Disentangling the Influences of Curiosity and Active Exploration on Cognitive Map Formation

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Abstract

Curiosity has long been assumed to promote exploration, and in turn, to support cognitive map formation. However, little research has directly investigated these claims. Recently, Cen et al. (2024) demonstrated that when participants feel more curious about specific virtual environments, they (1) explore those environments more thoroughly, and (2) display better memory for environmental layouts. These data support the existence of a relationship between curiosity and cognitive map formation; however, because participants always had the opportunity to act on their curiosity (by using it to guide their exploration), the precise nature of that relationship remains uncertain. Here, we ask whether curiosity itself directly promotes cognitive map formation, or whether its benefits depend on the ability to actively engage in curiosity-guided exploration. One group of participants – the Active Group – will rate their curiosity for and actively explore 16 virtual environments before completing a surprise memory test (as in Cen et al., 2024). A second, yoked group of participants – the Passive Group – will undergo the same general procedure except that, rather than directing their own exploration, they will watch screen-captured recordings of prior Active Group participants' exploration. This manipulation will allow us to disentangle the influences of self-reported curiosity (varying trial-by-trial across all participants) and active exploration (manipulated between groups) on cognitive map formation.

Curiosity – broadly defined as the desire to obtain information in absence of external reward (Gruber & Ranganath, 2019; Wang & Hayden, 2021) – plays a fundamental role in promoting learning and memory. To date, most research on curiosity has centred on epistemic knowledge. For example, in the context of a popular trivia paradigm, participants reliably show better memory for trivia items that they self-report feeling more curious about (e.g., Kang et al., 2009; Gruber, Gelman, & Ranganath, 2014; Wade & Kidd, 2019).

Interestingly, the benefits of curiosity appear to be wide-ranging. In at least some contexts (c.f., Hollins, Seabrooke, Inkster, Wills, & Mitchell, 2023; Keller, Salvi, Leiker, Gruber, & Dunsmoor, 2024), participants show enhanced memory not just for information that they are specifically curious about (e.g., trivia items), but also for incidental information encountered during high-curiosity states (e.g., faces presented during states of curiosity; Gruber et al., 2014; Murphy, Dehmelt, Yonelinas, Ranganath, & Gruber, 2021; see also Chen, Twomey, & Westermann, 2022). These benefits appear to be driven by curiosity-induced modulations within the dopaminergic circuit that bolster hippocampus-dependent memory (Gruber & Ranganath, 2019), suggesting that curiosity could index a general state of arousal in which encoding is more efficient (van Schijndel, Jansen, & Raijmakers, 2018).

Alternatively, curiosity might be beneficial not because it *directly* promotes encoding (e.g., through dopaminergic modulation), but instead because it energizes specific patterns of exploration that are conducive to learning about particular contexts. For example, in his seminal work on cognitive map formation, Tolman (1948) argued that the latent maze learning he observed among rats was motivated by curiosity. That is, the animal's curiosity triggers exploration of a new environment, and that exploration promotes memory for the environment (see also Berlyne, 1966; O'Keefe & Nadel, 1978; Wang & Hayden, 2021).

Of course, among both humans and nonhuman animals, it is difficult to determine whether specific patterns of exploration are motivated by curiosity or instead by other factors [such as anxiety (Gangnon et al., 2018), boredom (Geana et al., 2016), or the search for external rewards]. To date, surprisingly little work has investigated the relationships between curiosity, exploration, and cognitive map formation – in part due to the challenges of reliably inducing curiosity in laboratory settings.

Recently, Cen, Teichert, Hodgetts, and Gruber (2024) designed a *virtual exploration paradigm* to assess whether and how curiosity influences exploration patterns, as well as subsequent memory for explored environments. On each trial, participants saw a room label (e.g., 'Lounge') and rated their curiosity for it. Then, participants were given the opportunity to freely explore the corresponding virtual room: they were told to spend as much time in the room as they wished, and to leave whenever they felt ready. After all of the rooms had been explored, participants were given a surprise memory test that probed their memory for environmental layouts.

