiosity affects memory persistence

A thesis submitted for the degree of Doctor of Philosophy

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Abstract

Curiosity is the intrinsic motivational driver to seek information whereby the reward is new knowledge acquisition and uncertainty reduction. With this conceptualization, curiosity has been shown to shape what memories persist. It is thought that the hippocampus and regions of the dopaminergic system are responsible for modulating this memory persistence. While curiosity-enhanced memory effects appear to be fairly stable, less is understood about the mechanisms that result in incidental, and seemingly unrelated, information persisting over time when seen during states of high curiosity. It has been found that incidental faces can benefit from curiosity enhancement when shown in anticipation of information that triggers the initial curiosity. The timing of when faces appear in this anticipation phase also seems to impact what incidental memories persist. However, little is known about whether this incidental memory effect extends to stimuli other than faces and whether sleep consolidation is involved. Based on this gap in the literature, the following experiments attempt to address these questions. Furthermore, we explore different methodological parameters and analyses to understand how and when curiosity can influence what memories persist. The experiments conducted here find that, while there is strong evidence for curiosity-enhanced memory for target information, evidence for curiosity-enhanced incidental memory is weaker. In some experiments, we find a curiosity-related incidental memory effect, in others we do not. We discuss these findings in relation to the literature, we highlight some methodological shortcomings, and make suggestions for future work on curiosity.

Contents

Acknowledgments

This PhD journey has been something else. Two months in getting hit by a car at the hands of a drunk driver. Trebucheted over a bridge railing and into the river Taff. This is definitely not how I saw this journey starting out. I continue to deal with the repercussions of this. Traumatic brain injury, 3 of 4 cruciate ligaments in my left knee snapped. As a result of a C7 fracture, my pinkies and ring fingers no longer have the normal sensing capabilities. Reading and typing forever altered. Let's not forget the pandemic which threw in some huge curve balls for everyone. However, as with all PhD journies, there are many downs and many ups. And I cannot forget all the positive experiences and opportunities for growth and learning. I would like to thank many for their patience, their understanding, and support along the way. Of course there are some honorable mentions.

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"Skills can be taught. Character you either have or you don't have."

Data Collection Declaration

Data collection was solely carried out by the author of this thesis for chapters 3, 4, and 5. For chapter 2, the data collection was carried out in conjunction with Charlotte Murphy.

1 General Introduction

1.1 What is curiosity?

We have all felt curious about something. Maybe it was about some information on Wikipedia or a news article that kept us searching for more information. Maybe it is that sensation that keeps us turning the pages of a good book, eagerly waiting for what the plot will bring next. Without defining it explicitly, we have a general understanding of what curiosity is and can describe how we experience it. Researchers have been working on this concept since the 1960s and trying to understand what curiosity is and how we think about it (for a review, see Loewenstein 1994). This introduction will focus on curiosity's definition, how it is observed in non-human animals and human behavior and its neural mechanisms. It will discuss memory consolidation during sleep with the intention of illustrating what is known about how curiosity affects learning. Then finally, it will be highlighting how this thesis is advancing the field of curiosity research.

Curiosity is understood as an intrinsic motivational state, where uncertainty about the outside world is reduced through information seeking (Berlyne 1966; Loewenstein 1994; Gruber and Ranganath 2019). In other words, the information may not necessarily have any extrinsic value *per se*, or no overt utility to achieve a specific goal. There have been several theories defining curiosity. However, the most pertinent to this current research is the incongruity theory (Loewenstein 1994). It suggests that curiosity is a part of a broader mechanism that makes sense of the world and reduces uncertainty, which is triggered by expectation violations. These violations stem from a mismatch between what we expect to experience as we navigate the world versus what we actually experience. For example, we might approach a chair and expect to be able to sit on it, but then the chair is a three footed chair and catches you off balance. The chair's behavior violated expectations about what we would expect when interacting with it. Therefore, curiosity is not a constant state but an experience that depends on novel or uncertain external circumstances. Information gathering or attentional resources dedicated to that violation is then driven by curiosity to resolve the expectation violations (Gruber and Ranganath 2019). Early evidence

for this phenomenon lies in the findings that human participants spend more time fixating on varying stimuli than recurring stimuli (Berlyne 1966). As objects change, attentional resources are dedicated to tracking what they might be over time. Whereas when they do not change, then it is understood that things are perceived as remaining the same and curiosity is not elicited.

Another pertinent theory is the information-gap view of epistemic curiosity. This theory argues that curiosity is an intrinsic motivation to seek specific information when there is an information gap (Loewenstein 1994). Indeed, psychologists have argued that the motivation to seek information in the form of intellectual engagement is an important factor predicting academic performance (Stumm, Hell, and Chamorro-Premuzic 2011). The major proponents of epistemic curiosity see one function of curiosity as "the desire for knowledge that motivates individuals to learn new ideas, eliminate information gaps, and solve intellectual problems" (Litman and Spielberger 2003; Litman 2008). One of the most pivotal behavioral experiments in the last decade used to investigate epistemic curiosity used trivia questions and answers, akin to the ones you would find in your average box of trivial pursuit game. In the trivia paradigm (Kang et al. 2009), participants are shown trivia questions and asked how curious they are about finding out the answer. Following this they are shown the answers. These questions would cover trivia about geography, nature, science, or history. The rationale for this experiment was that when we see the question, there is an evaluation. This evaluation is two-fold. Firstly, do I know the question or not? And secondly do you wish to engage with it in order to close an information gap? The hypothesis being that the more curious we are to find out the information, we guide attentional resources to that information and thus influence memory consolidation processes. These processes are thought to increase the likelihood that stable memories are formed. Results in this particular experiment showed that individuals were more likely to recall trivia answers for information they rated as inducing high curiosity over middle and low curiosity. This curiosity-related memory enhancement for trivia answers was seen with a delay up to 11-16 days, suggesting that the curiosity-related memory enhancement was stable. The stability of this effect has also been observed after a period of 12 hour (Murphy et al. 2021), 24 hours (Stare et al. 2018), and even

seven days (Marvin and Shohamy 2016). Meaning that the effect of curiosity is also long last-ing. Curiosity enhanced memory has also been observed in participants across different age groups (Galli et al. 2018). Here, participants carried out the trivia paradigm in two different age groups. One with ages ranging from 18 to 26 and another ranging between 65-89. For both groups, trivia answers were recalled better for high curiosity answers over low curiosity answers. From a developmental perspective, children between 10-14 years of age also carried out the trivia paradigm, with curiosity-enhanced memory also taking place (Fandakova and Gruber 2021). As such, the above suggests that curiosity serves as a sense making mechanism that functions to guide attentional resources to update internal models of the external world. It is also crucial to note that curiosity researchers still do not have a full understanding of curiosity, so the incongruity and information-gap theory are not mutually exclusive and there is evidence that they combine to illustrate an underlying curiosity and information seeking mechanism (Gruber and Ranganath 2019).

While curiosity can be instigated by an initial evaluation of violations in expectation, this assess-ment is not always accurate. Little is known about an ongoing assessment that updates the value that we attribute to a piece of information already seen before. If we assess that information is more valuable in a second instance, than it was in the first instance, then there is a redirect of attentional or perhaps consolidation resources. These assessment discrepancies are known as information prediction errors (IPEs). They provide evidence that curiosity is one part of a larger system that takes input from the environment and guides us towards things that do not entirely match our internal models. Through curiosity and exploration, we can update our internal models about the external world. Indeed, with the trivia paradigm, both the curiosity initiation (seeing the trivia question) and curiosity satiation (seeing the answer) can affect what is remembered (Marvin and Shohamy 2016). This study found that the higher the curiosity, the more likely trivia answers were recalled. In addition, they also found that the positive difference between curiosity and answer interest (an IPE) to affect what memories persisted. Those answers that induced a higher interest than initial curiosity (positive IPE), were more likely to be recalled than those

with higher initial curiosity than subsequently lower interest (negative IPE). This effect was also seen in a group of children (Fandakova and Gruber 2021), with the older adolescent participants benefiting more from positive IPEs compared to the younger participants (pre-adolescent), thus indicating that this broader corrective system is pervasive across human development. It is also one more important process that needs further consideration in our prospective experiments. For example, do IPEs consistently affect memory of the target information that is modulated by curiosity enhancement?

Finally, there is also a temporal element to curiosity and curiosity satiation, suggesting that it is a fleeting state that waxes and wanes over time. Reflecting back on, and adding to, the idea that curiosity does not always happen (Loewenstein 1994). Again, using the trivia paradigm, a benefit was found when high curiosity information was satiated later, rather than immediately after the curiosity initiation. Participants were shown the trivia answer to a trivia question after 2, 4, or 8 seconds and the recall was better for the 8 second answer presentation window (Mullaney et al. 2014). This suggests that curiosity has a fluctuating temporal component and is not an on-off phenomenon and something to consider in how we design our studies.

1.2 Incidental memory

Interestingly, in the trivia paradigm (Gruber, Gelman, and Ranganath 2014) it was also found that presenting faces, which were not overtly tied to their experimental task, were recalled better in anticipation for high curiosity inducing trivia answers over low curiosity trivia answers. This was suggested to be a spillover effect from curiosity for trivia answers. Curiosity is suggested to be a state of anticipation for information where attentional resources are targeted, but sufficiently labile to capture other types of stimuli. However, as suggested above, there may also be a temporal component to this effect. In the trivia paradigm, when incidental faces were presented at different intervals within the anticipation phase, faces shown directly after curiosity initiation saw a benefit from curiosity spillover for high curiosity trials over low curiosity trials (Murphy et al. 2021). Therefore, there are critical time points to consider, where target and incidental

information have the largest potential to be consolidated. However, it is not clear how consistent the incidental memory benefit is.

This curiosity spillover effect has been replicated (Stare et al. 2018; Murphy et al. 2021) and appears to be broadly consistent across different age groups (Galli et al. 2018; Fandakova and Gruber 2021). In these studies, faces shown in anticipation for high curiosity eliciting trivia answers were recognized better than faces seen in anticipation for low curiosity trivia answers. In addition, it may be that it is the relative amount of trivia answer memory benefit that then serves as a spillover resource for incidental information. It was found that curiosity memory benefit for trivia answers (high curiosity minus low curiosity) positively correlated with incidental face memory benefit (Fandakova and Gruber 2021). This indicates that it is important to consider the degree of memory effect for each individual on any potential spillover effect. One additional component that is worthy of consideration for these studies is the time in which the memory test is carried out. Incidental face recognition tests have been carried out immediately after the encoding tasks (where individuals are exposed to curiosity elicitation and incidental stimuli, Gruber, Gelman, and Ranganath 2014; Galli et al. 2018; Fandakova and Gruber 2021) as well as after a 24h delay with a night of sleep in between (Gruber, Gelman, and Ranganath 2014; Stare et al. 2018; Murphy et al. 2021). As such, when using a novel incidental memory together with the trivia paradigm, it is important to include immediate and delayed testing to see whether there are any differences that could potentially point to whether curiosity primarily enhances encoding or later consolidation processes.

So far, we have motivated several different experimental questions. One, does curiosity spillover effects occur for other types of memory other than face recognition memory? Is the temporal proximity to curiosity elicitation pivotal for incidental memory effects to occur? Does time of memory testing matter? And if so does sleep-related memory consolidation play a contributory role in the effects of curiosity on memory? The clinical and educational implications of this are substantial. Imagine being able to trigger better memory for calendar events in patients with dementia with use of trivia questions. Or in educational settings, where attention spans vary and

grasping curiosity to enhance what gets remembered is of pivotal interest to maximize learning performance.

1.3   Reward processing and the dopaminergic system

Current evidence suggests that curiosity might rely on similar neural mechanisms as reward anticipation (Gruber and Ranganath 2019; Niehoff and Oosterwijk 2020; Lieshout, Lange, and Cools 2020; Cervera, Wang, and Hayden 2020). From a mechanistic perspective, reward anticipation studies will present a high-reward cue preceding some stimuli, but a low-reward cue preceding other stimuli. This will trigger processes that signal the value of information. Behaviorally, monetary reward, can affect what memories persist. In memory recognition tests, participants were asked to distinguish old objects from new objects. Performance in this task is better when a high reward compared to a low reward is associated with the old objects (Adcock et al. 2006; Mason et al. 2017; Cohen et al. 2019). This reward-enhancement was also seen in the ability for participants to learn word pairs (Studte, Bridger, and Mecklinger 2017). Reward cues can also affect information adjacent to rewarded targets that are presented prior to targets in a form of retroactive spillover (Murayama and Kitagami 2014; Patil et al. 2017), similar objects that were rewarded also boosted memory for non rewarded items experienced adjacent to rewarded ones. This resembles the spillover effect within the anticipatory phase of the trivia paradigm (Gruber, Gelman, and Ranganath 2014). One contradictory finding was that only information that individual's were not curious about, benefited from reward (Murayama and Kuhbandner 2011). Although it could be argued that curiosity was already enhancing memory persistence and so there is no head room for additional from motivational states, regardless of source. However, behavior does not give us the full picture.

It is well established that dopamine, a neurotransmitter, is involved in events that have motivational significance (for a review, see Shohamy and Adcock 2010) and reward anticipation enhances activity within the dopaminergic system and the hippocampus. Anatomically, connections have been demonstrated in macaque monkeys between the prefrontal cortex (PFC), a

region associated with cognitive control, and the substantia nigra and ventral tegmental area (SN/VTA) of the mesolimbic region. These two areas located in the midbrain directly adjacent to each other are associated with reward processing in general (Frankle, Laruelle, and Haber 2006). Functionally, the nucleus accumbens (NA) has also been associated with reward anticipation in humans (Bromberg-Martin and Hikosaka 2009; Yun 2004), which lies in the basal ganglia, having functional and physical connections to the VTA. These regions are then thought to impact hippocampus activity, which is crucial for memory encoding and consolidation, thereby enhancing memory formation of reward-related information (for a review, see Lisman and Grace 2005).

In a landmark study, this was indeed the finding. The VTA, NA, and hippocampus activity preceded stimuli for remembered, but not forgotten, high reward value objects during encoding (Adcock et al. 2006), meaning that these regions were more active for high value trials compared to low value trials. Furthermore, the degree of memory scaled with the degree of activity in the dopaminergic circuit. In addition, the SN/VTA have been shown to be active in macaque monkeys when they are more curious to find out additional information about reward size when they know a reward will be given (Bromberg-Martin and Hikosaka 2009). In humans, an object series was presented together with an associated reward - either high or low (Murty and Adcock 2014). Then the experimenters introduced an expectation violation, by showing the same object from a slightly different angle for some trials, but not others (where the objects' angle remained the same). Participants were asked to react as fast as possible to the slightly changed image. Reward affected reaction time positively and the hippocampus showed enhanced activation for expectation violations for high reward trials versus low reward trials, showing that the hippocampus is capable of behaving differently for high versus low priority information during encoding. Therefore, we would expect that in curiosity studies the hippocampus might also be sensitive to reward and violation of expectations.

Similarly, the functional connectivity between the anterior hippocampus and VTA during periods of rest in between encoding tasks predicted recognition memory for high value information over low value information (Murty et al. 2017). Specifically, hippocampal activity was predicted by the

VTA's own response to reward cues, indicating that VTA is partially responsible for being sensitive to the reward content of information and feeding that forward to the hippocampus. Because these neural dynamics were found during post-encoding rest periods, it is understood as an indication of reward-related early consolidation. This is quite a pertinent study as current curiosity literature has investigated activity during encoding, rather than consolidation mechanisms that occur after we have experienced the information the we are curious about. For example, in a now seminal experiment, Gruber, Gelman, and Ranganath (2014) found that NA and hippocampus activity during encoding were greater for high curiosity answers that were remembered versus those forgotten in the trivia paradigm, indicating the relevance of these regions for, curiosity driven, intrinsically motivated learning. It is important to emphasize that, during presentation of high curiosity answers, individual differences in SN/VTA and right Hippocampus activity were correlated with curiosity memory benefits.

There is also evidence of an incidental spillover effect within the reward literature. During a driving simulator task (Shneyer and Mendelsohn 2018), some roads were rewarded and others not. Participants recognized the incidental billboards they drove past better for rewarded roads than roads without a reward. As such, the similarities in the literature are abundant between curiosity and reward albeit with different origins. One internal and the other external, respectively. However, if they are the same then we would expect that curiosity memory enhancements would also rely on memory consolidation and not just encoding.

1.4   Sleep

Sleep has been associated with curiosity enhanced memory as previously discussed in section 1.2. However, this is a wide literature in and of itself and so a little introduction is warranted. Sleep is a staged process (for an overview, see Hobson and Pace-Schott 2002; Diekelmann and Born 2010; Carskadon and Dement 2011). It includes 4 stages. Stage 1 (N1), stage 2 (N2), stage 3 (N3), and rapid eye-movement sleep (REM). Sleep stages are normally characterized by the electrophysiological oscillations seen through an electroencephalograph (EEG) recorder. EEG

records the electric field potentials created by the electrochemical activity in the post synaptic membranes of a population of neurons. When a person is asleep, they will transition from N1 to N2, then transition from N2 to N3. They will continue to alternate back and forth in a series of changing cycles throughout the night, with more N3 at the beginning of the night and more REM towards the latter stages of the night. Each of these are defined by their own specific features.
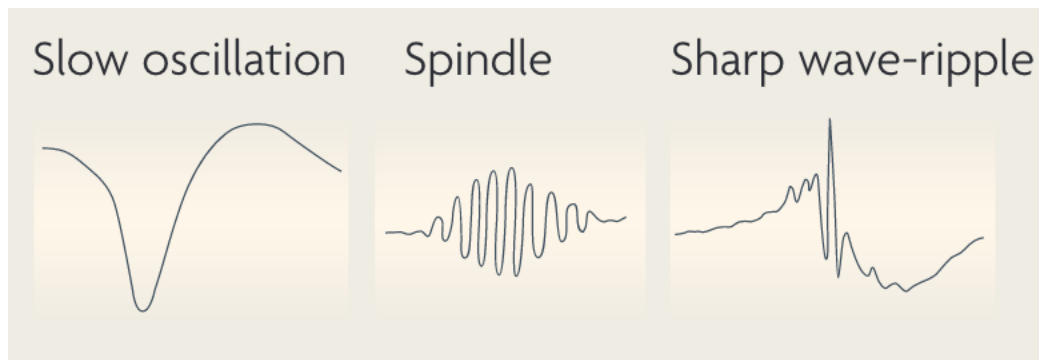
Figure 1: From left to right. Representation of slow oscillation, spindle, and a sharp wave-ripple. Taken from Diekelmann and Born, 2010.

N1 usually defines the onset of sleep. However, it is not a clear-cut transition (Carskadon and Dement 2011). It is described by the lowering of activity in the electrodes that measure movement of face muscles (electromyogram, EMG) and the transition of scalp electrodes from alpha rhythms to low-voltage mixed frequency patterns. These are oscillatory rhythms that carry out 8-13 cycles per second (also known as hertz, Hz).

Then N2 is described by the appearance of sleep spindles and sharp-wave ripple complexes (Figure 1 center and right). Sleep spindles are characterized as oscillations with a frequency range of ~11 to 16 Hz with a duration of 0.5 seconds or greater (usually 0.5–1.5 seconds). Spindles are thought to be important for hippocampal-dependent memory (Mednick et al. 2013). Sharp-wave ripple complexes on the other hand consist of a brief high-voltage peak, usually greater than $100\mu V$, followed by a slower opposite peak. Still within N2, we begin to see some slow wave activity. This is characterized by ~0.5Hz oscillation with a large amplitude of $> 75\mu V$ (Figure 1 left).

Furthermore, when slow waves occupy >20% of a 30 second epoch, it is agreed that N3 has begun (Berry et al. 2015). During N2 and N3 when slow wave activity is taking place, there are also sharp-wave ripples. These ripples are fast oscillations (80-150Hz) and originate in the hippocampus. These ripples are thought to orchestrate other activity in the brain during slow wave activity (Staresina et al. 2015; Skelin et al. 2021). When this slow wave activity is the predominant oscillatory feature, it is thought that hippocampal activity responsible for memory consolidation takes place. It is when memory reactivation takes place (i.e., the brain replays activity from preceding periods of wakefulness) to promote stabilization of information (Diekelmann et al. 2011). Slow waves in the neocortex, thalamo-cortical spindles, and hippocampal ripples occur with greatest incidence (Diekelmann and Born 2010) and there is strong evidence to suggest that they are in fact synchronized (Staresina et al. 2015). Spindles are modulated by a certain section of the slow-wave oscillation, which in turn dictates when ripples occur. This choreography of oscillatory activity is the main process by which subcortical structures communicate with cortical regions to promote long term formation of information.

Finally, there is REM sleep, which is characterized by muscle atonia, saccadic eye movements, and dreaming (Aserinsky and Kleitman 2003; Dement and Wolpert 1958; Ralph J. Berger and Ian Oswald 1962; Hobson and Pace-Schott 2002). It is uncertain what REM's function is, but some have suggested that it processes emotional content and non-declarative memory (for example, motor memory). To date, findings are still unclear (Diekelmann and Born 2010; Schäfer et al. 2020). However, what should be considered is the role of REM disruption and the first night effect (Goerke et al. 2013). The first night in a sleep lab can be disturbed and REM was found to be a contributor to deprecated memory performance. For example, the disruption of REM in rats can also deprecate object-location learning (Boyce et al. 2016). Therefore, we cannot completely rule out the contribution of REM, alongside N2 and N3, in our prospective analysis.

As previously stated, sleep has been related to memory consolidation processes. However, the wider sleep-related memory benefits literature show mixed evidence (Cordi and Rasch 2021). For example, sleep has been shown to help learning rules for a new language (Batterink et al. 2014).

Furthermore, in an early study in the field had participants learn word lists and then either engage in sleep or regular wakefulness between learning and subsequent testing (Ellenbogen et al. 2006). It was found that the sleep group showed less interference effects from learning a novel word list directly before being tested on the previously seen word list, suggesting that sleep assists certain memories in persisting over time. However, these findings have not been replicated (Bailes et al. 2020; Pöhlchen et al. 2021). Similar null findings were found in another word pair association learning task (Tucker et al. 2020) and other forms of declarative memory (Schönauer et al. 2014; Ackermann et al. 2015). However, when participants were told that learned information would come up in a future test, slow wave activity and spindle count positively correlated with recall performance (Wilhelm et al. 2011). Essentially, this study suggests that when participants knew that information would have future use, sleep brain activity would consolidate prioritized information. Similarly, when learning word pair lists and rewarding half of them, Studte, Bridger, and Mecklinger (2017) found the spindle count positively correlated with reward-related memory benefit (memory performance for rewarded versus non-rewarded world-pair lists), suggesting that reward and sleep can interplay to benefit memory persistence. Within the curiosity literature, Stare et al. (2018) used the trivia paradigm with encoding and testing phases interspersed by a night of sleep or a day of wakefulness. While the authors were were able to replicate the curiosity enhanced memory for trivia answers and incidental face images, sleep did not contribute to this.

Finally, associative memory, the memory for the association between two or more otherwise arbitrary pieces of information, has been widely used in sleep research to study memory effects, specifically reward memory effects. With word-pairs, as show above (Ellenbogen et al. 2006; Wilhelm et al. 2011; Bailes et al. 2020; Pöhlchen et al. 2021; Tucker et al. 2020), but also the association between objects and their locations (Rudoy et al. 2009; Dongen, Takashima, et al. 2012; Oudiette et al. 2013; Antony, Piloto, et al. 2018; Antony, Cheng, et al. 2018; Antony and Paller 2018). Using the association between an object and its location on the screen, it was found that reward impacted the accuracy of finding object locations for those in the wake group and sleep rescued the high reward locations from forgetting (i.e., they were forgotten to a lesser degree

compared to low reward object locations, Oudiette et al. 2013; Igloi et al. 2015; Prehn-Kristensen et al. 2018). In another study, faces were placed on unique location and participants had to find the face depending on clues. This task had a rigged ending so that some participants were rewarded with completing the task or not. Results found a positive relationship between spindles and rewarded tasks (Sterpenich et al. 2021). However, by leveraging the use of functional MRI during wake and sleep (e.g., during nap), it was possible to unpick activity patterns during both states. It was found that N3 activity in the VTA and Hippocampus were similar to the wake activity for rewarded versus non-rewarded tasks. This suggests that activity patterns in key memory and rewards regions are engaged during sleep and therefore we cannot rule out the role of sleep in reward or curiosity studies.

One criticism of the above literature is that there are methodological differences which make them difficult to compare. For example, some studies have investigated the associations between objects and locations. However, it was found that REM was negatively correlated with degree of forgetting (Oudiette et al. 2013), which is interesting considering we would expect N2 or N3 to be involved. On the other hand, others found an object location accuracy relationship with sleep, but purely with sleep duration as opposed to any specific sleep stage (Dongen, Thielen, et al. 2012), although these findings could not be replicated in a further study (Reverberi, Kohn, and Fernández 2020). As such, like Cordi and Rasch (2021) mention, sleep-related results are conflicting, mixed, and there is no real clear understanding as to whether sleep is needed for certain prioritized consolidation effects to take place. Indeed, conflicting results could arise from slight differences in tasks and stimuli used (Diekelmann and Born 2010). Recently, some have suggested that depending on the difficulty of the task, different sleep dependent effects will be seen (Petzka et al. 2021). With high retrieval demands revealing sleep consolidation effects for both weak and strong memories, but revealing only for weaker memories when retrieval demands are low. As such, It is a fundamental part of prospective studies in this PhD thesis as it could be that with the introduction of associative memory, instead of recognition memory in the trivia paradigm, makes the task much harder.

As such, a central driver for the present thesis is to see whether intrinsic, rather than extrinsic, motivation can also be modulated by sleep. Stare et al. (2018) examined this by taking the trivia paradigm and having the learning and test phases split either by a night of sleep or a night of regular wake activity. It was found that while curiosity enhanced memory effects for both target trivia answers and incidental faces, this, however, did not depend on sleep parameters. This presents an opportunity to contribute to the field, by using associative memory tasks commonly used in sleep research and may be better suited to investigate sleep-related modulation of curiosity-related memory enhancements.

This thesis will attempt to to understand better how sleep potentially modulates curiosity-related memory enhancement. In doing so, it will focus on the following:

1. Does memory persistence in the original trivia paradigm, using incidental face recognition, benefit from sleep (replicating Stare et al. 2018)?
2. Does the curiosity-related spillover effect extend to object-location associative memory?
3. Does proximity to curiosity elicitation have consequences for this type of incidental memory (Murphy et al. 2021)?
4. Does time of testing (immediate versus delayed) change what effects are observed?
5. Does complex scenery change the effects of curiosity on object-location associative memory accuracy within the trivia paradigm?
6. Do IPEs affect incidental memory persistence (Fandakova and Gruber 2021)?
7. Does curiosity enhanced memory benefit positively correlate with incidental memory benefit (Fandakova and Gruber 2021)?

In addition, for two experimental chapters, participants were given sleep monitoring wearables to use at home and record sleep EEG activity. Through sleep scoring, we hope to get a better understanding of whether sleep parameters are relevant for the potential consolidation of curiosity enhanced memory. Ambulatory sleep monitoring at home (instead of sleep monitoring in a sleep lab) was also done due to pandemic-related restrictions to lab access.

Throughout this thesis specific directional predictions are made alongside some exploratory analysis. For the directed hypotheses we use one-tailed p-values as there is prior evidence to suggest a particular directionality in the data. However, please note that for the exploratory analysis two-tailed p-values are used as we do not make specific predictions. Data on forthcoming analyses will be checked on whether it meets assumptions of normality. Shapiro-Wilkes tests are also carried but unreported. In situations where these assumptions and tests are violated or criteria not met, we will use non-parametric testing in lieu. In addition to these data quality controls, controlling for multiple comparisons is also be carried out using the Bonferroni correction method (Field 2017).

2 How sleep affects curiosity-related memory enhancements for incidental faces: an ambulatory polysomnography study

2.1 Abstract

Curiosity is understood as the intrinsic motivation to seek information whereby the reward is new knowledge acquisition and uncertainty reduction. This phenomenon is associated with the dopaminergic reward processing system and the memory consolidation region of the hippocampus. Curiosity has been shown to result in better memory recall for information we are highly curious about over information we are not so curious about. While curiosity memory enhancement appears to a fairly stable effect, less is understood about the mechanism that results in incidental, and seemingly unrelated, information also being positively affected by states of high curiosity. In this experiment we carry out the trivia paradigm with incidental faces appearing in one of four possible time points within the anticipation phase. Results show that curiosity memory enhancement for trivia answers was found, but that this did not extend to the incidental memory. There was some evidence to suggest the involvement of sleep in these memory effects and so it would be pertinent to investigate this with a larger sample. We discuss findings in relation to the extant literature and make suggestions on what future work can do to further understand how curiosity affects what memories persist.

2.2   Introduction

The process of learning something new is understood as being an integral part of the human experience. However, we often forget some of the things we encounter throughout the day. For example, when prepping for exams at school you are likely to have a favorite subject and a least favorite subject. If you prepared for both subjects you liked equally, you might be surprised that you remember more from the subject you liked. It is suggested that curiosity can drive some of this preferential memory retention. Curiosity is thought to be a 'reward anticipation' process , where the information attained is the reward itself (Gruber and Ranganath 2019). Therefore, curiosity can be understood as a process that guides us to remember what we find important as we go about exploring our environment everyday. An initial landmark study presented participants trivia questions similar to those found in a trivial pursuit game. The higher the curiosity towards finding out the trivia answers, the more likely the participants were to remember the answers in a later memory test immediately after learning the answers. This curiosity enhancement effect was also seen with delayed memory testing up seven days (Marvin and Shohamy 2016) at 11 to 16 days after the learning session (Kang et al. 2009). This has since been replicated by others (e.g., Gruber, Gelman, and Ranganath 2014; Murphy et al. 2021) and the overarching theme is that a dopaminergic system is sensitive to the reward value of information, such as the NA and SN/VTA , which affects reward processing, curiosity, and self-guided learning (Gruber, Gelman, and Ranganath 2014; Murty et al. 2017; Ripollés et al. 2016, 2018). Whereby, the modulation of these key regions guides attention and potentiates the likelihood that hippocampal consolidation mechanisms will transition memories from unstable transient experiences into long term stable storage.

It is thought that curiosity can spillover. theoretical ideas and findings on the influence of dopaminergic activity on hippocampus-dependent memory suggest that curiosity states might affect memory for incidentally encountered information while a heightened state of curiosity is present. Indeed, it has been found that face stimuli presented in this phase of heightened curiosity in anticipation for the trivia answer results being recalled better than faces seen when curiosity

for the answer is not heightened (Gruber, Gelman, and Ranganath 2014). This is also found after a 24-hour delay. That is, it is also found after a 24-hour delay (Gruber, Gelman, and Ranganath 2014, Exp.2). This effect was also found in an experiment examining immediate versus delayed testing and across a day of wake or a night of sleep (Stare et al. 2018).

In addition, in the above mentioned two studies participants return ~24 hours after the first session to do a memory test, which would involve a night of sleep. While it was found that sleep can prioritize rewarded memories (Studte, Bridger, and Mecklinger 2017), it may be that this effect does not translate to curiosity, or internally generated motivation. Indeed, it was found that sleep did not influence memory, including incidental information (Stare et al. 2018), despite a positive main effect of curiosity for answers and incidental faces being present. The more curious people were, the more likely they were to remember faces seen in the heightened state of curiosity, but that this might be independent of sleep. Indeed, others have found that wake and sleep functional activity in the Hippocampus and VTA are similar when a task is reward versus not rewarded. While N2 and N3 are suggested to be involved in motivated memory consolidation (Diekelmann and Born 2010; Cordi and Rasch 2021), as the first night in a sleep lab can be disturbed, REM has been found to be a contributor deprecated memory performance (Goerke et al. 2013). Indeed, the disruption of REM in rats can also deprecate object-location learning (Boyce et al. 2016). As such, REM should also be considered when using novel sleep recording wearables and the experimental design has a lack of adaptation nights.

More recently this spillover effect was replicated, but when the face is presented during the anticipation phase at different time points (Galli et al. 2018; Murphy et al. 2021), it was found that the closer the proximity of the incidental faces to the elicitation of curiosity, the more likely the spill over effects is to occur. This suggests that curiosity's effect is fleeting or constantly being redirected where necessary. In this study, we extend this research by carrying out a version of the trivia paradigm combined with the various different incidental face presentation time points. However, we also add ambulatory polysomnography sleep recording, so that we understand the degree of effect, if any, of sleep on what motivated memories endure. In addition, it has been shown that

individual differences matter (Fandakova and Gruber 2021). So outright memory performance might not be what demonstrates curiosity effects, but how much one can be influenced by the state. As we endeavor to unpick the behavioral mechanisms of curiosity, we will examine individual differences across participants by how much each person benefits from curiosity enhancement and how much this benefits their incidental memory.

This prompts questions that this chapter will attempt to address. Can the curiosity enhancement on answer memory be replicated. If so, does this also affect incidental information and the temporal proximity of this information to the curiosity trigger. Finally, does sleep add a contributory factor to consolidation for highly curious information. We hypothesize the following:

1. Trivia answers that participants are highly curious about are recalled better than answers they are not as curious about.

2. Curiosity will positively affect memory for incidental faces that are shown in anticipation of high curiosity answers over those seen in anticipation of low curiosity answers.

3. Individual differences in curiosity enhanced memory will positively correlated with curiosity enhanced memory for incidental information.

4. Sleep stage 2 and 3 will positively affect curiosity memory benefit (answers & faces).

2.3 Methods

2.3.1 Sample

The sample consists of a total of 16 participants (13 females) with a mean age of 19.38 (range = 18-24). From this overall sample, ten were used for the sleep analysis. Three participants failed to initiate the polysomnography recording, where as three others some others did not have a complete behavioral dataset through either not attending the second session of the experiment or through technical issues during the MR scanning (not used for this thesis). Participants gave informed consent to participate and were notified of the option to cease participation at any time without providing a reason. The experiment was approved by Cardiff University School of Psychology Ethics Committee.

2.3.2 Exclusion Criteria

Participants were included if they met the following criteria. The had to be between 18 and 30 years old. Had to have Native levels of English fluency, Normal or corrected-to-normal vision, normal hearing. They also had to be non-smokers with no history of psychological, neurological, or sleep disorders. They had to lack regular night work, a general regular sleep schedule and no trouble falling asleep. No habit of irregular daytime napping. Not had any long-haul travel in the 2 months preceding participation. They were also required to not be on medication or substances directly or indirectly affecting sleep quality (oral contraceptives are fine). Participants were asked to abstain from extreme physical exercise in the 12 hours before and throughout their participation. Finally, within 24 hours prior and during participation, participants were required to abstain from napping and the consumption of alcohol, caffeine, or any other psychoactive drug.

2.3.3 Materials

Stimuli used were a set of trivia question and answers pairs (n = 294), which can be found on the Open Science Framework repository (https://osf.io/he6t9/). The face stimuli were composed of photographs of emotionally neutral faces (used in Murphy et al. 2021; Bialleck et al. 2011).

In this experiment, 196 face stimuli were randomly sorted and counter balanced for each participant so no two participants experienced the same face stimuli. These were then pseudo-randomly divided into three sets to ensure equal number male and female faces across the three categories. Faces presented in anticipation for high curiosity answers, faces presented in anticipation of low curiosity answers, and faces to be used during the recognition memory test phase.

Naturalistic background scenes were also presented throughout the entire encoding phase for the purpose of helping train pattern classification analyses using the functional magnetic resonance imaging data (not part of this thesis). These scenes are not relevant to the analysis of this study.

2.3.4 Procedure

Participants took part in two sessions separated by 24 hours. In the first session participants completed the *screening* and the *encoding* session, while in the second session they completed the surprise memory tests. The thesis author was responsible for administrating the sleep EEG wearables and sleep scoring. Behavioral and scanning was carried out by a different researcher.

2.3.4.1 Screening Participants took part in an initial screening phase, where they went through a maximum of 294 trivia questions (for examples, see Table 1) and rated them from one to six. The first rating prompt was to a knowledge prompt (*How likely is it that you know the answer?*), where rating of one would refer to *extremely confident that you do not know the answer* and six to *extremely confident that you do know the answer*. The second rating was to a curiosity prompt (*How curious are you about the answer*), where a rating of one refers to *not at all curious* and a rating of six to *extremely curious*. Finally, participants were prompted to guess
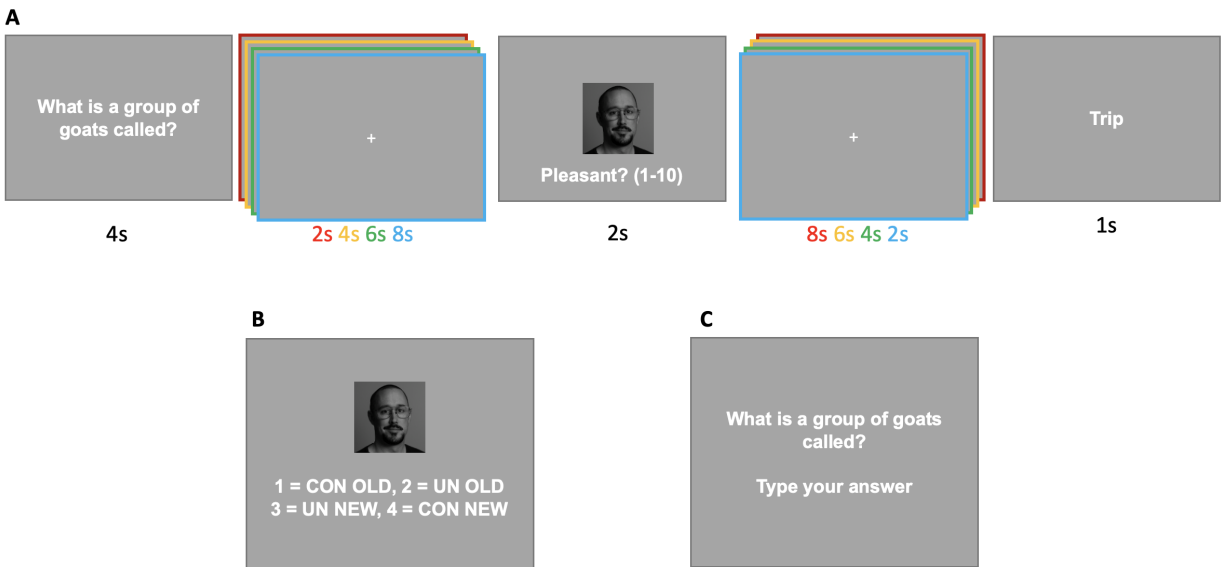
Figure 2: A Encoding phase where participants are exposed to a trivia question displayed on a screen for 4 seconds. Then there is an anticipation phase lasting a total of 12 seconds with a white fixation cross on the screen. A) face stimuli is presented for 2 seconds with an onset of 2, 4, 6, or 8 seconds from the beginning of the anticipation phase. B) Face recognition memory phase where faces were presented and then participants had to judge accross the old v. new and confident v. unconfident judgment types. C) Answer recall where participants read the trivia question and then were then asked to type out the answer.

Table 1: Examples of trivia questions and answers used in experiment.

Question	Answer
Which animal's milk is used to make authentic Italian mozzarella cheese?	water buffalo
Where in the body would you find the pisiform bone?	wrist
What is the main symptom for the virus Ebola?	vomiting
What is the longest river in Asia?	yangtze
What was the world's first National Park?	yellowstone
What is the color of mourning in Turkey?	violet
What was the surname of the first democratically elected president of Russia?	yeltsin
What is the name of the palace built in France by King Louis XIV?	versailles
In which country is "Angel Falls", the tallest waterfall, located?	venezuela
The human brain is 80% what?	water
What made Hugh Hefner go deaf?	viagra
What was the name of the first probe to send back pictures from Mars?	viking
Which planet in the solar system is the only one that rotates clockwise?	venus
What color are cranberries before they turn red?	white
What is the monetary unit in Korea?	won

what the correct answer might be. Participants carried this task out until a total of 64 trivia items were rated as low curiosity (1, 2, or 3) and another 64 items as high curiosity (4, 5, or 6) during the curiosity prompt. Trivia questions that were rated as 6 during the knowledge prompt were discarded from further use to only include trivia questions in the next phases of the experiment for which the answer was unknown. Once these conditions were met, the session ended. This task took between 30 to 60 minutes to complete. Participants who did not fulfill the criteria by the 294th trial were not allowed to participate further.

2.3.4.2 Encoding During the encoding phase which took part inside an MRI scanner, participants carried out the task in four, twelve minute runs (Figure 2A). In each run a trial would consist of a trivia question being presented on the screen for 4000ms. This was followed by an anticipation phase (as participants anticipated the answer) where a white fixation cross was presented, lasting a total of 12 seconds. Participants were instructed during this anticipation phase to "*please use this time to think about and anticipate what the answer might be.*" During this anticipation phase, a male or female face image would appear on the screen's center and

participants were instructed to rate the face on pleasantness, during the 2 second presentation window, from a scale of one to ten, with one being *not at all pleasant* and ten *extremely pleasant*. The face stimuli was only presented for 2000ms and once the faces disappeared from the screen, the white fixation cross returned for the remainder of the anticipation window. There were a total of four different face presentation windows, where a fixation cross would appear, then a face, then a fixation cross again. All variations of the face presentation window totaled up to the max of 12 seconds. The presentation windows were balanced and randomly assigned across high and low curiosity trivia question items. They were carried out as follows:

- 2 seconds fixation > 2 seconds face > 8 seconds fixation
- 4 seconds fixation > 2 seconds face > 6 seconds fixation
- 6 seconds fixation > 2 seconds face > 4 seconds fixation
- 8 seconds fixation > 2 seconds face > 2 seconds fixation

Following the anticipation phase, the answer would be presented centered on the screen. To finalize each trial, a prompt would ask participants *How interesting did you find that answer? (1-10)*, with one corresponding to *not at all interesting* and ten to extremely interesting. Each trial was separated by an inter-trial interval jitter between 2000ms and 4000ms. This session lasted about sixty minutes. Due to MRI scanner protocol issues, the total runs were reduced from 4 to 3. Meaning that the current sample only encoded two thirds of the total learning material.

2.3.4.3 Face memory test Twenty-four hours after the encoding phase, participants were re-invited to the laboratory where they were given surprise memory tests. For testing incidental face memory, participants were shown a picture of an old or new face with the instructions to use the following scale (Figure 2B):

- 1 = CONFIDENT OLD
  - You are confident that you *were* presented this image in study 1
- 2 = UNCONFIDENT OLD
  - You think you *were* presented this image in study 1

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- 3 = UNCONFIDENT NEW

  - You *were* not presented this image in study 1, but you are not confident

- 4 = CONFIDENT NEW

  - You are confident you *were* not presented this image in study 1

Note that here, study one refers to the encoding phase in the scanner that took place 24h before. Participants were encouraged to give a response as quickly and accurately as possible. This task took ~20min to complete. There were 144 trials in total, with 96 old faces (shown during encoding) and 48 brand new faces.

2.3.4.4 Answer Memory test After the face memory test, participants were shown trivia questions they had seen during the encoding phase on day 1 for 4000ms (Figure 2C). They were then prompted to type out the answer. If the participant did not know the answer, they were instructed to simply press *enter* and move onto the next trial. This session took approximately forty-five minutes to complete.

2.3.5 Polysomnography

Participants were given written instructions on how to use and place a Dreem v2.0 headband to monitor and record participants' duration in different sleep stages.The headbands use a 5 dry electrode system with 4 EEG derivations (Fp1-M1, Fp2-M2, Fp1-Fpz and Fp1-Fp2). Here the M sensors refer to the rear electrodes of the headband. The signal is processed at 250Hz and filtered within the 0.4-18Hz band. A 48–52Hz bandstop $6th$ order butterworth filter is used to remove European power line noise. Sleep data was then preprocessed using custom fieldtrip pipeline on Matlab that took the EDF files and prepared the channel headers to a format that was readable by a custom scoring GUI. Both of which can be downloaded HERE. Sleep stage scoring was carried out in accordance with the AASM guidelines (Berry et al. 2015). Due to the dry electrodes, the rule that dictates that only one electrode should be focused on for scoring was not followed as electrodes often lifted and returned contact with the skin when participants rolled over to other

Table 2: Mean and standard deviations of time spent in each sleep stage. Time is measured in minutes.

variable	n	mean	sd
REM	10	53.10	26.942
Stage 1	10	8.30	4.979
Stage 2	10	230.85	88.097
Stage 3	10	148.75	22.173
Total	10	465.05	101.861
Wake	10	24.05	13.623

side while sleeping. This scoring took on average 45 to 75 minutes per participant, resulting in twelve and a half hours of total scoring time. The scoring was carried by a secondary trained scorer according to the same AASM criteria. Table 2 shows mean time spent in each stage and total time.

2.3.6 Analysis

Analysis was carried out on RStudio (2022.07.1+554), with a variety of base, tidyverse, and ggplot functions for data manipulation and visualization. To understand the effects and interactions between curiosity enhancement and face stimuli onset on trivia answer memory recall, we carried out an ANOVA. The outcome variable was the % answers recalled and the within subject predictor variables were twofold. The curiosity predictor variable had two levels, whether the trivia answers had been classified during screening as inducing high curiosity or low curiosity. The face stimuli onset was included as we wanted to make sure that the faces were not having a conflicting effect on the answer memory benefit. This predictor variable had 4 levels, corresponding to whether the face stimuli onset was two, four, six, or eight seconds into the anticipation phase.

An ANOVA was also carried out for face recognition memory as an outcome variable. Again there were two predictor variables, curiosity and presentation window. Curiosity was a categorical predictor which had two levels, with either high or low curiosity items being experienced during the anticipation phase that the faces were shown in. The presentation window had four levels corresponding to when the faces were shown for two seconds during the twelve second anticipa-

tion window. This took place at either two, four, six, or eight seconds after the end of the trivia question presentation. Here face recognition memory accuracy was defined as proportional hits, where they had correctly seen the faces before (pressed "old" when in fact "old") minus false alarms (when participants categorized new faces as old, when in fact they were new).

Unless otherwise stated, all p-values are one-tailed as we have directional hypothesis.

2.4 Results

2.4.1 Curiosity enhances memory for high-curiosity versus low-curiosity answers
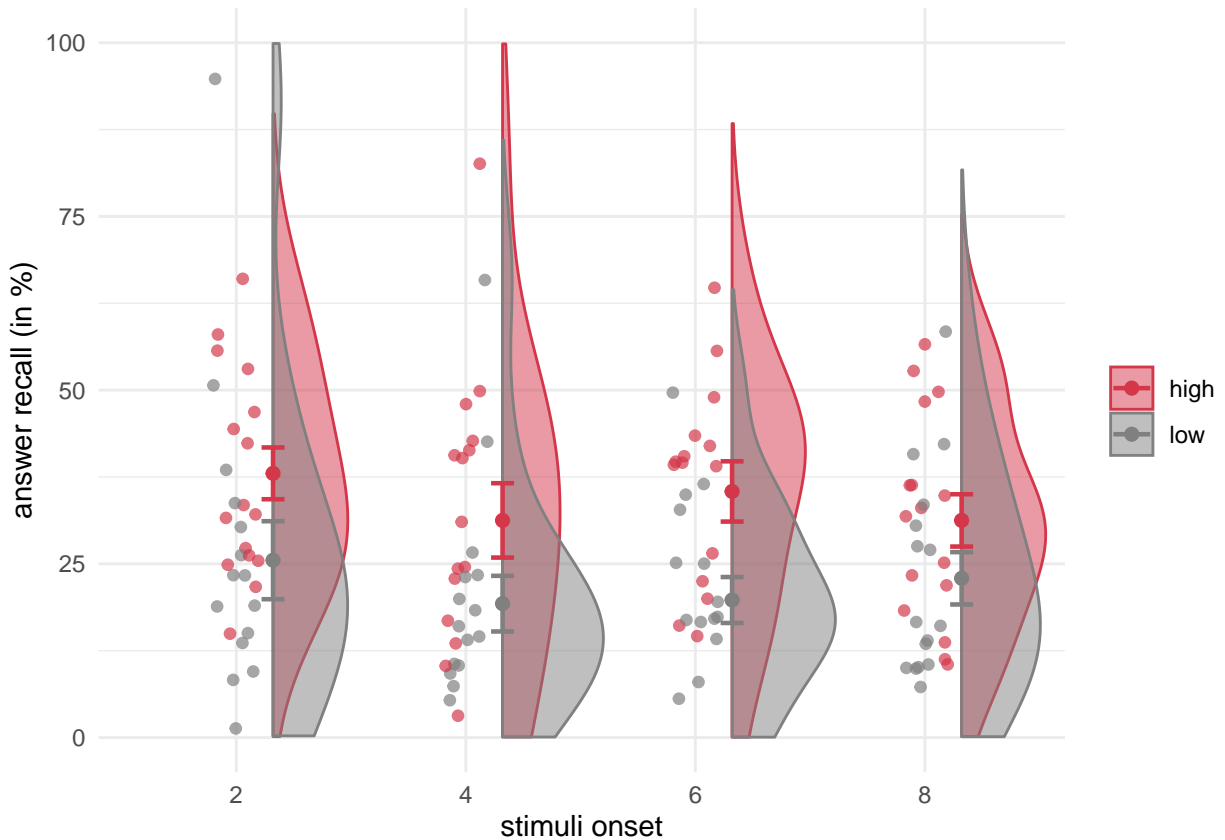
Figure 3: Curiosity-related answer memory benefit. X axis denotes the timepoint of incidental face image presentation within the 12 second anticipation period. Each half-violin plot shows the distribution of answer recall performance. The flamingo colored data represents high-curiosity answers and grey low-curiosity answers. The dot and whisker plots refer to the mean and standard error of measurement respectively.