Critically, Cen et al. (2024) found that participants who self-reported feeling more curious about specific virtual rooms (1) explored those rooms more thoroughly [exhibiting higher path roaming entropy (Path RE), an index of spatial variability] and (2) displayed better memory for environmental layouts (see also Sivashankar, Fernandes, Oudeyer, & Sauzéon, 2024, who found that curiosity promotes higher feelings of presence and better route memory among children). However, because participants in both Cen et al. (2024) and Sivashankar et al. (2024) had the ability to act on their curiosity – by using it to guide their exploration through each virtual environment – the precise nature of the relationship between curiosity and cognitive map formation remains unclear.

Here, we aim to disentangle this relationship by asking: is there a direct link between curiosity and cognitive map formation? Or, do the benefits of curiosity depend on the ability to actively engage in curiosity-driven exploration?

To address this question, we plan to conduct a replication and extension of Cen et al. (2024). One group of participants – the Active Group – will undergo the same procedure as in Cen et al. (2024), such that they rate their curiosity for, then freely explore a series of virtual environments before completing a surprise memory test. Additionally, and critically for our research question, we will extend Cen et al. (2024) by introducing a second group of participants: the Passive Group. Participants in this yoked condition will undergo the same general procedures as the Active Group except that, rather than freely exploring the virtual environments themselves, they will watch screen-captured videos of prior Active Group participants' exploration. This manipulation will allow us to disentangle the influences of self-reported curiosity (varying trial-by-trial across participants in both groups) and active exploration (manipulated between the Active and Passive Groups).

Among the Active Group, we expect to replicate Cen et al.'s (2024) findings (1) that curiosity predicts higher Path RE and (2) that curiosity and Path RE independently predict more accurate cognitive map formation. Additionally, and based on prior research surrounding the benefits of active learning (e.g., Craddock et al., 2011; Gaunet et al., 2001; Schomaker & Wittmann, 2021), we predict that participants in the Active Group will display better memory than participants in the Passive Group.

However, our critical analysis concerns the influence of curiosity within the Passive Group, compared to the influence of curiosity within the Active Group. If curiosity reflects a general state of enhanced encoding, then we expect Passive Group participants to display better memory for rooms that they are more curious about. Conversely, if curiosity exerts its influence on memory because it facilitates specific patterns of exploration, then we expect that Passive Group participants' memory will not differ as a function of curiosity.

Method

Participants

Sample Size Determination. Our main theoretical interest is the possible two-way interaction between experimental condition (Active vs. Passive Group) and curiosity. However, because our predictions concerning the direction and magnitude of this interaction are nonspecific, we plan to determine our sample size in accordance with a modified Sequential Bayes Factor design ("Sequential Bayes Factor with maximal *n*"; Schönbrodt & Wagenmakers, 2018). Specifically, we will collect data *either* until we obtain compelling evidence for or against a two-way [experimental condition x curiosity] interaction [defined here as Bayes Factor (BF) > 10 or BF < .10, respectively], *or* until we reach a prespecified maximal sample size of 120 participants ($N = 60$ in each of the Active and Passive groups). If we reach this maximum without meeting our prespecified evidential thresholds, then the final BFs will still be interpreted, but our Stage 2 report will specify that our criteria for compelling evidence were not met.

To reduce the likelihood of obtaining false positive evidence for or against the target interaction (which could result from variability within small sample sizes), we will only begin analysing our data once we have obtained a minimum sample size of 30 participants ($N = 15$ per group). If our evidential criteria for the two-way interaction between experimental condition and curiosity are not met, then we will continue collecting data, stopping to reanalyse after every 6 participants (*N* = 3 per group) until one of our stopping criteria is reached. Importantly, when Bayesian stopping criteria are properly specified and adhered to, they do not carry the risks commonly associated with optional stopping (i.e., inflation of Type I error rates; Sanborn & Hills, 2014; Schönbrodt & Wagenmakers, 2018; Wagenmakers, Gronau, & Vandekerckhove, 2019).

Recruitment and Condition Assignment. Participants will be Cardiff University students recruited from Cardiff University's subject pool (in exchange for course credit or monetary compensation) and/or from relevant university bulletins (in exchange for monetary compensation). Participants will be eligible as long as (1) they are between the ages of 18-35, (2) they have normal or corrected-to-normal vision, and (3) they have not participated in any prior studies from our lab that involved the same stimuli. Informed consent will always be obtained, and all experimental procedures have been approved by the Cardiff University’s School of Psychology Research Ethics Committee.