In order to understand whether the effect of curiosity on trivia answer memory was consistent across the anticipation phase, an ANOVA was carried out. With this analysis we are both looking at the main effect of curiosity on answer memory, but also checking that the presentation of the incidental face at different time points does not have a conflicting effect on answer memory. Say, if for example the presence of a face too soon after the question presentation would mean that participants did not have time to fully comprehend the question presented. The results (Figure 3) indicated a main effect of curiosity ($F(1, 120) = 15.84, p \leq .0001, \eta_p^2 = .117$). There was no

effect of presentation time point of the face image within the anticipation window ($F(1, 120) =$ .817, $p = .244$, $\eta_p^2 = .020$) nor was there an interaction between curiosity and anticipation window ($F(1, 120) = .241$, $p = .434$, $\eta_p^2 = .006$). High curiosity trivia answers when the face was presented in the 2 second presentation window were remembered with a mean of 38.02% (sd = 14.90%), whereas for low curiosity answers, they were remembered with a mean of 25.52% (sd = 22.46%). For the 4 second presentation window, high curiosity answers were remembered with a mean of 31.25% (sd = 21.41%) and low curiosity answers with a mean of 19.27% (sd = 16.02%). For the 6 second presentation window, high curiosity answers were recalled with a mean of 35.42% (sd = 17.35) and low curiosity answers with a mean of 19.79% (sd = 13.22%). Finally, in the 8 second presentation window, high curiosity answers were recalled with a mean of 31.25% (sd = 15.07%) and low curiosity answers with a mean of 22.92% (sd = 15.07%). Overall, these results indicate the general effect of curiosity enhancement on trivia answers memory, regardless of when the faces were presented, suggesting no interference or task switching effect.

2.4.2 Curiosity enhancement does not extend to incidental faces

Next, we investigated whether curiosity can spillover from the target information, trivia answers, and into seemingly arbitrary incidental information. Information that appears during the anticipation phase, leading up to curiosity being satiated when the answer is shown. The results (Figure 4) showed no main effect of curiosity ($F(120, 1) = 1.319$, $p = .127$, $\eta_p^2 = .011$) or presentation window ($F(3, 120) = .057$, $p = .491$, $\eta_p^2 = .376$). The interaction was also not significant ($F(3, 120) = 1.043$, $p = .188$, $\eta_p^2 = .025$). At the two second presentation window high curiosity faces were recognized with a mean of 32.42% (sd = 12.34%) and low curiosity faces with a mean of 33.59% (sd = 9.65). For the four second presentation window, high curiosity face were recognized with a mean of 32.42 % (sd = 9.74) and low curiosity faces with a mean of 33.98% (sd = 14.96). For the 6 second presentation window, high curiosity faces were recognized with a mean of 36.33% (sd = 16.01) and low curiosity faces with a mean of 30.01% (sd = 12.75). For the 8 second presentation window, high curiosity faces were recognized with a mean of 37.5% (sd = 11.41) and
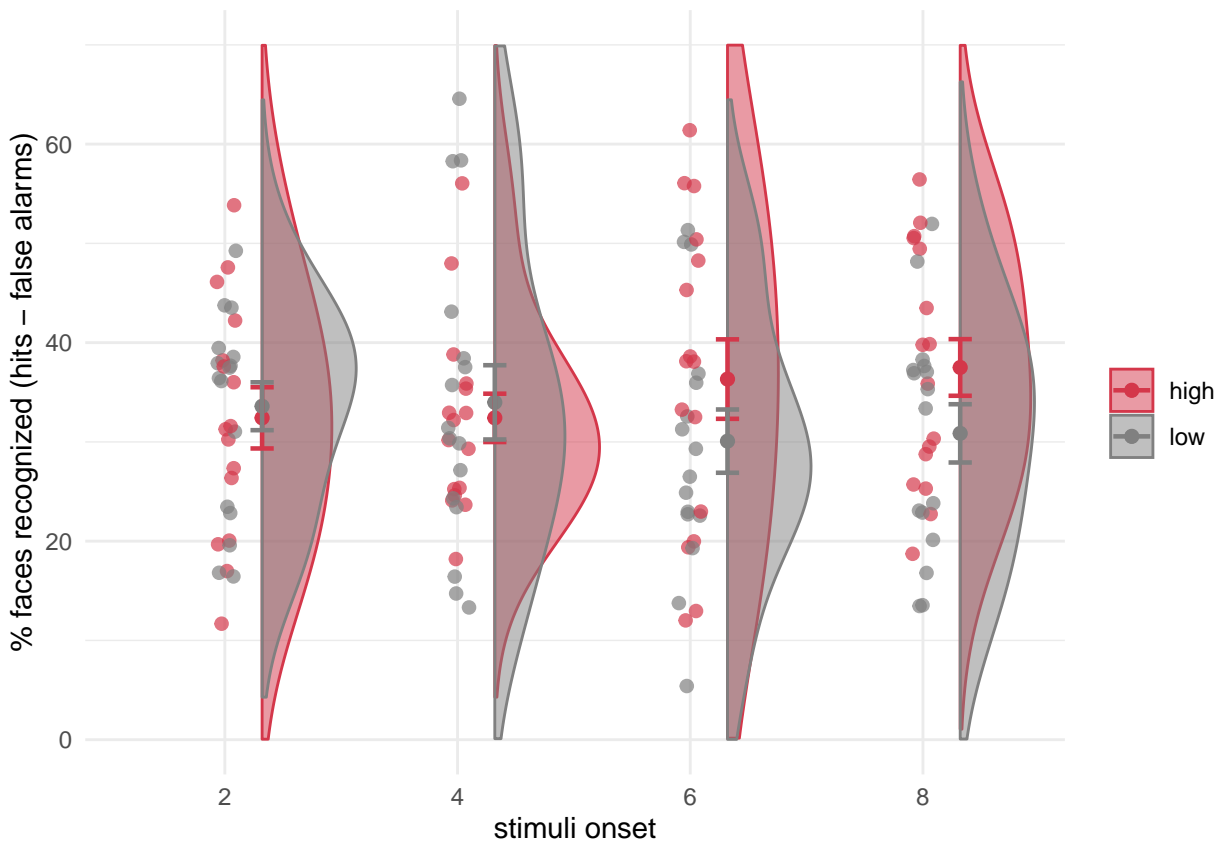
Figure 4: Curiosity-related memory benefits for incidental face images. The x axis denotes each of the four face stimuli presentation windows. The y axis represents face recognition memory (hits minus false alarms). the higher the value, the better recognition memory participants had. The flamingo colored data represents faces presented during high curiosity answer anticipation, grey colored low curiosity answer anticipation. The dot and whisker plots refer to the mean and standard error of measurement respectively.

low curiosity faces with a mean of 30.86% (sd = 11.74). This indicates the curiosity spillover effect did not occur for this particular sample as no faces seen in anticipation of high curiosity answers were recalled better than those in anticipation for low curiosity information.

2.4.3   Sleep duration predicts curiosity enhanced memory for trivia answers

To understand whether individual differences in sleep duration predict the degree of curiosity enhancement, a multiple regression was carried out with the degree of curiosity enhancement on answer memory (high curiosity answers minus low curiosity answers) as an outcome variable and total time spend on sleep stage 2, 3 and REM as predictor variables (Figure 5A). The overall regression was not significant ($R^2 = .41, F(3, 6) = 1.37, p = .170$). Results show that only one sleep stage predicted answer memory benefit. Stage 2 did not predict ($\beta = .000749, p = .295$), stage 3 did ($\beta = .00385, p = .0923, p = .0462$), and REM stage did not ($\beta = .00249, p = .0958$). Indicating that although we expected an effect for both stage 2 and 3, this was only statistically significant for sleep stage 3.

2.4.4   Sleep duration does not predict curiosity memory for incidental faces

We carried out the same multiple linear regression for the incidental faces to understand whether individual differences in sleep duration predict the degree of curiosity enhancement. The degree of curiosity enhancement on face memory (high curiosity faces minus low curiosity faces) as an outcome variable and total time spend on sleep stage 2, 3 and REM as predictor variables (Figure 5B). Results show that the overall regression was not significant ($R^2 = .34, F(3, 6) = 1.019, p = .50$). No sleep stages predicted answer memory benefit. Stage 2 did not predict ($\beta = .000271, p = .295$), nor stage 3 ($\beta = .00290, p = .0765$), and neither did REM stage ($\beta = .00156, p = .263$). As such, although somewhat exploratory, we had expected a positive effect of sleep stage 2 and 3 on curiosity memory enhancement for face recognition. As an additional control analysis we investigated whether sleep duration correlates with both overall answer memory and incidental face memory. We ran pearson correlations and corrected for
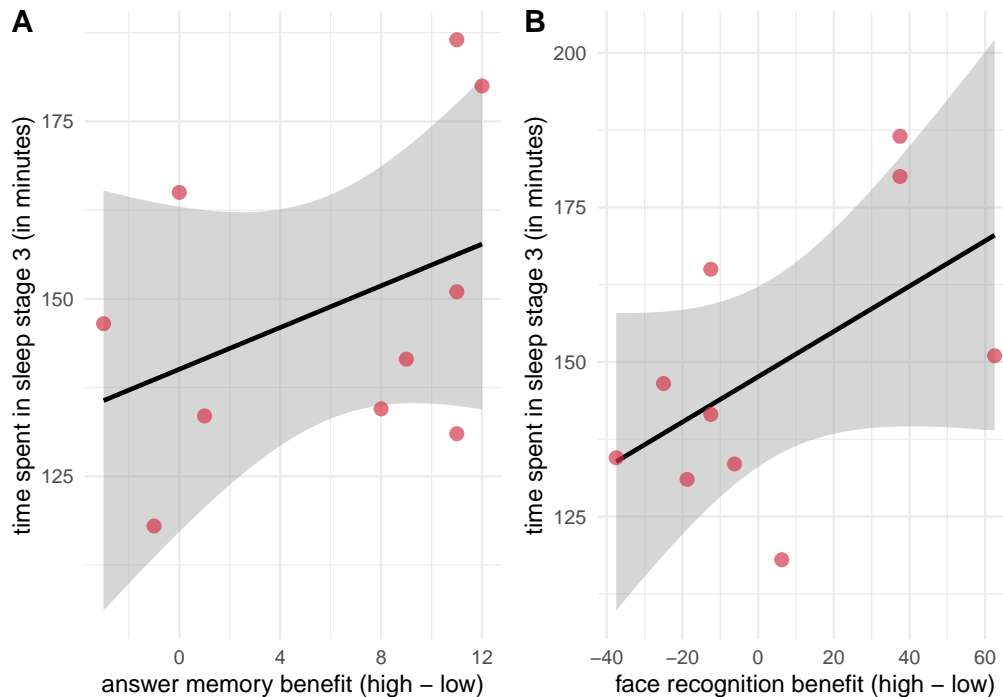
Figure 5: Scatter plots correlating total time spent in sleep stage 3 with A) answer memory benefit (high minus low) and B) face recognition benefit (high minus low).

multiple comparisons (p-value = .0125. No combination survived corrections. Answer memory performance does not correlate with sleep stage 2 ($t(8) = 0.41, p = .69, r = -.144$) nor sleep stage 3 ($t(8) = 0.275, p = .79, r = .09$). Incidental face memory also did not correlate with sleep stage 2 ($t(8) = 2.78, p = .026, r = .69$) or sleep stage 3 ($t(8) = 0.098, p = 0.93, r = .035$).

2.4.5 Those with greater curiosity memory enhancement benefit do not also benefit during location recall

We carried out a similar analysis to Fandakova and Gruber (2021) to understand whether it is the individual difference in curiosity enhancement that spillover to incidental memory performance. However, the correlation was positive, but not significant ($r(8) = .47, p = .085$). Results indicate that the data is trending towards curiosity enhancement benefit for trivia answers correlating positively with incidental memory benefit.

2.5 Discussion

The aim of this investigation was to establish whether sleep duration can affect curiosity enhanced memory. We found that memory recall for high curiosity trivia answers was better than for low curiosity answers, thus replicating previous findings (Kang et al. 2009; Gruber, Gelman, and Ranganath 2014; Murphy et al. 2021). This lends further credence to the notion that curiosity, much like money, can affect what memories persist. However, we did not find the curiosity memory enhancement for incidental faces. This is the case regardless of the presentation window faces were presented in within the anticipation window leading up to the the trivia answer. An individual differences analysis also did not reveal a positive correlation between curiosity answer memory benefit for incidental memory, however the data was on trend and in line with Fandakova and Gruber (2021).

However, we found that sleep, in particular SWS, predicted the degree of memory benefit (high curiosity information - low curiosity information). This evidence provides some indication that sleep is involved in processing rewarding memories. It corroborates with findings that found that sleep is positively related with the degree of monetary reward's effect on learned information (Studte, Bridger, and Mecklinger 2017) and is counter to the findings where sleep was not modulating memory enhancement (Stare et al. 2018). Indeed, a recent review shed some light on sleep research on memory effects as having a porous evidence base with mixed findings (Cordi and Rasch 2021). With the resources necessary to run well powered sleep studies, the incentive to carry them out may also be out of reach for several labs.

There are limitations in the present study. The sample size is quite small, and more so for the sleep analysis. This is likely to affect the generalizeability of the current findings. A larger sample size for future studies is warranted. There is also the remaining issue as to why participants' face memory did not benefit from curiosity enhancement. It could be that the MR scanner environment were too distracting, but this does not corroborate with previous experiments that found the effect despite having participants experience the incidental information inside an MR scanner (Gruber,

Gelman, and Ranganath 2014). However, 7T scanner bores are smaller than their 3T equivalents and so it may be that the discomfort interfered with the learning session. In addition, it is also pertinent to stress test this incidental information effect that is used to suggest that curiosity can spillover and enhance memory for seemingly unrelated information. Doing it out of a scanner and without using faces will tell us whether a 7T MR scanner in interfering with the encoding phase and whether the effect occurs because faces have specific visual features that draws our attention to a greater extent compared to everyday objects.

2.6 Future directions

This experiment was illuminating in several ways. The curiosity memory enhancement occurs despite participants being in a 7T fMRI scanner (with its smaller bore). We found that sleep could potentially contribute to memory enhancement. The experiment now needs to expand to memory of a different type (associative) and a different memory recall (cued recall) to see if the incidental curiosity memory benefit is truly content agnostic. We will first need to understand the immediate and delayed memory recall to understand how memory persistence progresses of over time. We will also aim to test whether we can induced the curiosity enhanced memory effect by presenting information auditorily to understand whether this effect can cross modalities (section 3). We will also investigate how other parameters, such as context, in the anticipation phase affect incidental memory persistence (section 4). Finally, we can then investigate the effect that sleep could have, compared to a similar period of wake, on what memories persist (section 5).

3 Curiosity Enhanced Memory: Beyond incidental faces and into object-location associative memory

3.1 Abstract

Curiosity is understood as the intrinsic motivation to seek information whereby the reward is new knowledge acquisition and uncertainty reduction. This phenomenon is associated with the dopaminergic reward processing system and the memory consolidation region of the hippocampus. Curiosity has been shown to result in better memory recall for information we are highly curious about over information we are not so curious about. While curiosity memory enhancement appears to a fairly stable effect, less is understood about the mechanism that results in incidental, and seemingly unrelated, information also being positively affected by states of high curiosity. Little is also understood about the progression of memories across a 24h period. In this experiment we carry out a modified version of the trivia paradigm with incidental objects appearing instead of faces during the anticipation phase. Results show that curiosity memory enhancement for trivia answers persists across time, but that this did not extend to the incidental memory. In fact we found the opposite relationship at immediate testing and no different at delayed. We discuss findings in relation to the relevant literature and make recommendations for future work.

3.2 Introduction

Memory research provides a range of fascinating insights into how our brain processes information from present experience to long term storage for later use. Recently, it has been examined how the mechanisms by which our own internal motivational states modulate the likelihood that information is consolidated into long term storage. Specifically, curiosity, which is thought of as the motivation for information acquisition whereby the reward is the knowledge itself (Kang et al. 2009; Kashdan et al. 2018; Loewenstein 1994; Marvin and Shohamy 2016). However, little is understood about what type of incidental information this heightened cognitive state can capture and therefore how much curiosity governs self-directed learning.

Researchers found that participant's curiosity towards finding out about answers to trivia questions related positively with activity in the dopaminergic system, a key region for processing reward and self-guided learning (Gruber, Gelman, and Ranganath 2014; Murty et al. 2017; Ripollés et al. 2016, 2018). The behavioral outcomes indicated that individuals are more likely to remember the answers to trivia questions when they are in this heightened state of curiosity, compared to when they are not curious about finding out the answer (Gruber, Gelman, and Ranganath 2014). This curiosity enhancement effect was seen after seven days (Marvin and Shohamy 2016) and even after 11 to 16 days (Kang et al. 2009). This has similarities to studies looking at monetary reward's effect on learning. When you reward a piece of information to be remembered, you are more likely to recall the information associated with high reward compared to low reward. In addition, there is also an associated activity within the ventral striatum and midbrain (including SN/VTA) that scales with the amount of reward sensitivity (Adcock et al. 2006; Gruber et al. 2013; Murty and Adcock 2014; Frank, Preston, and Zeithamova 2019; for review see Shohamy and Adcock 2010). This suggests a mechanism that works with frontal cognitive control regions in anticipation of reward (Bialleck et al. 2011) and signals the hippocampus with a value signal, regardless of whether they are predictable or not. Indicating to the hippocampus that some upcoming memories are more important than others; potentiating the likelihood of long term consolidation.

Further, the heightened state of curiosity experienced in anticipation for the answers spills over to information presented between curiosity initiation and satiation. For example, when faces were incidentally presented in anticipation for trivia answers, faces experienced during a state of heightened curiosity were more likely to be recalled later compared to those seen when in anticipation for answers that did not elicit curiosity (Gruber, Gelman, and Ranganath 2014; Galli et al. 2018; Murphy et al. 2021; Stare et al. 2018). However, there may be an individual differences component at play (Fandakova and Gruber 2021). If individuals do not generally benefit much from curiosity enhancement then incidental memory may also not benefit accordingly.

Learning of Dutch German word pairs also remembered better when associated with higher money value (Studte, Bridger, and Mecklinger 2017), object locations Antony, Piloto, et al. (2018), and object-context associations (Gruber et al. 2016). For example, participants recalled object locations associated with high reward more accurately compared to those associated with low reward (Antony, Piloto, et al. 2018). Given the similar effects of external monetary reward and internally generated curiosity, the question remains open as to whether curiosity can influence the likelihood that something other than faces is incidentally, yet favorably consolidated. For example, faces might be more salient or faces might be easier to associate with a trivia question, therefore you see a 'spillover' effect. As such, more neutral stimuli (e.g., objects) should be used to investigate the generalizability of curiosity's spill-over effect on different types of material.

In light of this gap in the literature, the current experiment proposes that by combining the trivia paradigm (Kang et al. 2009; Gruber, Gelman, and Ranganath 2014) with object locations during this critical anticipation phase (instead of faces), we would provide additional evidence for the robustness of this effect and its ability to influence consolidation likelihood for a different type of information. Therefore, we hypothesize the following outcome:

1. High curiosity trivia answers are recalled better than low curiosity answers.
2. Curiosity will have a similarly directional effect on incidentally object-location associates, as it does for answers recognition memory.

3. Degree of forgetting will be lower for high reward object locations compared to low reward locations.

4. Answer memory benefit will positively correlate with incidental memory benefit.

3.3 Methods

3.3.1 Sample

Of the overall sample (n = 34), two participants were removed due to incomplete data sets. A further two participants were removed due to their performance falling below 1.5 *IQR* in the answer recall portion of the experiment, as this was deemed too low a performance for them to be paying attention to the task. In addition, prospective participants were excluded on the same criteria as in section 2.3.2. The final sample is of 30 participants (19 females), with a mean age of 20.3 (range = 18-30). They were recruited from the Cardiff University campus population. The recruitment was carried out via the School of Psychology undergraduate participation credit framework, campus advertising, and word-of-mouth. For those participants that were not part of the credit scheme, their time was remunerated accordingly. Participants provided informed consent with the option to withdraw participation at any point without giving a reason. This experiment was approved by the Cardiff University School of Psychology ethics committee.

3.3.2 Procedure

Stimuli presentation were carried out using *MATLAB* (version 2019a. Mathworks inc.) and *Psychtoolbox* (version 3.0.15). The following experimental sections were presented on a high frame rate monitor (1920x1080; Iiyama 24", 144Hz). All stimuli were presented on a black background. Sound was administered via passive noise canceling headphones (MDR-ZX110NA, SONY Corp.) throughout the screening, encoding, and recall phases. Participants attended two sessions in a laboratory setting on campus. The first session included the *screening*, *encoding*, and *recall* phases. The second session only included the *Recall* phase. Session 2 took place 24 hours after session 1.

3.3.2.1 Screening Participants were asked to screen through trivia questions (see also Kang et al. 2009; Gruber, Gelman, and Ranganath 2014; Marvin and Shohamy 2016; Murphy et al. 2021) and rate their curiosity to find out the corresponding answers. In this *screening phase* (see Figure
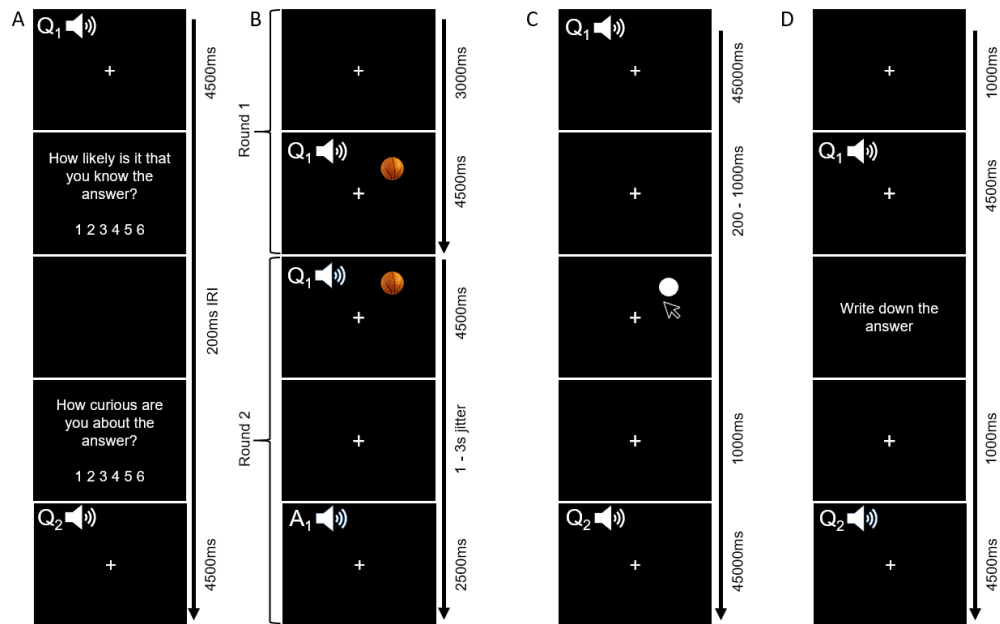
Figure 6: Experimental paradigm. A) Screening phase, B) Encoding phase, C) Location recall, phase D) Answer recall phase.

6A), each trial was composed of a 3000ms pause, where a cross is presented in the center of the screen followed by a trivia question that was presented auditorily for a duration of 4500ms (for example: the name of what animal literally means 'Terrible lizard'? Answer: Dinosaur). Text appeared showing the knowledge rating query, which stated *"How confident are you that you know the answer?"* This was self-paced and participants were instructed to, on a scale from 1 to 6, indicate how confident they were that they knew the answer. 1 indicated *not at all confident* and 6 *extremely confident*. Subsequently, after a pause of 200ms an additional question was presented (*How curious are you about the answer?*); to which participants were asked to respond using the same 1 (*not at all curious*) to 6 (*extremely curious*) scale. To respond, participants used the number keys directly above the letter keys on a keyboard. Of note, this *curiosity rating* is how this paradigm accounts for individual differences in what people are interested in. After all, none of us are curious in the same topics and information.

Participants carried out the *screening* phase for maximum total of 254 trials with randomly ordered trivia questions (see table 1). There were breaks every 25 trials. This phase would conditionally

end when the below criteria was met: 40 trials with a *curiosity rating* response of low curiosity (ratings 1, 2, or 3) and 40 trials as high curiosity (ratings 4, 5, or 6). Trials with a *confidence rating* of 6 were discarded regardless of curiosity rating as we wanted to see the effect of curiosity on memory when there is some degree of uncertainty about the associated answer. The first 4 trials were used as practice trials and therefore discarded from analysis.

3.3.2.2 Encoding In the *encoding phase* (see Figure 6B) participants were presented with 80 trivia questions they had previously rated. However, for each trial in addition to the auditory trivia question presentation, an image of a randomly selected object was presented at a randomly selected location on the screen. This lasted 4500ms. There was no grid background as this does not seem to impact participant's ability to learn (Deuker et al. 2013; Oudiette et al. 2013). Each trial was separated by an inter-trial jitter between 1000-3000ms. The images were sized at 160-by-160 pixels (4x4cm on a 24inch screen). Images were taken from the Bank of Standardized Stimuli (Brodeur, Guérard, and Bouras 2014). These objects were a mixture of animals, household items, traffic signs, and tools. A second round was carried out in another random presentation order for all 80 question-picture pairs with the same jittered parameters as the first round. However, after each question/picture presentation the answer for that question was presented for 2500ms with an intra-trial jitter of 1000-3000ms between the question-picture pair presentation and the answer presentation. The picture was not included during the answer presentation.

3.3.2.3 Location Recall The location task was self-paced and participants were instructed to listen to the 80 randomly sorted trivia questions (presented for 4500ms) and then once the mouse cursor appeared on the screen, participants were tasked to select the location they thought the picture had appeared during the encoding phase associated with that particular trivia question. No object was shown. They responded by moving the mouse cursor to the correct location on the screen and clicking the left mouse button (see Figure 6C).

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3.3.2.4 Answer Recall The 80 questions were again randomly sorted and presented auditorily to the participants for 4500ms, one question at a time. Once they had written down the answer, they pressed the space bar to continue to the next trial. This task was also self-paced. However participants were instructed to not spend too much time on each question and to write down on a sheet of paper the answer that first came to their mind. If they were unsure, they were asked to leave the section blank. No object was presented in each trial for this task and the questions were not shown in the answer sheet (see Figure 6D).

3.3.2.5 Delayed Memory tests 24 hours later, the participants returned to the lab and were told that they would complete the location and answer recall tasks again. To avoid rehearsal effects confounding the data, the order of presentation of the 80 questions in each of these two tasks was also randomly sorted. In the following sections these tests will be referred to as delayed memory tests where as the recall tests done directly after the encoding phase are considered the immediate memory tests.

3.3.3 Analysis

To derive the forgetting distance the absolute difference was taken between the actual location of object presentation and the *selected* location (during location recall) and the difference between immediate and delayed location recall tests. This calculation was defined (*equation 1*) as the absolute difference between presented location x and the selected location x_i in x coordinates. The same is done for y-coordinates (as denoted by y and y_i respectively). From these calculations the length of two sides of a right-angle triangle are known from which the third side can be derived using Pythagorean theorem and from this the error distance at either time point can be calculated. Forgetting is then calculated as the difference between a across the immediate and delayed time points. Positive values, participants got better over time, and negative, they got worst over time.

$$a = \sqrt{|x - x_i|^2 + |y - y_i|^2}$$

It is important to note that, as a result, this is a continuous measurement with an arbitrary unit as the length of a diagonal line is extrapolated from discrete x- and y- pixel dimensions. As such, this can result in error measurements that are a fraction of a pixel. Where noted in centimeters, this will reference to the length of the horizontal dimension of an AOC 28" monitor (approx. 62x34cm).

In addition, to correct for the increased chance of lower location error at the delayed time point when location error at immediate testing is far from the target location we use an adjusted forgetting score in line with the correction described in (Antony, Piloto, et al. 2018) and as depicted in equations *2 & 3*.

$$y = ax + c$$

$$k = ((x - z) - y) + \frac{(x - z)}{n}$$

Here, in expression 2, you find the linear predicted forgetting. Where y denotes predicted forgetting, a denotes gradient from linear relationship between location accuracy at immediate and delayed time points and c denotes an additional constant factor explaining the linear relationship. x denotes location recall at immediate memory testing. z denotes location recall at delayed memory testing. n denotes number of data points, here the number of participants is used. k is the chance adjusted forgetting.

The statistics presented in the results were carried in *RStudio* (2022.07.1 Build 554) and *ggplot2* (version 3.3.6). To analyse whether timepoint and curiosity affected answer memory, the ANOVAs had two within subjects factors. One with for the effect of the time point the recall task was carried out. This had two levels and was either immediate or delayed. While curiosity also had two levels,

which referred to whether the curiosity answer was rated as low (1, 2, 3) or high curiosity (3, 4, 5) during the *screening* phase. A similar ANOVA was carried out for the object location accuracy. An additional exploratory analysis was carried out to investigate the rate forgetting rate from the immediate to the delayed memory tests. For the forgetting rate, the object location measure was defined as delayed location accuracy minus immediate location accuracy. This was carried out for high and low curiosity items separately so that these two could be compared. Finally, for memory benefit analysis the difference is computed between high and low performance. For example, in answer memory benefit we subtract high curiosity answer memory performance from low curiosity answer memory performance. As we predict a directional outcome and unless otherwise stated, p-values are one-tailed.

3.4 Results

3.4.1 Curiosity promotes memory for highly curious information

To assess if curiosity affects memory consolidation and whether this effect interacts with the two different testing time points, we ran a repeated measures ANOVA where the outcome variable is the % correct answers. There were two within-subject predictor variables, curiosity for the particular answer, which had two levels (high or low) and the time point the memory test was carried out (immediate or delayed).
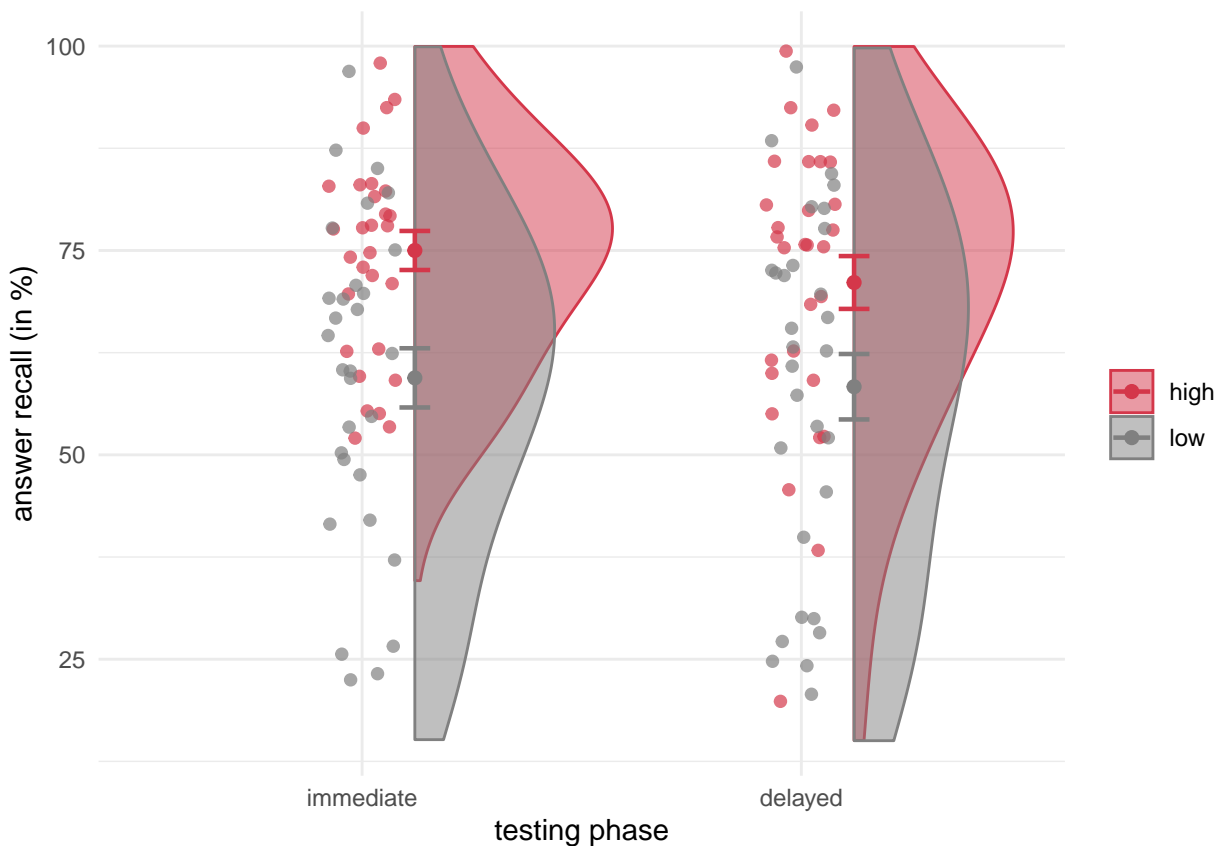
Figure 7: Answer recall performance across the two curiosity categories and the two testing time points. Flamingo colored data is for high curiosity trials and grey for low curiosity trials. Data points are jittered horizontally. The dot and whisker plots refer to the mean and standard error of measurement respectively.

Trivia answer recall was examined against curiosity level (high versus low) and at each time point (immediate versus delayed, Figure 7). The ANOVA indicates a main effect for curiosity level, $F(1, 29) = 48.66, p \leq .001, \eta_p^2 = .63$. No main effect of time point ($F(1, 29) = 2.26, p =$

$0.07, \eta_p^2 = .072$), but an interaction between both predicting factors ($F(1, 29) = 3.37, p = .039, \eta_p^2 = .01$) was found. To examine the main effect of curiosity level, pairwise comparisons were carried out. This revealed a difference between the % correct answers for low curiosity items versus high curiosity items at immediate testing ($t(30) = 7.25, p \leq .001$), with low curiosity answers being recalled with a mean of 59.42% (sd = 19.83%) and high curiosity answers with a mean of 75% (sd = 13.08%). Similarly, at the delayed testing (~24h after immediate testing) this pattern was also found; $t(30) = 5.81, p \leq .001$, with low curiosity answers being recalled with a mean 58.33% (sd = 21.93%) and high curiosity answers with a mean of 71.08% (sd = 17.70%). Pairwise comparisons between high curiosity answer memory across time points revealed no significant difference ($t(30) = -1.73, p = .094$) and neither was there one for low curiosity answer memory across time points ($t(30) = -0.85, p = .40$). Thus, indicating that high curiosity answers were recalled better than low curiosity answers, and that this effect did not differ across across testing time points.

3.4.2 Curiosity does not promote memory for object locations associated with high curiosity trivia answers

Next we assessed whether curiosity enhancement had a similar effect on participants' ability to accurately recall the location of objects associated with the trivia question and answer dyads, a repeated measures ANOVA was carried out with the outcome variable as the location error and the same predictor variables as the above analysis (figure 8A). Data conformed to the Shapiro-Wilk normality criteria. The ANOVA revealed no main effect of curiosity level ($F(1, 29) = 1.41, p = .123, \eta_p^2 = .45$), but revealed a main effect of testing time point ($F(1, 29) = 24.08, p \leq .001, \eta_p^2 = .45$) and an interaction between the two factors ($F(1, 29) = 8.458, p = .005, \eta_p^2 = .23$). Pairwise comparisons, corrected for multiple comparisons, revealed difference between items at high and low curiosity states in the immediate testing time point; $t(29) = 2.43, p \leq .05$, with low curiosity objects being recalled with a mean error of 447.35 pixels (SD = 149.29) and high curiosity objects with mean error of 474.326 (sd = 159.51). Whereas at the delayed time point, there was no

difference; $t(29) = -0.29, p = 0.387$, with low curiosity items being recalled with a mean error of 515.52 pixels (sd = 132.42) and high curiosity items with a mean error of 512.21 pixels (sd = 116.39). Indicating that the location error difference between high and low curiosity object locations occurred during the immediate testing phase and that participants were more accurate for low curiosity object locations than high curiosity object locations, but this curiosity-related recall difference disappeared after 24 hours This is contrary to our hypothesis. Comparing each curiosity level at the different time points is indicative of this trend. The high curiosity object locations were significantly different from each other across time points $(t(29) = 2.79, p = .009)$ as were the low curiosity object locations location $(t(29) = 6.71, p < .001)$. Indicating that at immediate time point participants were more accurate compared to delayed time point, regardless of the curiosity level experienced during encoding.

3.4.3   Degree of forgetting is greater for high curiosity locations

Given the unexpected reverse finding between the high and low curiosity object location in the immediate time point in the section above, we were interested in exploring the degree of forgetting across the two curiosity conditions (Figure 8B). This was the outcome variable and curiosity condition was the predictor variable. A repeated measures t-test revealed a difference in forgetting across the curiosity states; $t(29) = 0.76, p \leq 0.01$. Degree of forgetting during low curiosity states had an average forgetting of 494.34 pixels $(sd = 97.46)$, whereas during high curiosity states there was an average forgetting of 535.09 pixels $(sd = 126.97)$. This analysis suggests that low curiosity object locations suffered less forgetting overnight compared to high curiosity object locations.

3.4.4   Those with greater curiosity memory enhancement benefit do not also benefit during location recall

We carried out a memory benefit analysis on answer memory benefit versus incidental memory benefit for both immediate and delayed testing. In accordance with our hypothesis we would
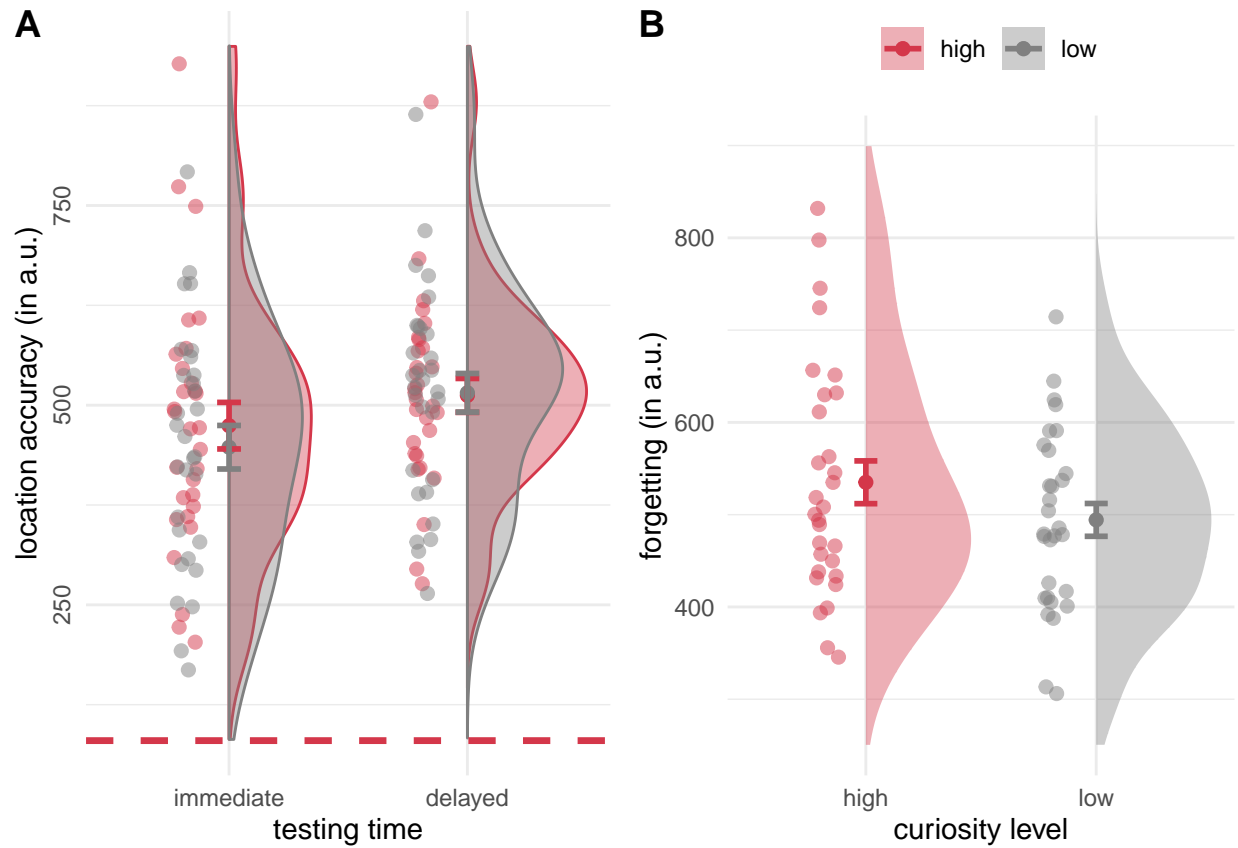
Figure 8: A) Object location error separated across testing time points and curiosity. Dashed line refers to the edge of the object margins and lower location accuracy value means fewer pixels between target location and selected location. B) Degree of overnight forgetting across the two curiosity conditions. Labels refer to curiosity conditions for both plots. The dot and whisker plots refer to the mean and standard error of measurement respectively.

expect a negative correlation as the smaller the incidental memory value, the more accurate individuals were at high minus low curiosity for incidental location memory accuracy. At immediate testing a negative correlation was not significant ($r(28) = -.20, p = .15$) and at delayed testing a negative correlation was also not significant ($r(28) = -.15, p = .22$).

3.5 Discussion

This experiment attempted to extend on the work of the previous chapter, by trying to understand whether curiosity enhanced memory spillover effect extends to the associative memory between objects and their locations. To see if curiosity can also enhance incidental object location associations when they are seen in a state of high curiosity. We present findings that indicate that the curiosity enhanced memory for trivia answers persists with the added complexity of incidental spatial associations appearing in the anticipation phase. Thus, we replicated past findings (Gruber, Gelman, and Ranganath 2014; Stare et al. 2018; Murphy et al. 2021). Furthermore, we also provide evidence that this pattern of memory enhancement persists across time. In both testing instances, participants were more likely to recall answers that participants were highly curious about. However, we did not find a curiosity enhancement for incidental spatial locations. Some differences were found in the immediate testing time point, but these reflected a difference in the opposite direction than what was initially predicted. That is, spatial locations associated with lower curiosity states were recalled closer to the target location than the high curiosity location associates. To understand more about this effect, we created a forgetting variable, which provided further evidence for this claim. This runs counter to the previous trivia paradigm incidental memory effects (Gruber, Gelman, and Ranganath 2014; Murphy et al. 2021; Stare et al. 2018), which found that incidental information benefited from curiosity enhancement. In addition, a memory benefit analysis was carried out. We would have expected that those who benefited more from curiosity enhancement for trivia answers would also benefit in incidental memory performance (Fandakova and Gruber 2021), even if their absolute performance was not that good. Our findings do not concur with with this hypothesis.

There could be several explanations for the unexpected location accuracy findings. The items that triggered low curiosity left a gap in attentional resources for object location, as participants no longer felt the need to retain attention towards the trivia question and answers being displayed. Another potential caveat is that this study's design used a 24 hour paradigm where participants inevitably underwent a period of sleep, which may have affected spatial location accuracy. Studies

have shown sleep to generally be positively related to rewards' effects on learning (Studte, Bridger, and Mecklinger 2017; Antony, Piloto, et al. 2018) and also associated with a reduction in the amount of object location error for high value objects versus low value objects (Oudiette et al. 2013). A pattern which we did not find as evidenced by the curiosity memory enhancement for trivia answers being similar across the two time points; rather than better after sleep. Although to full disentangle sleeps' role further investigation into sleep parameters would be needed. For the object location accuracy, the findings were in the opposite direction of what was hypothesized, that high curiosity objects locations were recalled less accurately compared to low curiosity object locations. In addition, the high curiosity object locations suffered more forgetting overnight and across a period of 24 hours compared to low curiosity object locations. A recent review sheds some light on the mixed effects in the sleep-mediated memory benefits literature. Findings of sleep effects occur as often as null findings (Cordi and Rasch 2021) and there may be something do with the task carried out. We used an incidental associative memory measure rather than a recognition memory one (Gruber, Gelman, and Ranganath 2014). Of course, it is unclear from this design for two reasons. One, no PSG was recorded and therefore it is hard to establish what specific effect sleep stages are having on either low or high curiosity items. Two, we also do not have a separate sample which did not experience sleep in between testing sessions, so cannot say that sleep is relevant for curiosity enhanced memory consolidation. In other words, for sleep to have a positive effect on curiosity enhanced memory, we would expect to see the curiosity memory benefit for trivia answers to be larger after sleep. Alternatively, we would expect to see that overnight this answer memory benefit would be rescued from the deleterious effects of forgetting. High curiosity information would be forgetting to a lesser degree compared to low curiosity information. However, this remains to be fully investigated. Studies comparing periods of wakeful and sleep rest can be large and resource intensive, but it is one way to fully understand how these different states of consciousness can interplay with curiosity to impact motivated memory consolidation.

An additional caveat, is the time at which the objects are presented. As in this case, some

paradigms will display the information that is to be learned at the same time Studte, Bridger, and Mecklinger (2017). However, some will create a string of sequences with no overlap in information Murphy et al. (2021). This study opted for the information to be presented with an overlap, but the sequential aspects of the original trivia paradigm may be less overwhelming for participants to experience and thus not introduce noise into the effect. It may be too much information to process at a given time and therefore the attentional resources triggered by curiosity do not have a chance to ramp up and affect how the object and its location are encoded. As such participants are having to task switch between anticipating the trivia answer and where the incidental object appeared; which explains why the low curiosity objects location accuracy was marginally better than high curiosity object locations.

It may be the nature of what the participants perceive on the screen. While some found learning effects in barren grey screens (Deuker et al. 2013; Oudiette et al. 2013), perhaps the environment is not sufficiently rich for participants to build contextual associations between what the object is, where it is, and what it is near. Picard et al. (2017) found virtual reality as a valid approach to study different aspects of memory in children and adolescents. It may be prudent to consider the role of being able to attach meaning between objects and their locations in space with respects to other things. Say for example, a birds-eye view of rooms in a house where objects appear within specific locations of that complex spatial context. Here participants will be able to attach meaning to objects by connecting it to the space they appear in. For example, the apple appeared in the kitchen. As opposed to objects appearing in a contextual vacuum, say a black or grey screen. Future investigations that take this into account in their experimental designs are needed.

3.6   Future directions

This experiment was one potential step in expanding the trivia paradigm and understanding curiosity's potential impact on incidental information. We presented the trivia information auditorily and found a curiosity memory benefit. However, we did not find an incidental memory effect. We identify that the role of context may play a role in enabling a state of heightened

curiosity to bind objects and their locations. The following experiment (section 4) will attempt to add context to the trivia paradigm and establish whether then incidental memory benefits from the state as seen in previous literature.

4 Curiosity and Incidental Information: The role of context

4.1 Abstract

Curiosity is understood as the intrinsic motivation to seek information whereby the reward is new knowledge acquisition and uncertainty reduction. This phenomenon is associated with the dopaminergic reward processing system and the memory consolidation region of the hippocampus. Curiosity has been shown to result in better memory recall for information we are highly curious about over information we are not so curious about. While curiosity memory enhancement appears to a fairly stable effect, less is understood about the mechanism that results in incidental, and seemingly unrelated, information also being positively affected by states of high curiosity. In this experiment we carry out a modified version of the trivia paradigm with incidental objects appearing at various locations within a scene, instead of faces, in the anticipation phase. Results show that curiosity memory enhancement for trivia answers was found, but that this did not extend to incidental object-location associative memory. We discuss findings and make recommendations for future work with reference to relevant literature.

4.2   Introduction

Curiosity is understood as the motivation for information acquisition whereby the reward is the knowledge itself (Kang et al. 2009; Kashdan et al. 2018; Loewenstein 1994; Marvin and Shohamy 2016). Curiosity guides us towards information, and when reality and predictions do not match, we then make a concerted effort to engage or attend that information so we are better prepared for future situations (Gruber and Ranganath 2019).

Indeed, it is known that individual's curiosity towards finding out trivia answers related positively with activity in the dopaminergic system, a key region for processing reward, curiosity, and self-guided learning (Gruber, Gelman, and Ranganath 2014). Similar activity in the dopaminergic circuit extend to reward motivated learning (Murty et al. 2017), learning language (Ripollés et al. 2016), and even in pharmacological modulation (Ripollés et al. 2018). In these experiments, participants are shown trivia questions, which are believed to trigger different levels of curiosity. In recent experiments this curiosity elicitation results in better recall for corresponding answers when a person is in a heightened state of curiosity versus when they are not (the answer was thought of as not being particularly interesting). Two, in anticipation for the trivia answer, if faces are incidentally shown to participants, recognition performance is better for faces seen during a state of heightened curiosity versus a state of low curiosity (Gruber, Gelman, and Ranganath 2014; Stare et al. 2018; Galli et al. 2018). Individual differences in curiosity enhanced memory benefit (high minus Low) were also shown to be positively correlated with incidental memory benefit (Fandakova and Gruber 2021). One easy way to test this is to show some incidental objects on the screen at an *early* onset and others at a *late* onset during the anticipation phase.

In addition, it was found that the curiosity can also affect incidental faces presented between curiosity elicitation and satiation (Gruber, Gelman, and Ranganath 2014; Galli et al. 2018; Murphy et al. 2021). High curiosity states positively relate with regions in the dopaminergic rewards system (Gruber, Gelman, and Ranganath 2014). It is theoretically thought that when curiosity is triggered the cognitive control frontal regions guide attentional resources. Then the dopaminergic

system tags important information preparing the hippocampus for consolidation (Gruber and Ranganath 2019). This then increases the likelihood that information we are curious about is consolidated into stable memories. In addition, the timing of incidental stimuli presentation may matter, with presentation closer to curiosity initiation being crucial for curiosity enhanced memory for incidental information (Galli et al. 2018; Murphy et al. 2021). However, it is not yet known if the curiosity spillover effect (for faces) generalizes across other types of incidental information.

However, as we saw in the previous chapter, it appears that this may not extend beyond face stimuli. We saw no curiosity-related memory enhancement for incidental object locations in an immediate and delayed recall test. Now, it could be that the environment the objects appear in is not sufficiently realistic and thus too hard for participants to create the association. As Petzka et al. (2021) found, the difficulty of the task can impact the memory benefits that are seen, at least for paradigms that involve a period night sleep. In addition, using a virtual reality 3D approach, it was found that the higher the curiosity to investigate virtual environments, the better the recognition memory for incidental objects (Cen, Gkoumas, and Gruber 2021). Even depending on whether we prefer 2D or 3D videogame environments can affect the outcome of an unrelated recognition memory task (Clemenson and Stark 2015). Indeed, such virtual environments exploration paradigms have shown to be sensitive to measuring incidental memory from 6-year-old children to grown adults (Picard et al. 2017). Meaning that virtual enrichment can affect our ability to build associations between otherwise unrelated things. It is suggested that those richer environments elicit better pattern separation, so when objects appear in a similar location the relation to nearby landmarks can assist consolidation. Whereas, if the locations are too similar across objects then interference can affect consolidation processes. It would be interesting to see whether a more visually rich environment would affect the curiosity spillover effect for incidental object-locations associations.