Because a new Active Group participant must be run before each Passive Group participant (to enable yoking), condition assignment will be non-random. In general, participants will be sequentially assigned to each group, except in cases where rearrangement is necessary to meet our yoking criteria (see below) or where multiple participants are run in the same timeslot (CUBRIC has the equipment to run up to five participants simultaneously, but Active and Passive Group participants will never be run concurrently to avoid revealing that there are two conditions in the study.) Yoked Active-Passive participant pairs will be matched according to gender and payment type (course credit vs. monetary compensation).

Questionnaires & Trait Measures. As an index of trait (rather than state) curiosity – which predicted the strength of the relationship between curiosity ratings and Path RE in Cen et al. (2024) – all participants will be asked to complete the Five-Dimensional Curiosity Scale Revised (5DCR; Kashdan, Disabato, Goodman, & McKnight, 2020) after completing the other experimental procedures (detailed below). Additionally, and only once the experiment has otherwise concluded, participants will be asked to complete a brief series of supplementary questionnaires indexing topics such as ADHD symptomology and mood. These supplementary questionnaires will be analysed by undergraduate students at Cardiff University as part of their final year research projects, but those analyses are not central to the research question described here, and they will not be reported in our Stage 2 submission.

Materials and Apparatus

This study will use the same virtual environment as in Cen et al. (2024). The environment was created in Unity 3D (version 2019.4.15, Unity Technologies), and it comprises 18 virtual rooms (one room encountered per trial) alongside one outdoor space (encountered on every trial).

Participants will begin each trial in the outdoor space, which consists of a zig-zag shaped pier that connects the starting location (at one end of the pier) to the virtual room (at the opposite end of the pier). The category label for the room (e.g., ‘Lounge’) will be prominently displayed both next to the starting location and above the room’s entrance. Participants will be asked to navigate down the pier and then to enter the room itself.

Snapshots of each virtual room are provided in Figure 1. Two of these rooms – the bridal shop and the cinema – will be designated as practice rooms to be encountered in the Familiarization Phase (see Procedure). The remaining 16 rooms will be designated as experimental rooms to be encountered in the Exploration Phase.