In addition to these curiosity enhancements and spillover effects, some researchers found that the absolute curiosity for information is only one pathway by which information can be prioritized

and remembered. The so-called information prediction error (IPE) is another mechanism. IPEs are the discrepancy between initial valuation of a piece of information and a later valuation. Indeed, it was found that participants have better recollection for the details of a movie excerpt when there is an unexpected interruption to the scene (Sinclair et al. 2021). This is also seen in rats who examine unexpected cues longer at the detriment of time spent exploring cues that will give them a reward (Steinberg et al. 2013), indicating that IPEs can also be a driver for learning and memory. Within a trivia paradigm context, participants are asked to rate curiosity for trivia answers, but then also asked how interested they were about the answer. Indeed, this provides a novel way to probe about the interest in the answer. particularly in those circumstances where the initial curiosity is not high, but upon finding the answer one has an "a-ha" moment. It was found that as these IPEs increase, the more likely a trivia answer is to be remembered (Marvin and Shohamy 2016; Fandakova and Gruber 2021). This suggests that internal mechanisms responsible for eliciting curiosity effects may be a part of a larger information gathering and prediction making system. Indeed, one of the theoretical frameworks that underlies curiosity research suggests that there can be unexpected changes in the environment or violations in expectations that are incongruent with prior knowledge. This then triggers a cascade of activity that promotes the likelihood of a memory being formed (Gruber and Ranganath 2019). Therefore, it would be interesting to see if this updating mechanism can also affect incidental information, particularly whether it behaves like IPEs broadly in the neuroscientific literature as part of future predicting mechanisms, motivation, and learning (Ouden, Kok, and Lange 2012).

As such, with this experiment, we will present objects in locations within a context rich environment, to investigate whether heightened curiosity states can enhance object location memory within a context rich environment. For example, the object 'apple' is next to a tree in a specific scene, rather than the apple being in a certain location in a certain location in a grey background (as it was manipulated in the previous chapter). We hypothesize the following:

1. High curiosity trivia answers will be recalled better than low curiosity answers (Gruber, Gelman, and Ranganath 2014; Stare et al. 2018).

2. Object locations seen in anticipation for high curiosity answers will be recalled better than locations in anticipation for low curiosity answers. This will be better for objects shown closer to curiosity elicitation (Murphy et al. 2021).

3. Individual differences in answer memory benefit will positively correlate with incidental memory benefit (Fandakova and Gruber 2021).

4. IPE positively scales with the likelihood that an answer persists.

4.3 Methods

4.3.1 Sample

The sample was composed of 32 participants, of which 25 were female, with a mean age of 19.97 (sd = 2.2). The sample was recruited from the Cardiff University campus population. Based on similar studies (Gruber, Gelman, and Ranganath 2014; Murphy et al. 2021) and the desired analysis, it was aimed to collect data from 32 participants. We also carried out an outlier detection on the overall answer recall performance. This is a stable effect and therefore we reasoned that if participants perform at the extremes in this task, then it was deemed that participants are either not paying attention or they were cheating. The criteria set was 3 standard deviations. No participants were removed from the sample due to this criterion.

Participants were excluded based on the same criteria as set in the first experimental section 2.3.2. In addition, to make sure that participants were accessing the online experiment at the same time of day, an additional criterion was added that participants' timezone had to be within ± 1 hour of the experimenter's timezone. One participant did not meet this criterion and was not allowed to resume the study. Participants started the online experiment via Zoom at ~20:00. They were instructed and guided through and would complete all tasks at approximately ~21:30. Before a bed time of ~22:00. Participants would return after a 12-hour delay for retesting in the morning at ~08:00. This second session lasted ~45 minutes, where participants were accompanied throughout by the experimenter over zoom. Participants received either class credit or money for their time. Prior to participation, consent was obtained and the ability to cease participating without providing a reason was stated. This research was approved by the Cardiff University School of Psychology ethics committee.

4.3.2 Procedure

The experiment (Figure 9) was built using *PsychoPy* (version 2022.1.1) and the Pavlovia platform so that the experiment could be conducted on a web browser. As a result of the online imple-

A

What does a Geophage do?		Eats earthy substances	How interesting did you find the answer?
4 seconds	8 seconds	2 seconds	Self-paced

B & C   **D**

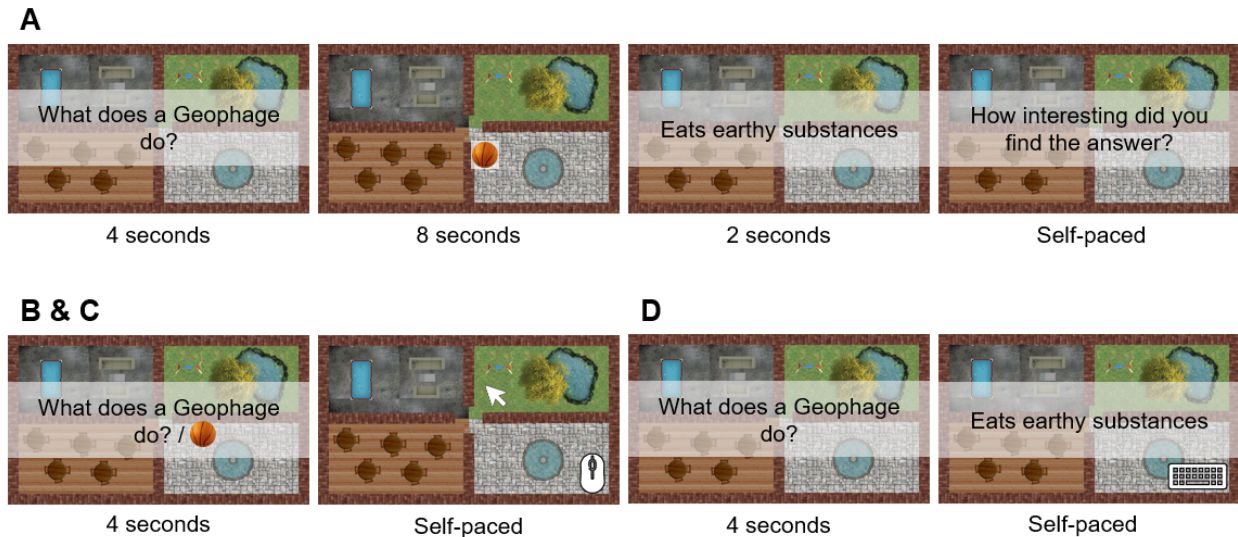|			
What does a Geophage do? /		What does a Geophage do?	Eats earthy substances
4 seconds	Self-paced	4 seconds	Self-paced

Figure 9: Experimental paradigm showing the A) encoding task where an object was presented on the screen onset at either early or late timepoints. B and C) Location recall tasks. This tasks were identical with the exception of the trial prompt being a trivia question or an object. D) Answer recall task.

mentation, the frame-rate varied across each machine (as a result of the online implementation). However, the method of presentation was kept to an aspect ratio of 16:9 to maintain procedural consistency. In other words, regardless of the size of the screen, the aspect ratio was identical throughout. Object stimuli were taken from the standardized image bank (Brodeur, Guérard, and Bouras 2014) and were shown in color, sized as 10% (1.6 x 1.6) of the longer side of the screen aspect ratio (16:9). As in Petzka et al. (2021), a square with 50% transparency was placed behind the object as it appeared on the complex environment (Figure 9A).

4.3.2.1   Screening   Participants were presented trivia questions (taken from Murphy et al. 2021). They were tasked with rating their curiosity towards finding out the answer (Gruber, Gelman, and Ranganath 2014; see also Marvin and Shohamy 2016). In this *screening task*, each trial consisted of a 4000ms exposure to the trivia question centered on the screen. As the environment was constantly present, to improve readability text was presented in front of a 50% transparency rectangle (Figure 9A). This was then followed by the prompt, *"How confident are you that you know the answer?"*. Participants were instructed, on a 1-6 scale, to indicate how confident they

were that they knew the answer. A rating of one meant *not at all confident* and six *extremely confident*. Subsequently, an additional prompt was presented stating *"How curious are you about the answer?"*. Participants were asked to respond using the same one (*not at all curious*) to six (*extremely curious*) scale. Participants did this phase for a maximum of 254 randomly ordered trivia questions. There were breaks every 25 trials. The phase would end conditionally when 40 trials were responded to with a *curiosity rating* of low curiosity (ratings 1, 2, or 3) and 40 as high curiosity (ratings 4, 5, or 6). Trials with a *confidence rating* of 6 were discarded, regardless of curiosity rating. This phase was self-paced, but participants took roughly 45 to 60 minutes to complete.

4.3.2.2   Encoding   In the *encoding task*, participants were presented with 80 randomly sorted trivia questions that they had previously screened through. In each trial, the trivia question was presented for four seconds (Figure 9A). Then for eight seconds, in anticipation for the answer, the anticipation phase of the task occurred, whereby an object was presented at a predetermined location on the screen. The objects appeared on the screen for a total of four seconds, with the onset occurring either at zero seconds (*early*) or 4 seconds (*late*) during the anticipation phase. The object onset was balanced across high and low curiosity items. Following the anticipation phase the answer was displayed centered on the screen for two seconds. Following this, two prompts appeared. The first prompt asked participants to rate how interesting they found the answer to be (*"How interesting did you find the answer"*), on a scale from one to six. One being of *low interest* and six *highly interesting*. To make sure that participants were encoding the object's location, the second prompt asked participants to respond in which of the four quadrants of the screen the object appeared (the upper left, upper right, lower left, or lower right) of the screen. Participants were only presented with each trivia question-answer dyad once. This task took about 26 minutes to complete.

The objects in the anticipation phase did not appear on the horizontal or vertical mid lines of the screen to avoid confusion as to what room the objects were in. To make sure these distinct object

locations had the least overlap possible, we used ten possible x-axis coordinates and 2 y-axis coordinates for each of the four quadrants. This gave us a total of 80 object x- & y-coordinate combinations which were shuffled for each participant before the encoding phase so that the combination of these three parameters, as well as, the trivia question-answer dyads was never the same for each participant. These locations were also balanced across curiosity level and object onset.

4.3.2.3 Location Recall

Question prompt. This recall test was self-paced and each trial was composed of a trivia questions presentation for four seconds with a 50% transparency bar behind the text for clarity. Once the trivia question disappeared from the screen, participants were tasked with selecting where they thought the object was presented during the anticipation phase of the encoding task (Figure 9B). They did so by moving the mouse to the location on the screen and clicking the left mouse button. Participants did this for all 80 trials and the task lasted ~13 minutes.

Object prompt. Participants carried out another location recall test (Figure 9C). This second test had the same timing parameters as the first. Objects were presented for four seconds instead of trivia questions (as in the previous task) and participants were instructed that as soon as the object disappeared, they were to select, using their mouse, where they thought the object was presented during the anticipation phase of the encoding task. They also did this for a total of 80 trials and the task lasted about ~13 minutes.

4.3.2.4 Answer Recall

After the location recall, participants carried out the answer recall. The 80 questions were again randomly sorted and in each trial a question was presented for four seconds. Participants were instructed to type out the answer that came to mind and to not spend too much time on each individual question. No pictures other than the background were presented during these trials (Figure 9C). The task took about 12 minutes to complete.

4.3.3 Analysis

The variables used in the analysis of our results section are defined below.

For answer recall we simply used the % of answers correct for that given categorical variable. Therefore, overall recall is out of 80 total questions, high v. low curiosity split would be out of 40 questions each. With the onset, the total for each category is 20 total questions.For object location accuracy we used the same Pythagorean method, as defined in a previous chapter 3.3.3, to ascertain the direct distance between presented object location and selected recall location. Due to fact the fact that there is no consistent screen size used across the sample, the location accuracy is given in a.u. as we cannot establish actual distance or pixel density of each individual screen. The IPE is characterized as the interest for the trivia answer as measured during the *encoding task* minus the initial curiosity for the trivia answer (rated during the *screening task*). A positive IPE refers to a greater interest after finding out the answer than initial curiosity. A negative IPE would refer to a higher initial curiosity compared to the post-answer interest. A neutral IPE means participants were as interested in the answer as they were curious about finding out the answer.

For the analysis of curiosity enhancement on memory for trivia answers and object location accuracy, ANOVAs were carried out with two predictor variables. The first predictor variable was the curiosity level (high or low) assigned to a particular trial based on the *curiosity rating*. The second predictor variable was the object onset, or when during the anticipation phase the object appeared (early v. late). The ANOVAs are also accompanied by checks for normality and homogeneity of variance. Unless otherwise stated, no violations of these checks occur. We carried out correlation between answer memory benefit and location accuracy benefit. For this analysis, we took the difference between high and low curiosity performance. As such, positive values mean that performance in high curiosity trials was better than low curiosity trials.

We also carried out mixed effects modelling analysis on the trial by trial level data in order to gain an understanding of the impact of IPEs on answer recall and location accuracy. Models will

use a participant cluster centering for the IPE variable in the models (Enders and Tofighi 2007). In addition, we allowed random slopes for the IPE clustered around each participant as it was assumed that while each individual might benefit from higher IPEs, that each participant's slope would have its own gradient and starting point.

Finally, for memory benefit analysis the difference is computed between high and low performance. For example, in answer memory benefit we subtract high curiosity answer memory performance from low curiosity answer memory performance.

We additionally carried out a chance threshold analysis to see if participants were performing above chance. the chance calculation was defined as follows:

$$P(A) = (\frac{a * b}{x * y}) * i$$

Here the formula is calculating at the probability of A (within the boundaries of the image) happening by chance considering the size of the overall visual space. Where a and b and the height and width dimensions of the image. x and y are the height and width of the screen and i is the number of iterations a participant carried out object localization (i.e.; trials).

Unless otherwise stated, we present p-values as one-tailed.

4.4 Results

4.4.1 Chance level performance at locating objects

24 out of 32 participants (75%) performed above chance for the location recall task where question prompts were presented and 27 out of 32 participants (84%) when the object prompt was presented.

4.4.2 Curiosity enhances memory recall for trivia answers
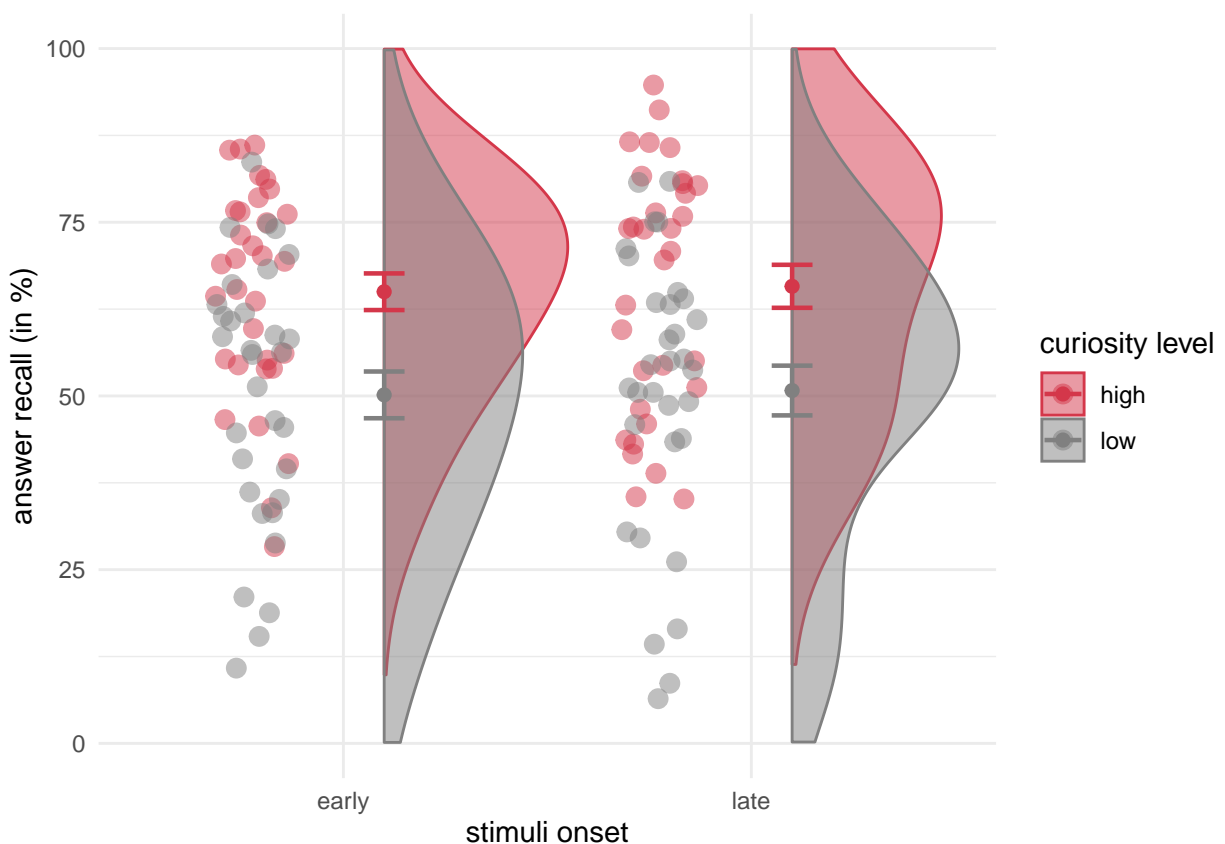
Figure 10: Trivia answer recall across object onset and curiosity levels. The ball and error bars refer to the mean and standard error of measurement. Individual data points are jittered in the x axis for viewing ease. Flamingo color refers to high curiosity items and grey low curiosity items. The dot and whisker plots refer to the mean and standard error of measurement respectively.

First, we investigated whether the curiosity enhancement effect on trivia answers is still evident when the set of questions, incidental objects, and answers were presented on top of a complex environment image (Figure 10). In addition, we also wanted to check whether image onset

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would have a conflicting effect on the answer memory benefit. The ANOVA revealed a main effect of curiosity level ($F(1, 31) = 49.85, p \leq .001, \eta_p^2 = .62$) and no main effect of object onset ($F(1, 31) = .181, p = .337, \eta_p^2 = .006$). There was no interaction between curiosity level and onset of object ($F(1, 31) = .003, p = .480, \eta_p^2 \leq .001$). At early object onset, high curiosity trivia answers were recalled with a mean of 65% (sd = 14.92%) where as low curiosity trivia items with a mean of 50.16% (sd = 19.03%). For the late objects onset, high curiosity trivia answers were recalled with a mean of 65.78% (sd = 17.51%) and low curiosity with a mean of 50.78% (sd = 20.25%). These results indicate that curiosity enhances memory for trivia answers and this effect is not interfered by object presentation onset.

4.4.3 Curiosity memory benefit does not extend to location recall accuracy
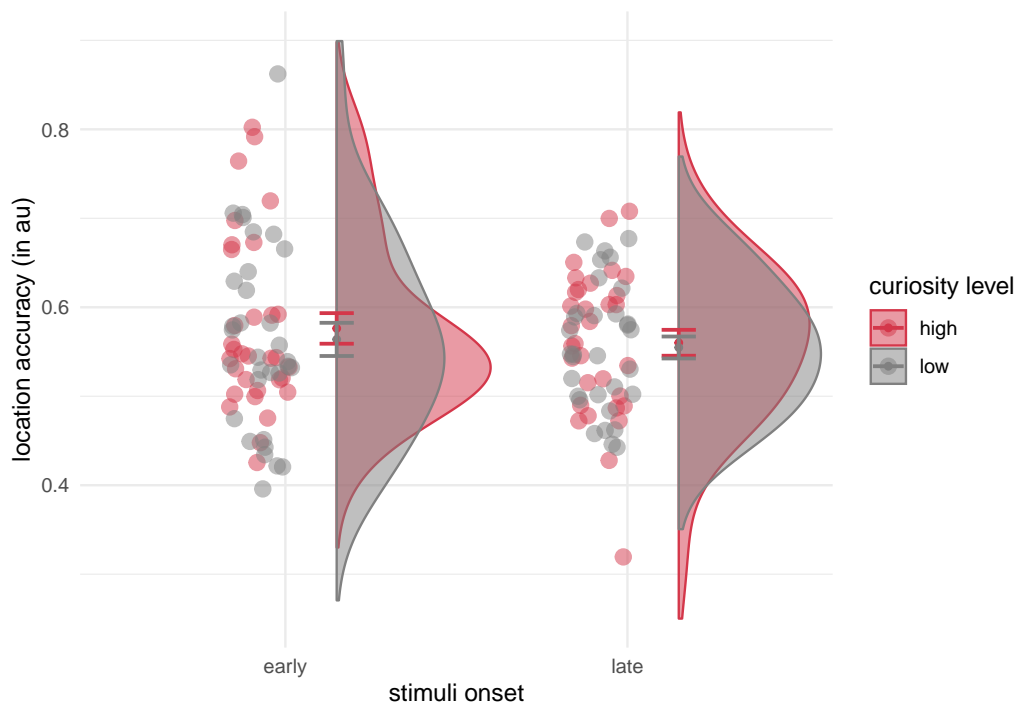
Figure 11: Object location accuracy with trivia question prompts. The y-axis shows accuracy in arbitrary units and the x-axis shows the time of object onset. Colors reflect whether the object was shown in anticipation of a high or low curiosity trivia answer. Flamingo colored data refers to high curiosity items and grey low curiosity items. The dot and whisker plots refer to the mean and standard error of measurement respectively.

We wanted to examine whether the effect that curiosity has on trivia answers spills over into object

locations. Specifically, the strength of the association between question and object location. For this, the a question prompt was placed at the beginning of each trial (Figure 11). The ANOVA revealed no main effect of curiosity ($F(1,31) = 0.333, p = .284, \eta_p^2 = .011$) nor object onset ($F(1,31) = 1.371, p = .126, \eta_p^2 = .042$). There was also no interaction between curiosity and object onset ($F(1,31) = .103, p = 0.375, \eta_p^2 = .003$). These results indicate that curiosity-related memory enhancements for trivia answers did not spillover onto memory for the object locations as evidence by the difference in accuracy between high versus low curiosity object locations. At early onset, participants recalled high curiosity object locations with an average of .576 units (sd = .097) and low curiosity objects with an average of .564 units (sd = .105). At late object onset, participants recalled high curiosity object locations with an average of .560 units (sd = .082) and low curiosity object locations with an average of .555 units (sd = .070). Results indicate no enhancing spillover effects of curiosity onto object locations.
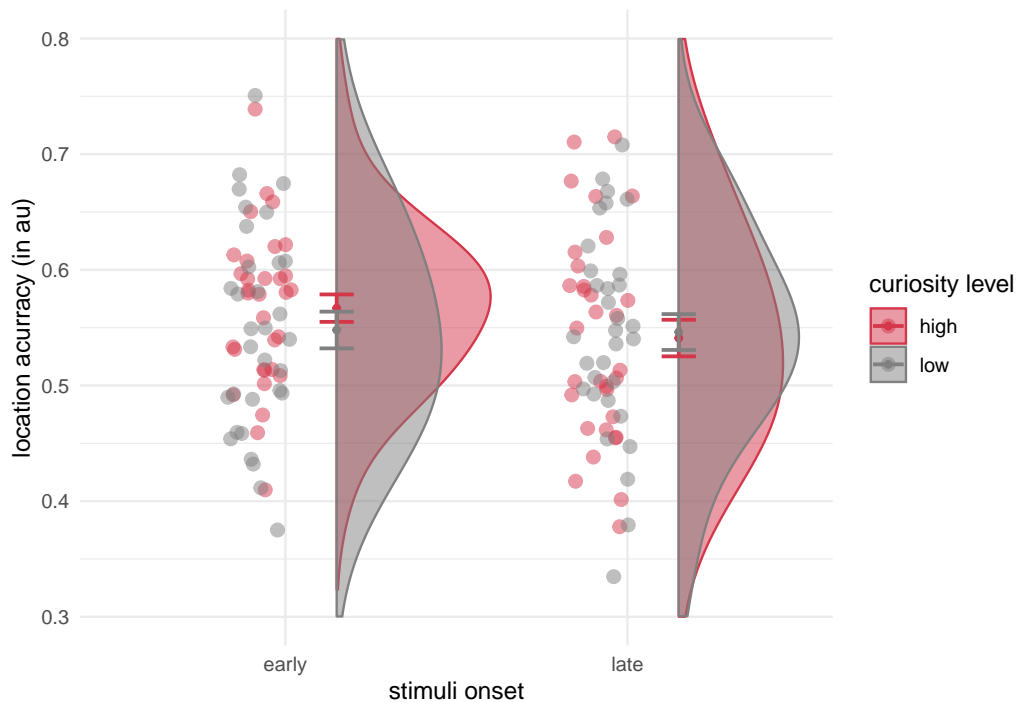
Figure 12: Object location accuracy with object prompt. The y-axis shows accuracy in arbitrary units with a lower number reflecting greater accuracy. The x-axis indicates object onset. Colors reflect whether the object was shown in anticipation of a high or low curiosity trivia answer. Flamingo colored data refers to high curiosity items and grey low curiosity items. The dot and whisker plots refer to the mean and standard error of measurement respectively.

Next, we investigated whether curiosity-related spillover effects would impact the strength of object to location association. For this, the object instead of a trivia question was presented before participants were tasked with locating an object as accurately as possible (Figure 12). An ANOVA showed no main effect of curiosity ($F(1,31) = .974, p = .166, \eta_p^2 = .01$) or object onset ($D(1,31) = .316, p = .289, \eta_p^2 = .01$). There was also no interaction ($F(1,31) = .948, p = .169, \eta_p^2 = .03$). For the early onset, participants recalled high curiosity object locations with a mean of .567 units (sd = .067) and low curiosity object locations with a mean of .548 units (sd = .09). For late onset, participants recalled high curiosity object locations with a mean of .541 units (sd = .09) and low curiosity object locations with a mean of 0.546 units (sd = .088). This indicates no effect of curiosity enhancement on object location.