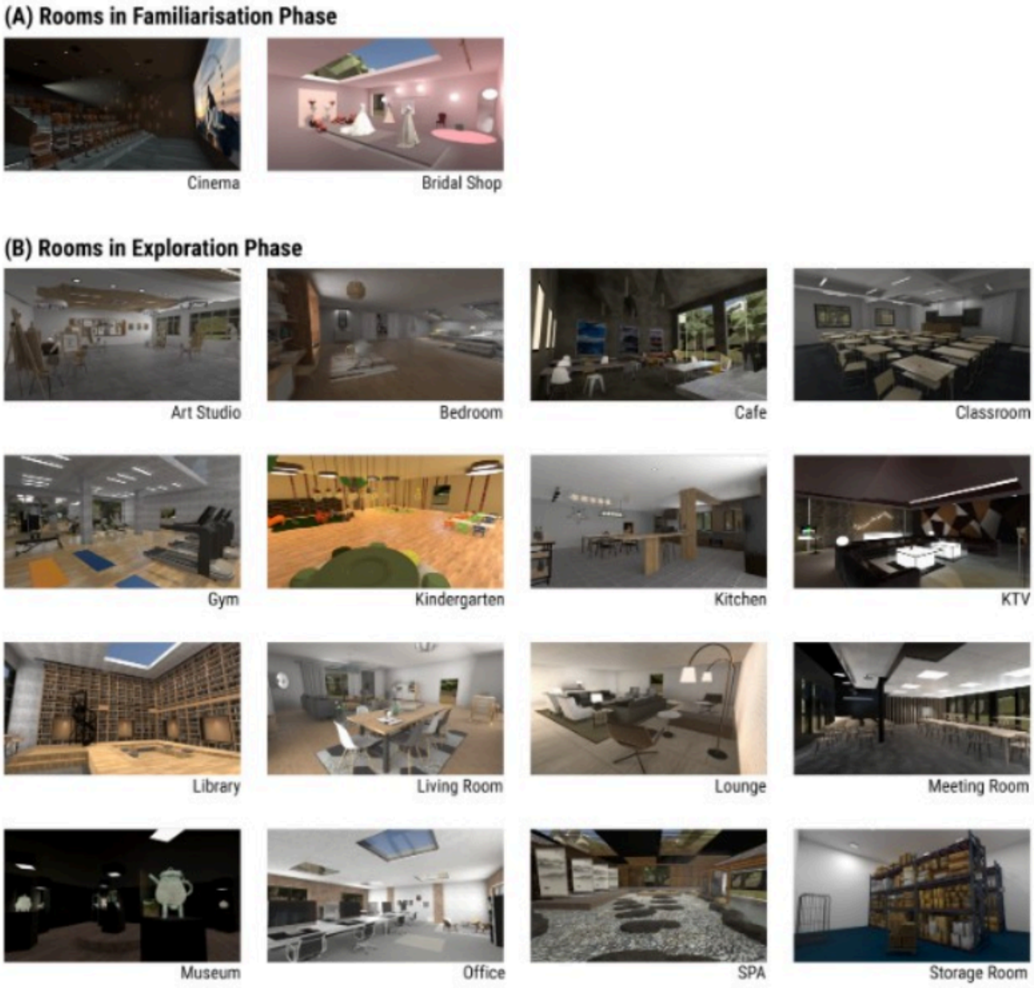

Figure 1. Screenshots of the 18 virtual rooms. Two rooms (the Cinema and the Bridal Shop) will exclusively be encountered in the familiarization phase; data from this phase will not be analysed. The remaining 16 rooms will be encountered in the Exploration Phase. Figure reproduced with permission from Cen et al. (2024).

Each of the 18 rooms spans 16 x 16 m in virtual space and contains a variety of furniture and decorative objects, all of which were obtained from online 3D asset stores (ArchVizPRO Interior packages and 3d66.com)

The experiment will be conducted in the Cognitive Testing Laboratories at CUBRIC, Cardiff University. Participants will be seated in front of a 1920 x 1080 desktop monitor with a 60Hz refresh rate. Navigation will be conducted using both keyboard (‘W’ to move forward; ‘S’ to move backward; ‘E’ to enter a room; ‘B’ to leave a room) and mouse (which changes the viewing angle, allowing participants to steer their avatar). Movement speed will be fixed at two avatar eye-heights per second, simulating a brisk walking pace.

Active Group Procedure

Participants in the Active Group will undergo the same experimental procedures as in Cen et al. (2024). After providing informed consent, participants will begin the experiment, which involves three phases: Familiarization, Exploration, and a Memory Test[1]. The instructions provided to participants at the beginning of each phase are available in the Supplemental Materials (please see the 'Supplemental Materials' folder at https://osf.io/8vpjg/). Importantly, participants will not be informed about the Memory Test phase until after the Exploration phase is complete.

The Familiarization Phase will comprise three trials, and the goal of this phase is to ensure that all participants are comfortable with the navigation controls and the experimental flow. Data from this phase will not be analysed. On the first trial, participants will progress down the virtual pier, enter an empty room, and leave it at their leisure. On trials 2 and 3, participants will experience the same trial structure as in the Exploration Phase (see below). On these trials, participants will explore the Cinema and the Bridal Shop (Figure 2A; one room per trial with order counterbalanced). After the three familiarization trials are complete, the experimenter will ensure that participants feel comfortable with the controls and answer any questions before progressing to the full Exploration Phase.

The Exploration Phase will consist of 16 trials (one unique room encountered per trial). Each trial will begin at the starting point on the virtual pier (Figure 2). Participants will see an on-screen prompt that asks them to rate their curiosity for the to-be-explored room, based on a room label visible next to their starting location (10-point Likert-type scale; 1 = not at all curious, 10 = very much curious). They will then navigate down the walkway, enter the room, explore it freely, and leave it at their leisure. Exploration time is unlimited and stopping is self-paced. After leaving, participants will see a second on-screen prompt asking them to report how interesting they found the room (10-point Likert-type scale; 1 = not at all interesting, 10 = very much interesting). After the participant responds, the program will automatically progress them to the next trial.