4.4.4   Those with greater curiosity memory enhancement benefit do not also benefit during location recall

We wanted to understand whether on an individual differences basis, the amount of curiosity memory enhancement would predict location accuracy, even if location accuracy overall is poor . A pearson correlation showed a negative but non-significant correlation between answer memory benefit and question-location association benefit (Pearson's $r(30) = -0.270, p = .066$, Figure 13A). Between answer memory benefit and object-location association benefit, the correlation was non-significant (Pearson's $r(30) = -0.068, p = .356$, Figure 13B). These results suggest that even though there was a trivia answer memory benefit, this did not correlate with location accuracy, regardless of the prompt presented during the location recall test.

4.4.5   IPEs can enhance the likelihood that a trivia answer will be remembered

In addition to understanding the effect of curiosity on memory, we also wanted to understand the effects that the discrepancy between initial curiosity and later interest (IPE) can have on the probability of a memory being formed (Figure 14). A mixed effects model was carried out on trial-by-trial data which revealed that participant centered IPE had a slight, but significantly
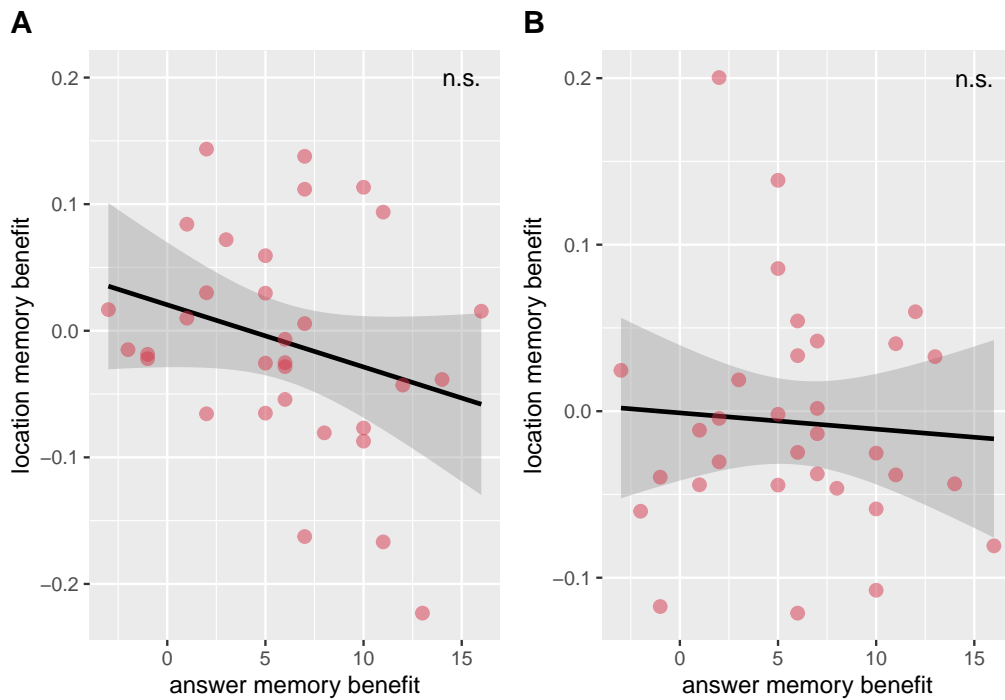
Figure 13: Answer memory benefit versus location memory benefit with A) question prompt and B) object prompt. the higher the value in x-axis the greater the performance for high curiosity answers compared to low curiosity answers. For the y-axis, a positive value reflects a better location accuracy for low curiosity objects compared to high curiosity items. A negative value reflects a better performance at locating high curiosity objects versus low curiosity objects. The dot and whisker plots refer to the mean and standard error of measurement respectively.
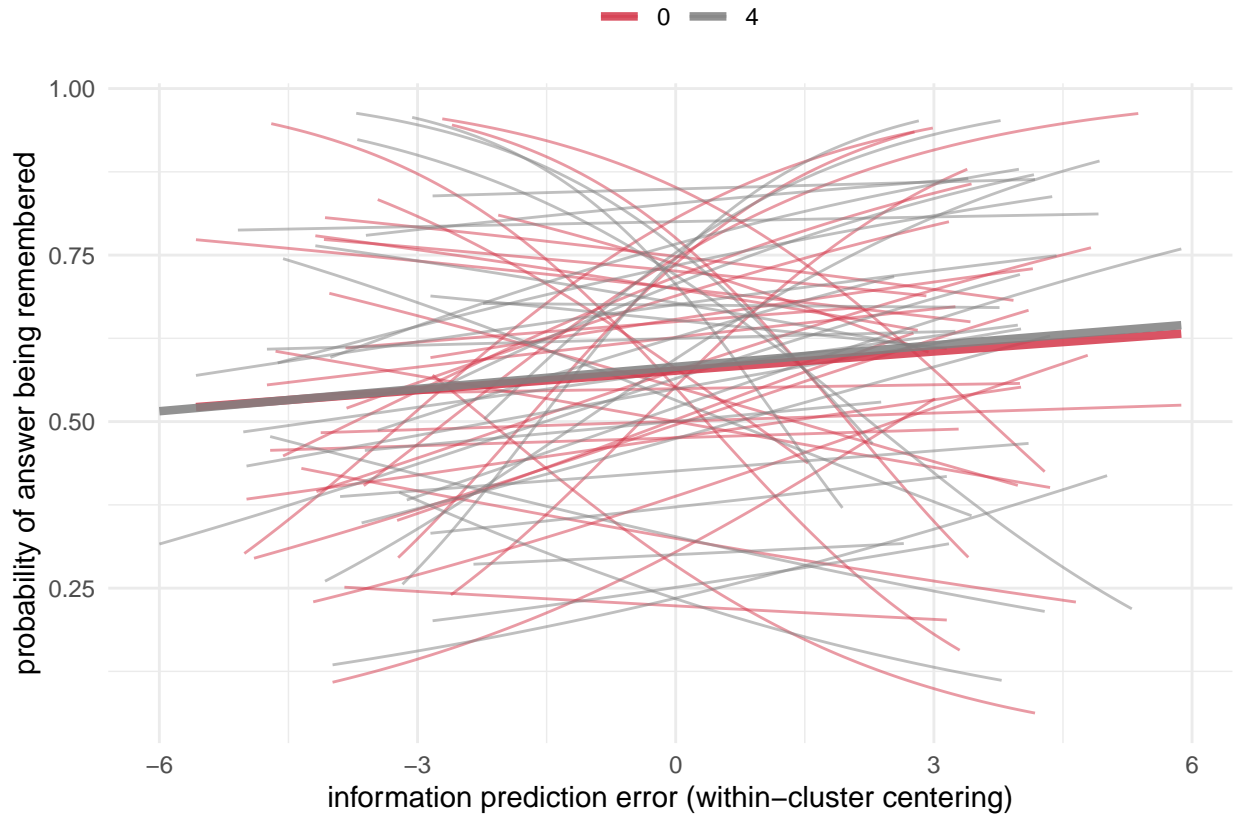
Figure 14: Binomial logistic regression for answer memory IPE effects, the y-axis reflects the likelihood of an answer being remembered with 1 being remembered and 0 being not remembered. The x-axis the IPE which is centered within each participant cluster. A positive IPE means that initial curiosity rating was lower than later interest rating. Flamingo colored data refers to early onset (zero seconds) and grey late onset (four seconds).

positive effect on whether an answer was likely to be remembered ($\beta = .028, p = 0.024$), whereas object onset had no effect ($\beta = .01679, p = .372$). Suggesting that IPEs can affect what memories persist.

4.4.6 IPEs and location
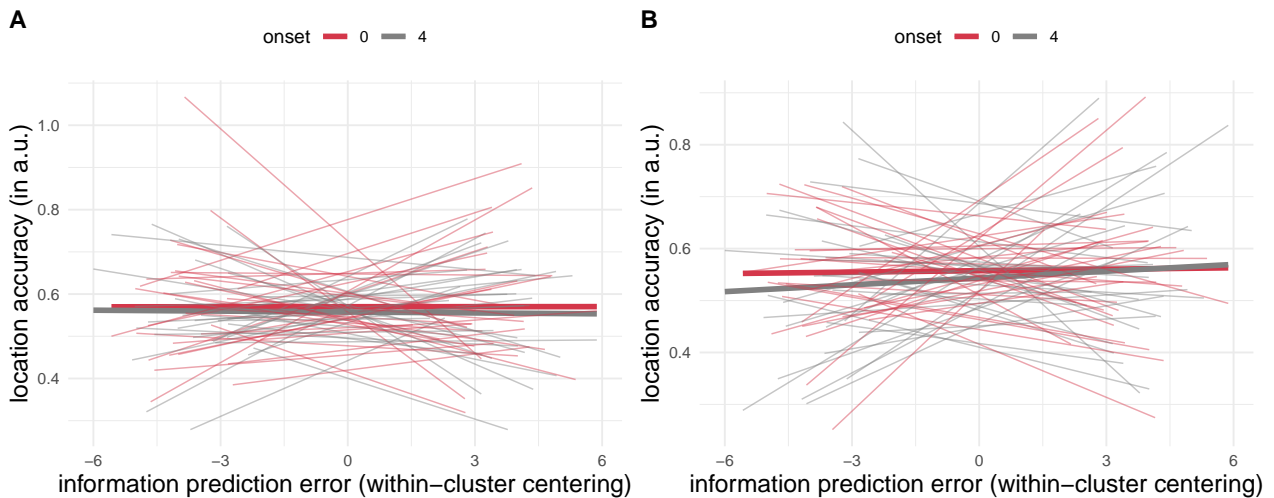
Figure 15: Mixed effect modelling for object location accuracy. A) question-location association B) object-location association. Flamingo color refers to early object onset (zero seconds) and grey late onset (four seconds).

Finally, in an exploratory analysis, we specified a mixed effects model for the object-location accuracy in the same way as we did for answer memory IPE benefit. In the question-location association test, both IPE ($\beta = -0.0004, p = 0.91$) and object onset ($\beta = -0.014, p = 0.29$) had a non-significant effect on location accuracy (Figure 15A). Similarly, for the object-location association test, both IPE ($\beta = 0.0026, p = .48$) and object onset ($\beta = -0.012, p = .23$) had non-significant effect on location accuracy (Figure 15B). Results suggest that IPEs do not effect what incidental associative memories persist.

4.5   Discussion

This experiment attempted to investigate whether a richer contextual background would increase the likelihood that high - compared to low - curiosity states would positively affect object location memory accuracy. In previous chapters, this effect did not replicate. Curiosity memory enhancement for trivia answers was found, replicating previous findings (Kang et al. 2009 ; Mullaney et al. 2014; Marvin and Shohamy 2016; Galli et al. 2018), with high curiosity answers being recalled better compared to low curiosity answers. It was also found that the more positive an IPE is the higher the likelihood of a trivia answer being recalled, mirroring previous findings (Marvin and Shohamy 2016). However, this did not extend to object locations, regardless of the object location task type. However, we did not find similar pattern of effects for incidental memory as others have (Gruber, Gelman, and Ranganath 2014; Stare et al. 2018; Murphy et al. 2021; Fandakova and Gruber 2021).

The lack of a spillover effect on the accuracy for object locations warrants further discussion. Previous findings found that recognition memory for faces was greater for those faces seen in anticipation for high curiosity answers over those in anticipation for low curiosity answers. Here, we attempted to see if this would extend to different stimulus types as well as a shift from recognition memory to associative memory. It was expected that heightened curiosity would spillover and increase the likelihood that object locations in anticipation for high curiosity answers would be recalled closer to the target location. The null finding is consistent regardless of whether the memory recall task was probing for the question-location association or the object-location association. These results suggest, that perhaps individuals were not able to segment the anticipation events and appropriately associate object locations with the corresponding trivia questions and answers. It is interesting that objects interacted with in a paradigm like that seen in Cen, Gkoumas, and Gruber (2021), showing an incidental memory. However, event this study probed recognition memory and not associative memory. From an individual differences perspective, it is promising that even if location accuracy was not enhanced by curiosity, that evidence was trending in the predicted direction. That is, that the more curiosity memory benefit

one had for trivia answers, the better a participant was at locating high versus low curiosity objects (albeit only for the question-location association test). It would be interesting to see whether findings change with a substantially larger sample of participants; perhaps, and multi-site implementation or an online only experiment.

It was also found that IPEs positively scale with whether a memory will be formed, replicating the findings of Marvin and Shohamy (2016) and lending further credence to the notion that curiosity is but one component of a larger uncertainty reduction, information seeking, and self-guiding learning mechanism (Gruber and Ranganath 2019; Ouden, Kok, and Lange 2012). It is interesting though that not all participants exhibited similar IPE curves. What drives this individual difference? is it merely that these future predicting mechanisms can only increase the likelihood of consolidation? That ultimately, some important information will fall through the gaps of our mind. Or are there other variables which can explain these difference? Indeed, not much is know about IPE memory consolidation mechanisms and what enables certain memories to persist over others. Given that many studies have the learning and testing phases interspersed by a night of sleep, it may be prudent to carry out a similar experimental design to that seen in Stare et al. (2018). Future research will elucidate on this matter further.

It could be that sleep based consolidation might have something to do with it. The literature on sleep mediated memory effects is large, but the conclusions are not straightforwardly clear (Cordi and Rasch 2021). However, object location was positively affected by reward, and rescued from forgetting after a night of sleep (Antony, Piloto, et al. 2018). Other researchers, have found that memory recognition for rewarded information scaled positively with sleep spindles, an electrophysiological phenomenon that occurs during sleep stages 2 and 3 (Studte, Bridger, and Mecklinger 2017). Future investigation is required (given similarities between curiosity and reward). Given that polysomnography might be helpful in determining whether inter-individual differences in sleep might affect incidental memory findings, then this could be one avenue of further investigation.

The current experiment is not without its drawbacks. Had there been another 32 participants who carried out the same protocol, but with a regular day of wakeful activity in between both sessions we could possibly answer some of the above questions regarding sleep and its effect on motivated memory consolidation. With polysomnography we would also be able to ascertain what about sleep is partly, if at all, responsible for an effect. Finally, it may also be that for objects and locations, only a fully immersive 3D experience, not 2D, elicits this spillover effect (Clemenson and Stark 2015). As Cen, Gkoumas, and Gruber (2021) found, a curiosity spillover effect on incidental objects, it may indeed be that curiosity can only spillover so far and that for more immersive naturalistic environments, the standards for how we test memory have to be modified and recognition memory is no longer appropriate. Indeed, as task parameters change, so does the effects one finds (Petzka et al. 2021). Future research methods are promising and a combination can answer how information gets noticed, chosen, investigated, and consolidated into memory for future use as is theorized in the PACE model (Gruber and Ranganath 2019).

4.6   Future directions

This experiment elucidated on curiosity's ability to impact incidental memory beyond face recognition memory. In this experiment we added contextual helpers and while this improved participant performance, an incidental memory effect was not evident. In the next experiment we will focus on whether sleep can potentially explain something about which memories persist, both for target information as well as incidental memory (section 5). As we saw in section 2 and in previous literature, sleep can promote the consolidation of rewarding memories. The sample will be split into a wake group and a sleep group to give further insight into whether these two periods have differential effects on which memories persist.

5 Incidental locations: A do-it-from-home pandemic sleep experiment

5.1 Abstract

Curiosity, the intrinsic motivation to seek information, is associated with the dopaminergic reward processing system and the memory consolidation region of the hippocampus. Curiosity has been shown to result in better memory recall for information we are highly curious about over information we are not so curious about. Little is understood about the mechanism that results in incidental, and seemingly unrelated, information also being positively affected by states of high curiosity. We suspect, based on the literature that sleep may also be relevant for curiosity enhanced memory consolidation. In this experiment we carry out a modified version of the trivia paradigm with incidental objects appearing at various locations, instead of faces. Crucially we have two groups, one which experienced a period of sleep, and the other wake, between learning and testing sessions. The sleep group had their sleep recorded with EEG wearable headbands. Results show that curiosity memory enhancement for trivia answers was found, but that this only extended to incidental object-location associative memory for the sleep group. IPE analysis revealed an alternative pathway with which memories can persist. We discuss findings and make recommendations for future work and shortcomings of the present research.

5.2   Introduction

Curiosity is understood as the motivation to seek out information to close information gaps. This is thought to occur so that we update internal models about the outside world and therefore be better prepared for future potential situations. In a sense it is thought that the information acquisition is a reward in and of itself (Kang et al. 2009; Kashdan et al. 2018; Loewenstein 1994; Marvin and Shohamy 2016). However, recently it was found that through curiosity, certain information can be prioritized over others (Gruber, Gelman, and Ranganath 2014). A recent theoretical model proposes that we are continuously scanning and predicting incoming information (Gruber and Ranganath 2019). When information runs counter to internal predictions, we appraise whether we engage with that information or ignore it. If we decide to engage, we explore that information in a heightened state of curiosity and this results in enhanced encoding and memory consolidation. This heightened state of curiosity increases the likelihood that valued information gets processed into longer term memory stores (Gruber and Ranganath 2019). It is thought that curiosity enhanced memory consolidation processes are the result of activity within the dopaminergic system (Gruber, Gelman, and Ranganath 2014; Murty et al. 2017; Ripollés et al. 2016, 2018), responsible for processing reward, curiosity, and self-guided learning

In laboratory studies it has been shown that curiosity enhances recall for specific high curiosity eliciting information over other (Gruber, Gelman, and Ranganath 2014; Kang et al. 2009; Fandakova and Gruber 2021; Marvin and Shohamy 2016; Galli et al. 2018, 2018; Mullaney et al. 2014; Murphy et al. 2021; Stare et al. 2018). Participants rate how curious they are to find out the answer to a particular trivia question. They are presented with the question and after an anticipation period they are shown the corresponding answer. Participants are then tested on their ability to recall the answers to the trivia questions. Findings show that questions that were rated as eliciting high curiosity were recalled more frequently than those that were rated as low curiosity. It is suggested that this state of heightened curiosity facilitated the consolidation of valued information. However, this state of curiosity has also been shown to affect memory for information that is incidentally presented in anticipation for the answer. For example, when a

face was presented between the trivia question and answer, during this anticipatory period, the face was more likely to be remembered if they were presented after a high curiosity eliciting trivia question (Gruber, Gelman, and Ranganath 2014; Stare et al. 2018; Galli et al. 2018; Murphy et al. 2021). We call this the spillover effect of curiosity on incidental information. This effect may also not be an absolute memory performance metric. It was found that an individual differences component might be at play (Fandakova and Gruber 2021). Here, the answer memory benefit (difference high curiosity, versus low, trivia answers) positively correlated with incidental memory benefit.

In addition, evidence has suggested that this state and the spillover effect are not stable throughout the anticipatory phase. Depending on when, in the anticipation phase, the incidental faces were presented, the higher or lower the incidental face recognition would be. Specifically, in proximity to the elicitation of curiosity (i.e., shortly after the trivia question is presented) versus closer to when the curiosity state is resolved (answer presentation). Indeed, the period closer to elicitation seems to be pivotal for this incidental information spillover effect to take place (Galli et al. 2018; Murphy et al. 2021). Replication of these findings remains to be seen.

Some researchers have suggested an additional pathway by which memories can be prioritized for consolidation. These are called information prediction errors (IPEs) and they occur when our internal models do not match what we perceive. Indeed, it was found that participants have better recollection for details of a movie excerpt when there is an unexpected interruption in a scene (Sinclair et al. 2021). This is also seen in rats who examine unexpected cues longer than exploring cues that will give them a reward (Steinberg et al. 2013). These unexpected events create a state of uncertainty about a novel object or novel experience. This uncertainty is one part of what initiates the drive to seek information (Brydevall et al. 2018). In the context of curiosity this can happen when we find out what the answer is. Indeed, participants are more likely to remember trivia information accurately the higher the IPE (Marvin and Shohamy 2016), independently of the positive effect initial curiosity has on memory. This effect has also been seen in children (Fandakova and Gruber 2021). This suggests a two-pronged memory prioritization effect that

essentially serve the same uncertainty resolving mechanisms. To illustrate, when we see a trivia question that does not initially evoke curiosity, but upon finding out the answer, we realize that the answer is more interesting than initially predicted (a positive IPE). It is known, exactly what happens when positive IPEs occur and what mechanisms are involved, but again we prioritize attentional resources to that information regardless of what our initial assessment might have been and this is seen by better memory outcomes the more positive an IPE is. As such it is also important to study how these IPEs impact memory.

From an adjacent field of research, there is evidence that rewarded memory learning, where participants learn the association between two words or objects with varying levels of monetary reward, is positively associated with sleep (Studte, Bridger, and Mecklinger 2017); specifically sleep spindles within sleep stages two and three. The reward literature has extended beyond word-pair learning and found that monetary reward can positively influence memories for spatial information. For example, the location of high rewarded items were recalled more accurately than low reward items (Oudiette et al. 2013; Cohen et al. 2019). So it posits the question as to whether curiosity, the intrinsic motivator, can also positively impact different types of incidental information, such as spatial information. In conjunction, it is fundamental to understand whether sleep has an impact in curiosity-enhanced memory effects. This is particularly important as certain curiosity studies contain a period of sleep in between learning and testing (Gruber, Gelman, and Ranganath 2014; Murphy et al. 2021). Curiosity enhanced memory has shown to not interact with sleep consolidation (Stare et al. 2018). During a trivia paradigm study, participants took part in two different conditions. In one condition the two experimental sessions were split by a night of sleep. For the other condition, the sessions were separated by a day of wakeful activity. Participants who experienced a night of sleep did not see greater curiosity-related memory enhancements for trivia answers and faces. Indeed, it is still an open debate as to how robust sleep memory benefits are (for a review, see Cordi and Rasch 2021). While several studies have not replicated the sleep effects on memory (Schönauer et al. 2014; Ackermann et al. 2015; Tucker et al. 2020), others have (Scullin 2013; Backhaus et al. 2006). This does not unequivocally suggest

that the effect does not take place. It was found that sleep stage 3 sleep activity was classified with significantly higher likelihood as being similar to the reward state experience during wake (Sterpenich et al. 2021). This reward related activation in wake was predominantly seen in the VTA and hippocampus. Given what we know about the similarities between reward and curiosity. It seems highly plausible that some elements of sleep brain activity are responsible for motivated memory consolidation. However, the literature has mixed findings (Cordi and Rasch 2021). In addition, it was found that the first night in a sleep lab can be disturbed and when this occurs REM was found to be a contributor to deprecated memory performance (Goerke et al. 2013). Indeed, the disruption of REM in rats can also deprecate object-location learning (Boyce et al. 2016). As such, REM should be considered for paradigms that use novel sleeping with wearable equipment and lack adaptation nights.

It is not yet known to what extent the curiosity memory benefit can impact other forms of incidental information other than faces. In line with this gap in the literature, we will present incidental objects in 2D space within the anticipatory phase in order to understand whether the spillover effects extends to spatial information. The satisfaction of the answer will also be probed so that we can examine any IPE effects that might be contributing to what gets remembered and replicate the findings of Marvin and Shohamy (2016). As we also want to explore the role of sleep in driving the effects of the trivia paradigm, half of our sample will experience a night of sleep between learning and recall sessions (*sleep group*). The other half will experience a day of wakeful activity (*wake group*). Those in the sleep group will have their sleep monitored by EEG devices and polysomnography will provide an indication as to whether time spent in each sleep stage predicts memory benefits, especially in sleep stages 2 and 3. We predict the following:

1. Curiosity will enhance memory recall, with more high curiosity answers persisting than low curiosity answers.
2. Curiosity will spillover to the incidental objects and enhance memory for object locations seen in anticipation for high curiosity trivia answers.
3. Incidental memory will benefit from being presented closer to curiosity elicitation.

4. Increased sleep duration in sleep stages 2 and 3 will positively correlate with curiosity-enhanced target information, incidental information, and IPEs.

5. Curiosity answer memory benefit will positively correlate with incidental memory benefit.

6. IPEs will be positively relate with an increased likelihood that a trivia answer is remembered.

5.3 Methods

5.3.1 Sample

Based on similar studies(Gruber, Gelman, and Ranganath 2014; Murphy et al. 2021) and the desired analysis, we aimed to collect data from 32 participants in each group for a total of 64 participants. The current sample (n = 64, of which 16 were male), is composed of 32 participants in the wake group (24 females) and 32 in the sleep group (24 females), with a combined mean age of 19.86 (sd = 2.336). The sample was recruited from the Cardiff University campus population. Participants were excluded based on the same criteria as in previous experimental chapters (see section 2.3.2). As this experiment was entirely carried out online for half of the sample, an additional criterion was imposed whereby participants had to be in a timezone within 1 hour of the timezone of the experimenter. One participant took part who was 6 hours ahead of the experimenter and they were excluded from the sample. We also carried out an outlier detection on the overall answer recall performance. This curiosity enhanced memory for target information is a stable effect and therefore we reasoned that if participants perform at the extremes in this task, then it was deemed that participants are either not paying attention or they were cheating. The criteria set was 3 standard deviations. A total of 3 participants were removed from the sample due to low performance.Participants received either class credit or money for their time. Prior to participation, consent was obtained and the ability to cease participation without providing a reason was stated. This research was approved by the Cardiff University School of Psychology ethics committee.

5.3.2 Procedure

All stimuli presentations (Figure 16) were carried out using *PsychoPy* (version 2020.1) via the Pavlovia platform. The experiment was presented at a variety of frame-rates on various monitors (as a result on the online implementation). However, the method of presentation was kept to an aspect ratio of 16:9 regardless of monitor in order to maintain some procedural consistency.
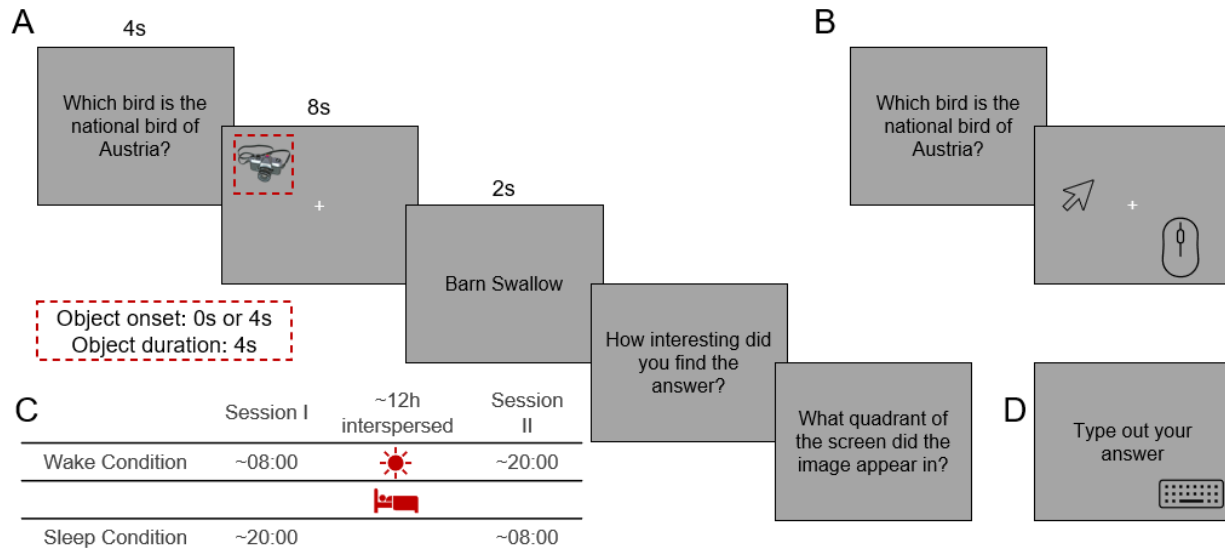
Figure 16: A) Encoding task, where participants are exposed to a trivia question, eliciting either high or low curiosity, displayed on a grayscale screen for 4s. Then an anticipation phase lasting eight seconds with a white fixation cross on the screen. An object was presented on a randomly assigned location of the screen. The object was presented for four seconds, onset at either 0s or 4s. B) The location recall task, whereby participants were presented trivia questions they had previously seen. After the question disappeared, participants were instructed to move their mouse, as accurately as possible, to the location where the object associated with that question was presented. C) Timetable depiction for either condition, interspersed with either a night of sleep or with daytime wakefulness. D) Answer recall task. The trivia questions were randomly reordered and in each trial, each question was presented for four seconds, and then participants were instructed to type out the answer.

Participants were not able to carry out the tasks on their phone and had to use a laptop or desktop to complete the experiment. Object stimuli were taken from a standardized image bank (Brodeur, Guérard, and Bouras 2014) and were shown in color, sized as 10% (1.6 x 1.6) of the longer side of the screen resolution (16:9). Participants took part in either the wake or sleep group (Figure 16C). The wake group would begin session 1 testing at approximately 08:00 and session 2 at 20:00. Whereas the sleep group, participants started session 1 at approximately 20:00 and session 2 at 08:00. For both groups, participants completed the screening phase and the encoding phase during session one and the location and answer recall in session two.

5.3.2.1 Screening Participants were presented trivia questions and asked to rate their curiosity towards finding out the answer (Gruber, Gelman, and Ranganath 2014; see also Marvin and Shohamy 2016) in a self-paced manner. In this *screening task*, each trial was composed of a 4000ms exposure to the trivia question centered on the screen. It was followed by the *knowledge* prompt, *"How confident are you that you know the answer?"*. Participants were instructed to, on a scale from one to six, indicate how confident they were that they knew the answer. One meant *not at all confident* and six *extremely confident*. Subsequently, another prompt was presented stating *"How curious are you about the answer?"*. Participants were asked to respond using the same one (*not at all curious*) to six (*extremely curious*) scale. Participants did this phase for maximum total of 254 randomly ordered trivia questions. There were breaks every 25 trials. The phase would conditionally end when 40 trials with a *curiosity rating* were responded to as low curiosity (ratings 1, 2, or 3) and 40 as high curiosity (ratings 4, 5, or 6). Trials with a *confidence rating* ratings of 6 were discarded. This task took about 45 to 60 minutes to complete.

5.3.2.2 Encoding Then followed the *encoding task*. Here participants were presented with 80 randomly sorted trivia questions they had previously rated. In each trial, the trivia question was presented for four seconds. Then for eight seconds, an anticipation phase followed, where on a gray scale screen with a cross at the center, an object was presented at a randomly selected location on the screen. There was no grid background, as this does not seem to impact learning

(Deuker et al. 2013; Oudiette et al. 2013). The objects appeared on the screen for a total of four seconds, with the onset happening either at 0 seconds (*early*) or 4 seconds (*late*) during this anticipation phase. The object onset was balanced across high and low curiosity conditions. After the anticipation phase, the answer was displayed centered on the screen for two seconds. Following this, there were two prompts. The first asked participants to rate how interesting they found the answer to be, on a scale from one to six. One being of *little interest* and six *highly interesting*. To make sure that participants were encoding the object's location, the second prompt was presented asking participants to respond in which quadrant the object appeared in. The upper left, upper right, lower left, or lower right quadrant. Participants were only presented with each trivia question-answer dyad once. This task took ~30 minutes to complete.

5.3.2.3 Location Recall This recall task was self-paced and participants were instructed to read the randomly ordered trivia questions one at a time (presented for four seconds). After each question prompt, once the mouse cursor appeared on the screen, participants were tasked to select the location the picture had appeared in during the anticipation of the encoding task (Figure 16B). They confirmed the location by moving the mouse to the location on the screen and clicking the left mouse button. Participants did this for all 80 trials without breaks and it took about ~12 minutes to complete.

5.3.2.4 Answer Recall The 80 trivia questions were again randomly sorted for this recall task. Each trivia question was again presented for four seconds. The question then disappeared and a prompt appeared asking participants to *"please type out the answer"*. They were able to correct spelling and when ready press the return key to confirm their responses. Participants were instructed to not spend too much time on each question and type out the first thing that came to mind. No pictures were presented during these trials. Additionally, the task was self-paced and took about ~12 minutes to complete (Figure 16D).

Table 3: Mean and standard deviations of time spent in each sleep stage. Time is measured in minutes.

variable	n	mean	sd
REM	32	63.609	30.760
Stage 1	32	10.359	9.556
Stage 2	32	226.312	80.467
Stage 3	32	142.984	37.998
Total	32	480.016	111.890
Wake	32	36.188	29.791

5.3.3   Polysomnography

Participants were given written instructions on how to use and place a Dreem v2.0 headband to monitor and record participants' duration in different sleep stages. The headbands use a 5 dry electrode system with 4 EEG derivations (Fp1-M1, Fp2-M2, Fp1-Fpz and Fp1-Fp2). Here the M sensors refer to the rear electrodes of the headband. The signal is processed at 250Hz and filtered within the 0.4-18Hz band. A 48–52Hz bandstop $6th$ order butterworth filter is used to remove European power line noise. Sleep data was then pre-processed using a custom fieldtrip pipeline on Matlab that took the EDF files and prepared the channel headers to a format that was readable by a custom scoring GUI. Both of which can be downloaded HERE. Sleep stage scoring was carried out in accordance with the AASM guidelines (Berry et al. 2015). Due to recording issues inherent with using dry electrodes, the rule that dictates that only one electrode should be focused on for scoring was not followed. Electrodes often lifted and returned contact with the skin when participants rolled over to other side while sleeping. This scoring took on average 45 to 75 minutes per participant, resulting in twelve and a half hours of total scoring time. The scoring was also carried out by a second trained scorer according to the same AASM criteria. Table 3 shows mean time spent in each stage and total time.

5.3.4   Questionnaires

Sleep questionnaires were administered at the beginning of each session. They would provide an indication of alertness prior to engaging in tasks and addressing any confounds that may arise

from different levels of alertness. Participants were administered the Karolinska Sleepiness Scale (Kaida et al. 2006) and the Stanford Sleepiness Scale (Herscovitch and Broughton 1981).

5.3.5 Analysis

The variables used in the results section are defined below.

IPE is characterized as the interest for the trivia answer measured during the *encoding task* (Figure 16A) minus the initial curiosity for the trivia answer (rated during the *screening task*). Positive IPE refers to a greater interest after finding out the answer than the initial curiosity. A negative IPE would refer to a higher initial curiosity compared to the interest A neutral IPE means both prompts were responded to equally and participants were as interested with the answer as they were to find out the answer.

The location recall was measured using a Pythagorean theorem calculation, as used in previous chapters (see section 3.3.3).

For answer recall we simply used the % of answers correct for that given categorical variable. So for overall recall is out of 80 total questions, high v. low curiosity split would be out of 40 questions each. With the onset, the total for each category is 20 total questions. Finally, we also used categorical variables. Group refers to which group participants were placed in (wake v. sleep, Figure 16C), curiosity level refers to the level of initial curiosity for the answer, and object onset refers to the onset of the object within the *anticipation phase* (early vs. late).

We carried out 2x2x2 ANOVAs in order to understand the impact of group, curiosity level and object onset on trivia answer memory. We ran a separate one with the same categorical parameters for object location. For the analysis where we examine sleep stage duration predicting trivia answer and location memories, we used a multiple regression with the outcome being the memory benefit (difference between high curiosity memory performance minus low curiosity memory performance). The predictors were sleep stages 2 and 3, where sleep spindles and slow wave activity occur.

Finally, we carried out mixed effects modelling analysis on the trial by trial data in order understand the impact of IPEs on answer recall and location accuracy. Models used a participant cluster centering for the IPE variable in the models (Enders and Tofighi 2007). In addition, we allowed random slopes for the IPE clustered around each participant as it was assumed that while each individual might benefit from higher IPEs, that each participant's slope would have its own gradient and starting point. Unlike in section 4.4.6, modelling of IPE effects on object location memory also included the condition participants were in.

Finally, for memory benefit analysis the difference is computed between high and low performance. For example, in answer memory benefit we subtract high curiosity answer memory performance from low curiosity answer memory performance. Unless otherwise stated, all p-values are one-tailed.

5.4 Results

5.4.1 Participants chance performance

To understand the difficulty of the object location task, a chance calculation was done like the on in the previous chapter (Section 4.3.3). Out of the 64 participants, only 29 participants (45.31%) performed above chance. These results are lower than the chance performance in the previous chapter (Section 4.4.1).

5.4.2 Does sleepiness differ between the wake and sleep groups?

To check if memory performance was not due to the state of sleepiness experienced during the elicitation of curiosity, we used sleepiness scales at the beginning of the encoding session. For the sleep group this would be at 20:00 and the wake group at 08:00. An independent sample t-test found no difference between the sleep and wake group in sleepiness according to the Karolinska Sleepiness scale ($W(61.998) = -0.68172, p = .498(two - tailed)$). Here, the sleep group had a mean alertness of 4.812 (sd = 1.655) and the wake group a mean of 4.531(sd = 1.646). For the Stanford Sleepiness scale ($W(61.974) = .37285, p = .7105(two - tailed)$), the sleep group has a mean vigilance of 2.906 (sd = 0.995) and the wake group a mean of 3.00 (sd = 1.016). Both groups had a similar level of sleepiness leading up to the encoding task.

5.4.3 Curiosity positively affects trivia answer recall

We wanted to understand whether participants recalled more high curiosity answers compared to low curiosity answers (Figure 17). The ANOVA revealed no main effect of onset ($F(1, 62) = 0.114, p = .368, \eta_p^2 = .002$). It did, however, reveal a main effect of group (sleep v. wake, $F(1, 62) = 5.283, p = .0125, \eta_p^2 = .079$) and a main effect of curiosity level (high v. low, $F(1, 62) = 114.416, p \leq .001, \eta_p^2 = .65$). There was no significant interaction between group and curiosity level ($F(1, 62) = .187, p = .667, \eta_p^2 = .003$), between group and onset ($F(1, 62) = .811, p = .371, \eta_p^2 = .013$), nor between curiosity level and onset ($F(1, 62) = 1.321, p = .255, \eta_p^2 = .021$).
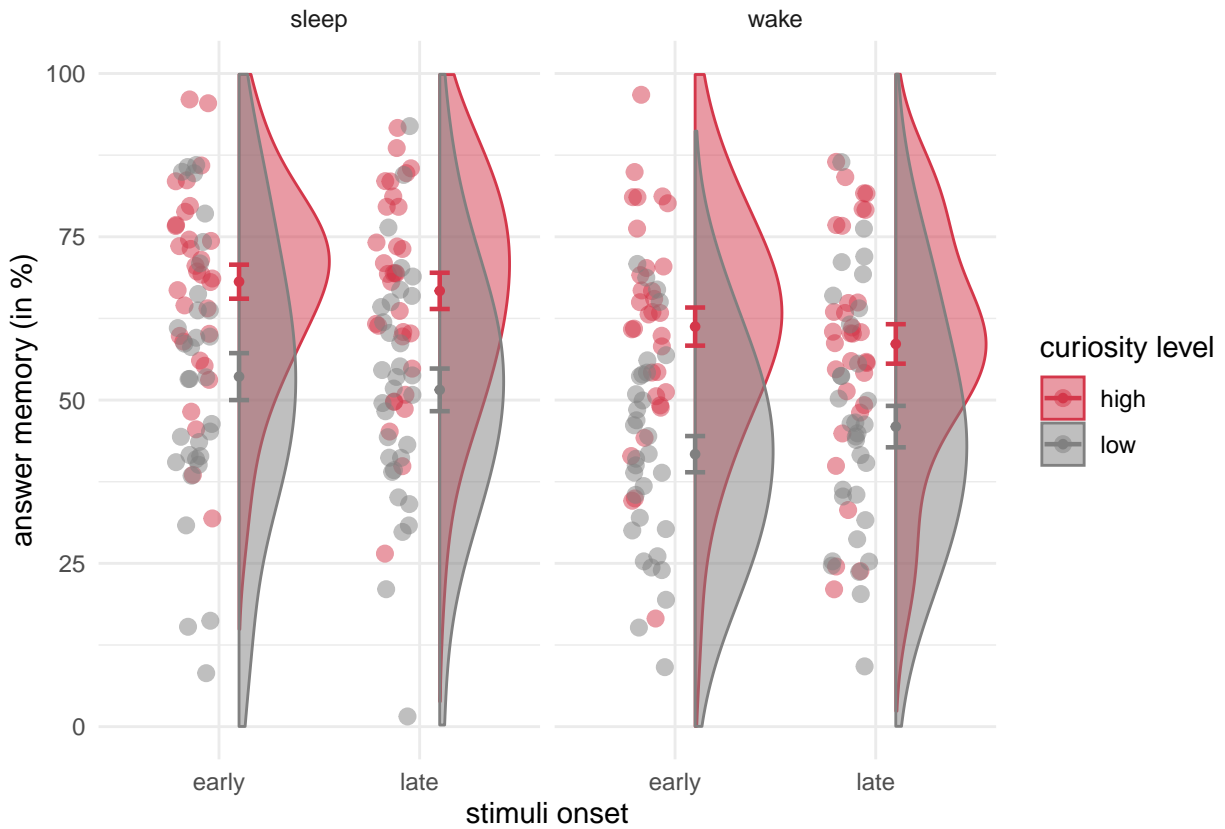
Figure 17: Answer recall in percentage across condition and curiosity levels. The point at each condition refers to the mean and error bars refer to the standard error of measurement. Flamingo color shows high curiosity data and grey low curiosity data. The dot and whisker plots refer to the mean and standard error of measurement respectively.

Finally, the three-way interaction was also not significant ($F(1, 62) = 1.903, p = .172, \eta_p^2 = .03$). Participants in the sleep condition recalled a mean 68.1% (sd = 14.7) of high curiosity answers in the early object onset condition. Versus a mean of 53.6% (sd = 20.3) of low curiosity answers. In the late onset condition, participants remembered a mean of 66.7% (sd = 15.7) of high curiosity answers versus a mean of 51.6% (sd = 18.5) for low curiosity answers. For the wake condition participants also recalled a higher percentage of high curiosity answers in the early onset condition (mean = 61.3%, sd = 16.5) than low curiosity items (mean = 41.7%, sd = 15.7). In the late onset condition participants recalled more high curiosity answers (mean = 58.6%, sd = 17.1) than low curiosity answers (mean = 45.9%, sd = 17.9). These results indicate that while curiosity can enhance answer memory, object onset does not appear to be causing interference to this effect. While sleep does appear to have an effect, this may be for both high and low curiosity answer memory.

5.4.4 Sleep does not predict curiosity related answer memory benefit

To understand whether sleep polysomnography measures correlate the curiosity memory enhancement beyond curiosity levels, we carried out a multiple regression. The outcome variable was the curiosity-related answer memory benefit (high curiosity minus low curiosity answer performance); predictor variables considered were curiosity level (high v. low), total sleep stage 2 duration, total sleep stage 3 duration, and total REM duration. The overall regression was not statistically significant ($R^2 = .046, F(2, 29) = .449, p = .72$). It was found that sleep stage 2 did not predict answer memory benefit ($\beta = .008, p = .465$), nor sleep stage 3 ($\beta = .011, p = 0.70$), and neither did REM sleep duration ($\beta = .027, p = .39$).

5.4.5 Curiosity enhancement may spillover to object locations

To understand whether curiosity memory enhancement spills over into the object's location shown in the anticipatory period, a similar ANOVA was carried out as for the answer memory (Figure 18). There was no main effect for group ($F(1, 62) = 1.44, p = .118, \eta_p^2 = .023$), image
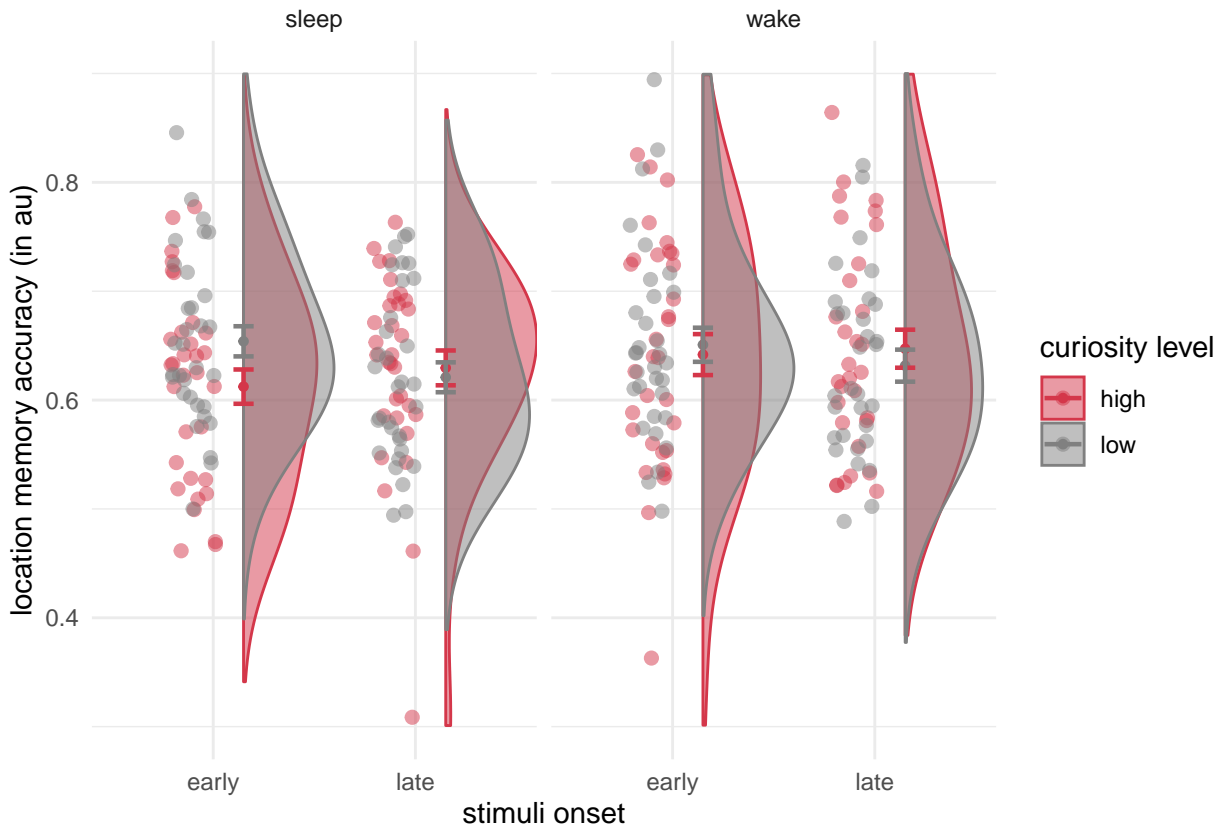
Figure 18: Location memory accuracy is the distance between location of object presentation and where the participants thought the object was presented. A smaller value reflects better object location accuracy. Data points are jittered along the x-axis for ease of viewing. The dot and whisker plots refer to the mean and standard error of measurement respectively.

onset ($F(1, 62) = .107, p = .373, \eta_p^2 = .002$), or curiosity level ($F(1, 62) = .516, p = .258, \eta_p^2 = .007$). The interaction between group and object onset was also non-significant ($F(1, 62) = .327, p = .29, \eta_p^2 = .005$), as was the interaction between group and curiosity level ($F(1, 62) = .358, p = .18, \eta_p^2 = .014$), but the interaction between onset and curiosity level was significant ($F(1, 62) = 2.88, p = .048, \eta_p^2 = .044$). Finally a three-way interaction between group, curiosity level, and object onset was also non-significant ($F(1, 62) = .369, p = .27, \eta_p^2 = .006$). For the sleep group, participants located high curiosity objects presented early with a mean of .612 (sd = .089) and low curiosity objects with a mean of .654 (sd = .078). For the late image onset presentation participants located the objects with a mean of .630 (sd = .09) and low curiosity objects with a mean of .621 (sd = 0.078). In the wake group early object onset, participants located the high curiosity objects with a mean of .642 (sd = .106) and low curiosity objects with a mean of .651 (sd = .089). For late object onset, participants located high curiosity objects with a mean of .656 (sd = .107) and the low curiosity objects with a mean of .641 (sd = .097).

We explored whether our sleep condition location error findings were similar to the findings in Murphy et al. (2021). As such, we carried out an analysis with the sleep group subset from the overall sample. In their study all participants experienced a period of sleep between encoding and recall. Two t-tests were carried out comparing high v. low location memory accuracy across the two object onset time points. Late onset was not significant ($t(31) = 0.58, p = .28$), but early onset was ($t(31) = -2.03, p = 0.026$), with participants locating high curiosity objects presented early with a mean of .612 (sd = .089) and low curiosity objects with a mean of .654 (sd = .078). For the late image onset presentation participants located the objects with a mean of .630 (sd = .09) and low curiosity objects with a mean of .621 (sd = 0.078). These results indicate that if we analyze incidental memory as seen in Murphy et al. (2021), we find that early only in early object onset, a curiosity memory enhancement for incidental memory is found.

5.4.6 Sleep does not predict incidental location accuracy

To understand the influence of sleep stage duration on location accuracy benefit (high curiosity accuracy minus low curiosity accuracy), we carried out a multiple regression using total time (in minutes) spent in N2 and N3 as predictors of location accuracy benefit. The overall model was not significant ($R^2 = 0.087, F(3, 29) = 0.228, p = .88$). According to this model, N2 did not predict location accuracy benefit ($\beta = -.00001, p = .93$), neither did N3 ($\beta = -.0003, p = .49$), and neither did REM, ($\beta = -.0002, p = .76$). These results suggest that sleep stage duration does not predict incidental object location memory.

5.4.7 Those with greater curiosity memory enhancement benefit do not also benefit during location recall

The correlation between curiosity memory benefit for trivia answers and incidental object location memory accuracy was positive but non-significant (Pearson's $r(62) = .029, p = .41$). These results indicate that curiosity enhanced memory benefit does not correlate with incidental object location memory accuracy.

5.4.8 Information prediction errors affect the likelihood that an answer is recalled.

To understand the effect that information prediction errors have on the likelihood that an answer is remembered correctly we carried out a binomial logistic regression on the trial-by-trial level data. The parameters in our basic model state that the within participant cluster centered IPE (Enders and Tofighi 2007) would predict probability of answer recollection with additional predictor variables of group (sleep vs. wake) and object onset (early vs. late). The model finds that as IPE increases the more likely an answer is to be recalled ($\beta = .070, p \leq .001$) and that whether you were in the sleep or wake group had an effect ($\beta = -.224, p = .019$), with those in the sleep group experiencing a higher likelihood that an answer is recalled compared to the wake group, regardless of IPE level (Figure 19). Object onset did not have an effect on answer recollection likelihood ($\beta = -0.011, p = .763$).
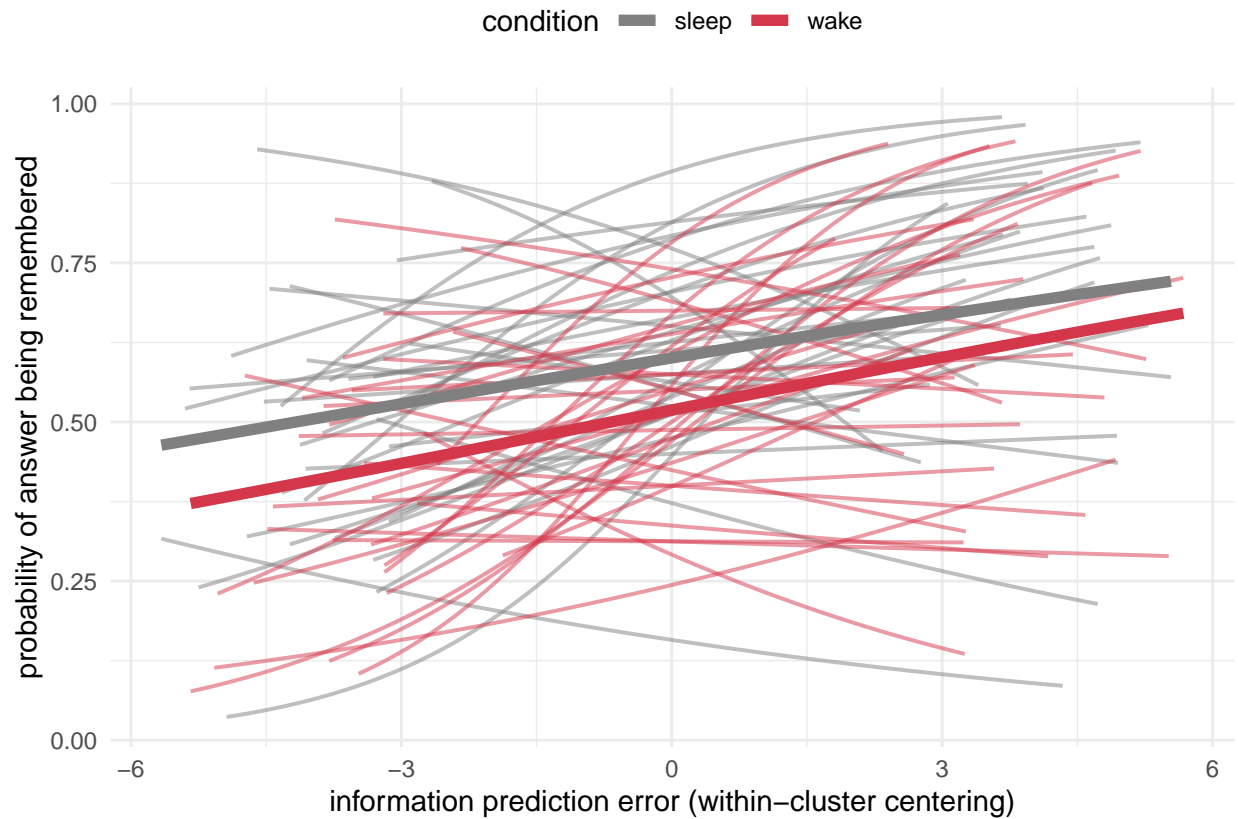
Figure 19: Probability that an answer will be remembered depending on its information prediction error. The y-axis reflects the likelihood of an answer being remembered with 1 being remembered and 0 being not remembered. Information prediction error is the answer satisfaction minus initial answer curiosity. IPEs are centered within participant clusters.

5.4.9 IPEs also impact incidental object location accuracy
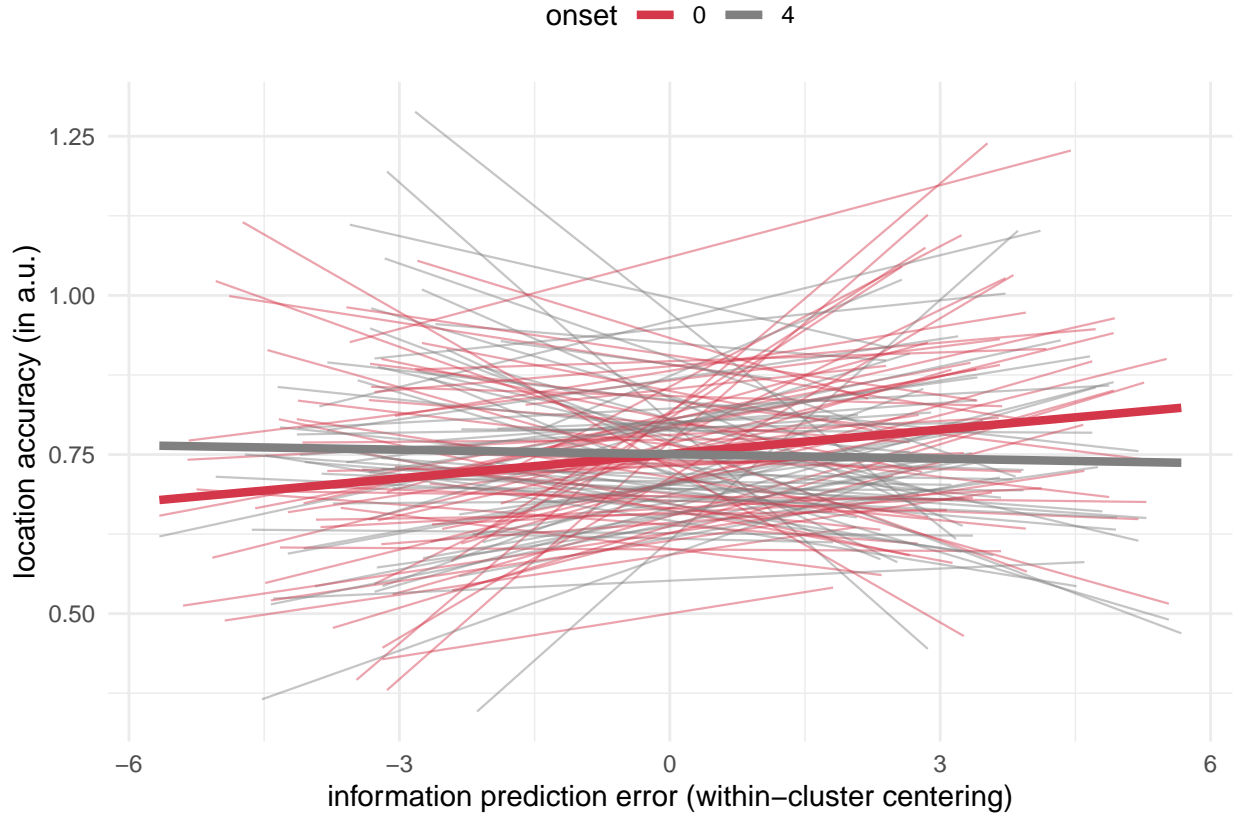
Figure 20: Location accuracy over IPE. Lower values in location accuracy means more accurate object location. Information prediction error is the answer interest minus initial answer curiosity. Flamingo refers to early object onset and grey, late object onset.

Similarly to section 4.4.6, we carried out a mixed effects model to understand whether IPEs impact incidental memory for object locations. While, the group (sleep v. wake, $\beta = 0.017, p = .23$) and object onset ($\beta = -.0003, p = .49$) did not promote object location accuracy, IPEs did ($\beta = .0054, p = .049$). The interaction between IPE and object onset was also not significant ($\beta = -.008, p = .3$) These results suggest that IPEs also benefit incidental memory persistence, but object onset does not (Figure 20).

5.5 Discussion

The recent findings indicate that the curiosity memory enhancement occurs regardless of the onset of the incidental object presentation. Thus, mirroring previous findings on the curiosity enhanced memory for target information (Gruber, Gelman, and Ranganath 2014; Stare et al. 2018; Murphy et al. 2021). We also found a sleep vs. wake group effect. However, further analysis revealed that curiosity level, and not sleep stage parameters had an effect on what answers were remembered. Participants in both groups remembered more high curiosity answers than they remembered low curiosity answers. The spillover effect into incidental object location does not positively affect the ability for participants to recall object location. however, when we subset the sample into just the sleep group and analyze the data similarly to Murphy et al. (2021), we found that there was a curiosity memory enhancement for incidental information, but only for incidental objects presented close to elicitation of curiosity. However, the memory benefit analysis did not reveal a positive relationship between answer memory benefit and incidental location memory benefit, unlike the findings found in Fandakova and Gruber (2021). Furthermore, the duration spent in N2, N3, or REM did not predict the answer recall or the incidental location accuracy, mirroring the findings of Stare et al. (2018) and running counter to the the findings of Studte, Bridger, and Mecklinger (2017). Mixed effects modelling revealed that IPEs positively predict the probability that an answer will be recalled and how accurately an incidental object location will be selected. This resonates with previous findings (Marvin and Shohamy 2016). Interestingly, the object onset appeared visually to be modulated by IPE (Figure 20) with early onset having a positive relationship and late a negative onset. However, this was not significant. In addition, there was also a significant contribution of sleep to the model for trivia answer memory, with the condition having a positive impact on the probability of recall throughout the IPE range for trivia answers. Our investigation into the effects of IPE on incidental memory persistence also showed to be significant, with object onset having not effect in this model.

To put all of these findings into context, we have shown that the curiosity memory benefit for trivia information benefits high curiosity information over low curiosity information. This is congruent

with previous findings Wade and Kidd (2019). There is no clear modulation of sleep on this effect. Similarly to the findings of Stare et al. (2018), individual differences in sleep stage duration did not predict answer recall. The spillover effect on incidental object location accuracy that we did find was weak and we could only see a trend when we subset the sleep group from the total sample and carried out an analysis similar to Murphy et al. (2021). Perhaps, the task was too difficult. There is indication that task difficulty, when modulated, can impact the effects that researchers observe (Petzka et al. 2021), thus making the interpretation of sleep effects on incidental object location challenging. It could be that because the task is too hard, curiosity is periodically safeguarded from potential conflicts so that it is maintained for what is more important. Where in an easier incidental task, conflicts would not reach the threshold where participants inhibit incoming information and therefore curiosity can positively enhance incidental memory. The IPE analysis revealed that we know little about alternative information prioritization routes. We found that there is this additional route by which memories can be categorized as important, regardless of what the initial curiosity level might have been. This adds to the findings seen in Marvin and Shohamy (2016). The higher the IPE, the more likely an answer is to be remembered and, novel in our findings, might also impact incidental memory. This suggests that curiosity is one part of a larger uncertainty reducing mechanism that rewards information acquisition. This mechanism, at least with our experimental design, was not modulated by sleep.

As previously stated, it is difficult to interpret the spillover effect on the object location memory accuracy. Indeed, Oudiette et al. (2013) and Petzka et al. (2021) used a background where the objects could appear in relation to either a grid, a color, or a boundary between colors. While, chance performance in the previous chapter was better than the current chapter, it is difficult to attribute that specifically to whether there was a background or not. The idea being that by making the task easier, participants could learn associations between the curiosity eliciting trivia questions, object locations, and the location relative to landmarks in the particular background scene the object was placed. However, the previous chapter's results were not better at indicating the existence of a spillover effect. Recent findings suggest that curiosity can at least affect how

much of a 3D environment one explores (Danlu Cen, Carl. J. Hodgetts, and Matthias J. Gruber 2022), even if this curiosity does not affect memory for incidental information. Replications are needed. There is also the issue of how the objects are presented. Not all objects are shaped the same (basketball vs. a pen). As such, it could possibly be difficult to easily and consistently ascertain where the center of an object is.

In conclusion, the present study provides further evidence of the curiosity memory benefit. We found a less clear spillover effect, potentially exacerbated by the difficulty of the task. However, the trends seen do open the door for future avenues of research. For example, if the location task is being inhibited, by the sustained curiosity, then how long does the anticipation have to be until the curiosity is no longer sustainable and individuals reallocated resources to the incidental task? This task only tested an anticipation phase of 8 seconds, it may be that the sustaining curiosity is not without limits and there is something akin to an attentional supply and demand curve at play. Future investigation could elucidate on this matter.

6 General Discussion

6.1 Research aims

This thesis and the experiments enclosed aimed to address some open questions within the curiosity literature. One, attempt to replicate the curiosity enhanced memory effect (Gruber, Gelman, and Ranganath 2014; Murphy et al. 2021; Fandakova and Gruber 2021). Two, we investigate the involvement of sleep in curiosity-enhanced memory consolidation (Stare et al. 2018) and two, whether curiosity can enhance non-face incidental memory (Gruber, Gelman, and Ranganath 2014; Galli et al. 2018; Stare et al. 2018; Fandakova and Gruber 2021; Murphy et al. 2021). Within this theme of incidental memory, we also investigated the effect of the time point when tests were carried out. In addition, we also examined the impact of incidental information proximity to curiosity elicitation has on what memories persist (Murphy et al. 2021). The difficulty of the task itself was also focused on (Petzka et al. 2021). In particular as it pertains to how the difficult obfuscates or exposes particular memory effects. Finally, we also investigated whether IPEs and individual differences could be important drivers on curiosity enhanced memory and incidental object-location associative memory (Fandakova and Gruber 2021). The following section provides a summary of these research questions, what we found in relation to existing literature, and make some acknowledgements of specific experimental shortcomings that could have impacted those findings. Finally, avenues for future research will be suggested.

6.2 Curiosity consitently promotes trivia answer persistence

Importantly, the time point of when a test was carried out did not show to be relevant for curiosity enhanced trivia answers. We directly tested this in one of the chapters (section 3), by using a immediate and delayed protocol. However, trivia answers persisted with greater incidence for high curiosity information compared to low curiosity information regardless of the study. Thus providing additional evidence of the findings seen by others (Gruber, Gelman, and Ranganath 2014; Stare et al. 2018; Murphy et al. 2021; Fandakova and Gruber 2021). One point of emphasis should be directed at our study that found that curiosity enhanced memory for trivia answers also occurs when the trivia questions and answers are displayed auditorily (section 3). This evidences the stability of the effect, but also the flexibility with which future studies can induce a curiosity-enhanced memory effect.

6.3 The role of sleep-related consolidation in curiosity memory enhancement

One of the major goals of this work was to understand whether sleep plays a role in consolidating curiosity-enhanced memories. A prediction based on reward literature showing that reward memory enhancement in delayed memory test and consistent with the idea that dopamine affects memory encoding and memory consolidation (Bromberg-Martin and Hikosaka 2009; Yun 2004; Oudiette et al. 2013; Igloi et al. 2015; Studte, Bridger, and Mecklinger 2017; Prehn-Kristensen et al. 2018; Sterpenich et al. 2021). Indeed, in section 2 we found that time spent in N3 (i.e., slow-wave sleep) correlates positively with curiosity-related answer memory benefit. However, our sample size was small and as such, jeopardized the generalizability of the findings. Especially given the study with a large sample size in section 5, we did not find N2, N3, nor REM to be positively correlated with answer memory benefit or incidental memory. One major caveat with our sleep research is that while most studies on the effects of sleep on memory test memory after a night of sleep, some studies suggest that sleep-related memory consolidation effects might only emerge after several days or even weeks (Igloi et al. 2015; Cordi and Rasch 2021). This suggests that sleep-mediated consolidation operates at a different timescale than wake consolidation. When testing for memory, maybe it is also necessary to test weeks or months after the initial learning event.

It is also important to note that sleep quality can be affected but first night effects (Goerke et al. 2013), where a participant has disturbed sleep during the first night of sleep in the lab. While our participants slept at home, they did take wearables home and only wore the headbands for one night. This could recreate the first night effect at home through the novelty of sleeping with the wearable. Alternatively, the wearable could mean better sleep as the headband is different to sleep lab EEG setups and participants are sleeping in their own bed. It is challenging to discern from our findings, what could be affecting sleep quality. Another point worth discussing is that the explicit future utility of information may impact what is consolidated during sleep (Fischer and

Born 2009). In this study, participants were told about an upcoming test relating to a learning task. In our experiments the testing was only mentioned directly before doing the test, and therefore it was a surprise memory test so that participants did not strategically learn certain information over other information. Note that this is the standard procedure in the trivia paradigm. However, such a simple manipulation change in the trivia paradigm that could be carried out in the future. Another potential avenue for future research is sleep deprivation. It may be that sleep modulates curiosity mediated memory effects only when there is not enough sleep, as it has been shown to bias reward processes. It was found that participants who were sleep deprived, had larger activity reactions to pleasure related stimuli in the VTA compared to controls (Gujar et al. 2011). Showing a bias towards positively valenced stimuli.

Finally, it is important to emphasize that using the wearable headbands produces different quality data for sleep scoring compared to lab based EEG setups. For one, this makes scoring sleep easier, but it also enables signal processing analysis of more complex phenomena, such as cross-frequency phase-amplitude coupling analyses or N3 slow wave amplitude (Staresina et al. 2015) that could correlate with curiosity enhanced memory performance. It may be that looking at sleep stage duration is insufficient to unpick what happens during curiosity-related sleep consolidation. In addition, there are alternative experimental protocols that could be employed. Naps instead of overnight sleep could be an option, as indeed some have used (Antony, Piloto, et al. 2018). This could modulate what effects are seen. Our studies used full nights of sleep and it is not systematically understood how a full night of sleep over a nap will affect what memory persist. Naps also enable access to different neuroimaging techniques, such as fMRI (Sterpenich et al. 2021). In particular this allows us to investigate neural activity during wake and sleep and investigate how neural activity differs across the two states of consciousness. Therefore, future studies could pinpoint how and to what neural activity could scale with how many memories persist.

6.4 Information Prediction Errors

In the final two studies, we also examined how IPEs might affect memory persistence. We know from previous research that positive IPEs promote memory persistence for trivia answers (Fandakova and Gruber 2021). However, our results suggest that while the IPEs promote memory persistence for trivia answers quite consistently, this is not the case for incidental memory. Of the two experiments where this analyses was carried out (sections 4 & 5), we found that the more positive an IPE is the more likely a trivia answer was to be remembered. This was consistently significant in both experiments. Only in the final study, which included both a sleep and a wake group plus a larger sample size, was there an evidence for IPE effects on incidental memory. Here we found that positive IPEs increased the likelihood that an object was accurately located worse. In other words, IPEs have a deleterious effect on incidental memory persistence. This could possibly be masking spillover effects from revealing themselves in the way we would expect. This is reflective of the broader theme that the boundary conditions of a spill-over effect on incidental object-locations are not clear yet. One potential future avenue of investigation would be to see whether positive IPEs employ a different mechanism altogether. A review highlighted that the norepinephrine system may be employed in surprise related memory (Thorp, Clewett, and Riegel 2020) where we would perhaps expect a greater effect of the norepinephrine system for positive IPEs when they create that surprise "ah-ha" moment. The moment when interest is greater than initial curiosity. As this moment occurs, this alternative system may be active. A potential fMRI study could elucidate on the matter. Indeed, little is known about the mechanism that drives IPEs and would help distinguish curiosity from surprise/novelty effects.

6.5   Spillover effect for incidental object-location associative memory

The other goal of this thesis was to further investigate the curiosity-related spillover effect on incidental memory that has been seen in several studies (Gruber, Gelman, and Ranganath 2014; Galli et al. 2018; Stare et al. 2018; Fandakova and Gruber 2021; Murphy et al. 2021). It was critical to understand of the spillover effect was content agnostic or is there something special about face recognition that facilitates this spillover effect. Indeed, past studies used recognition memory for faces, whereas our studies used associative memory between objects and their spatial locations. Of the three studies carried out that used this associative memory approach (sections 3, 4, & 5), none found a curiosity spillover effect. There were procedural differences here. In section 3, we showed incidental information multiple times. In section 4 the procedure mimicked the trivia paradigm more closely, but with a background scene. Finally, section 5, where objects appeared in a gray background. Nonetheless, in our final study (section 5), when we subset the sample to replicate the protocol and behavioral findings as seen in Murphy et al. (2021) (experiment 2), did we find an indication of a spillover effect when using the same analysis approach. Linked to this finding, we also found this spillover to be dependent on proximity to curiosity elicitation. Here, participants were more accurate in locating objects that were seen in anticipation of high curiosity answer over low curiosity answers, but only for objects shown proximaly to curiosity elicitation (early onset). Crucially, our studies used only two different incidental presentation slots, whereas the original study used four (Murphy et al. 2021). It is not known what impact this will have on memory persistence. However, the greater uncertainty of when the object appears could enhance what memories persist. This remains to be investigated. One other parameter is the task itself, as others have found incidental objects to benefit from curiosity (Chen, Twomey, and Westermann 2022). However, this paradigm studied infants the extent to which look at gazed at incidental objects. How this translates into an adult sample remains to be seen, but it does suggest that understand the impact of curiosity on incidental, and seemingly unrelated, information is a nascent area of investigation.

In addition, we were also interested in how sleep would correlate with the incidental memory

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curiosity-related enhancement. The hypothesis was that if sleep enhanced memory persistence, then the degree of forgetting over time would be less for high curiosity object-locations compared to low curiosity object-locations (Oudiette et al. 2013). However, our results (section 3) showed that at immediate testing, high curiosity object-locations were recalled less accurately than low curiosity objects-locations and no difference at delayed testing. In addition, the degree of forgetting between the two time points was greater for high curiosity object locations than low curiosity object locations. One explanation is that these findings could be due to the task difficulty. The possibly harder task of locating objects compared to recognizing faces means that participants are gating their attention towards the primary task of trivia answers. The relatively better performance in low curiosity object-location accuracy compared to high curiosity object-location accuracy is consistent with this logic. When participants are not interested in anticipating the answer and therefore are able to allocate greater resources to the object-locations. In line with the theme of task difficulty, we know from previous findings that task demands reveal different memory outcomes (Petzka et al. 2021). In line with this we conducted a study where objects appeared in a scene as opposed to a blank screen (section 4). The idea being that the scene could help anchor the objects within a contextual location (i.e., object is left of the tree) making the task easier. As a result incidental object-locations would be more susceptible to the curiosity spillover effect. While chance performance for incidental memory accuracy was better, findings still did not reveal a curiosity-related incidental memory spillover effect. did not change the outcome of our findings for incidental memory, where curiosity enhanced memory for trivia answers persisted (section 4 & 5).

As mentioned earlier, it may be that explicitly stating the presence to tests is required to see a curiosity effect on associative memory (Fischer and Born 2009). Alternatively, testing at later time points (e.g., several weeks or months) could reveal incidental memory in line with our predicted hypothesis, as the importance of what is seen is reemphasized and consolidation happens over several nights. One way to immerse motivational tasks within a real life activity would be to use a driving simulator as seen in Shneyer and Mendelsohn (2018). It was found that for rewarded

sections of road, participants were more likely to recall the incidental billboards. One could

adapt this task to curiosity by displaying trivia questions auditorily and then showing incidental

billboards in anticipation for the answer. researchers could then also ask participants where in

the map they saw the billboard. With this paradigm we can assess curiosity-related memory

benefit, incidental billboard spillover effects, and associative object location accuracy.

6.6 Individual differences

Throughout the series of experiments, we carried out an individual difference analysis. The logic here being that each individual will be affected by curiosity to a different degree (differential between high and low trivia answer performance) and therefore their memory performance differential between high and low incidental memory will also differ to a greater or narrower extent. In a previous study it was found that the larger the curiosity memory benefit, the more incidental memory benefit there was (Fandakova and Gruber 2021). As such, there was a positive correlation between trivia answer memory benefit and incidental memory benefit. However, we did not find evidence for this. A reason for this could be the general difficulty that participants had in locating the objects. In the experiment where performance was better for the object-location associative memory test (section 4), the findings were in the predicted direction and nearly significant ($p = .066$). Indicating that the object-location memory task was perhaps too difficult. Future curiosity research should employ such individual differences analysis so that we can, on an individual basis, understand to what extent curiosity benefits spillover to incidental information and under what conditions we can maximize this effect.

6.7   Other limitations

Above and beyond the outcome of our findings, this research advanced the field by using wearable sleep EEG monitoring devices. The implementation of this technology is novel in curiosity research. These were concessions made as a result of the COVID pandemic, when access to the laboratory environment was severely restricted. In light of this, The methodological adaptation o having participants record their sleep at home also meant that for two of our experiments, participants carried out the tasks at home and under limited supervision (section 4 and 5). For future studies with similar designs, this means that we do not really know how much or how well they were paying attention to the task. With ethics and participant consent it would have been a methodological improvement to use eye tracking through personal device webcams. Through this approach one could establish some level of confidence that eye gaze was directed at the task throughout. However, this was not something that could be done easily in time before the research was carried out. In addition, the variable screen size across two studies could have contributed to the incidental memory findings not lining up with our hypothesis. Again, due to pandemic concessions it was not possible to host participants in the labs for extended periods of time.

6.8   Conclusions

In conclusion, we found a consistent curiosity enhanced memory effect for trivia answers. This effect of memory persistence was also found when trivia questions and answers were presented auditorily, a field first. We also found a consistent effect of IPEs on trivia answers, showcasing an alternative pathway to memory persistence independently of sleep. However, there was no consistent evidence for a spillover effect although boundary conditions need to be further explored when using an associative memory measure.

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