[1] Note that Cen et al. (2024) included three memory tests – Room Drawing, Free Recall, and Introspective Recall -- however, only the data from the Room Drawing test were analysed. Our predictions are likewise centred on the Room Drawing test, so we have not included the Free Recall and Introspective Recall tasks in our planned design.

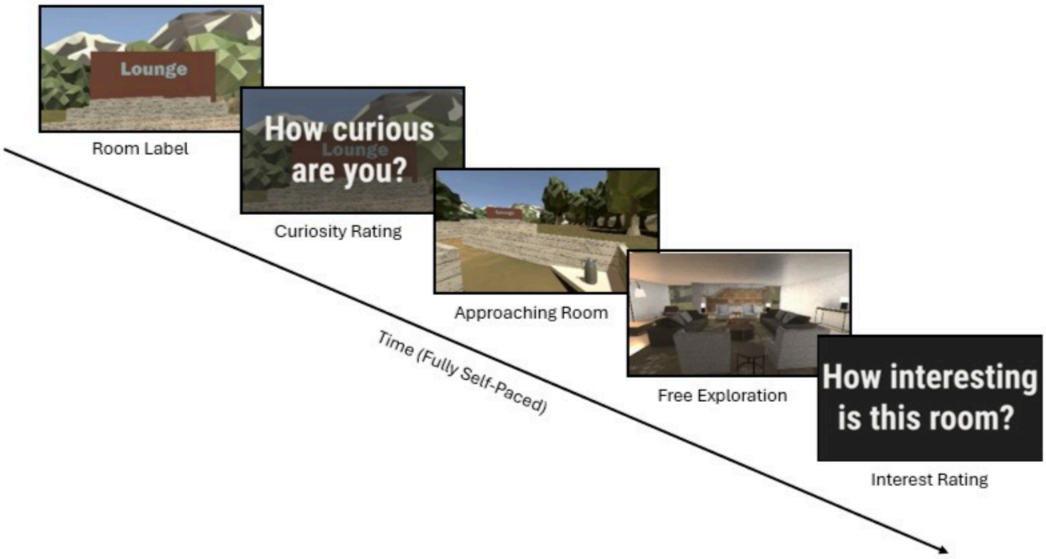

Figure 2. The trial structure for the exploration phase of the virtual exploration paradigm (adapted from Cen et al., 2024). On each trial, participants begin at the starting location at one end of the virtual pier, where they first rate their curiosity along a 10-point Likert-type scale based on a room label. Participants then proceed along the pier and enter the room itself, which they can freely explore. Once participants choose to leave the room, they self-report their interest in it along a 10-point Likert-type scale.

Once the full Exploration Phase is complete, participants will take a 5-minute break (during which they will be asked to complete a series of math problems as a distractor task) before starting the final phase: the Memory Test. On each trial, participants will be provided with a sheet of paper marked with a label that corresponds to one of the rooms that they previously explored (e.g., 'Lounge') and an anonymized participant identifier. Room labels will be presented in a random order. For each label, participants will be asked to sketch the corresponding top-down room layout in as much detail as they can recall. By way of instruction, participants will be provided with sample sketches corresponding to the two rooms that were encountered in the Familiarization Phase (the Bridal Shop and the Cinema). Participants will also be instructed that the artistic quality of their drawings is irrelevant; rather than attempting to accurately draw the objects in each room, they are welcome to draw simple labelled boxes (e.g., 'chair') in the appropriate positions.

Passive Group Procedure

Participants in the Passive Group will undergo the same procedures as above, except that they will be yoked to members of the Active Group.

Functionally, this manipulation entails two procedural changes. First, Passive Group participants will encounter the virtual rooms in a non-random order; instead, across all phases, they will experience the same room order that was previously experienced by their yoked Active Group participant. Second, and critically, Passive Group participants will *not* have the opportunity to actively direct their own exploration through the virtual rooms. On each trial, Passive Group participants will still self-report their curiosity based on a given room label (e.g., 'Lounge'), navigate freely down the pier toward the room, and press the 'E' key on their keyboard when they reach the room entrance. However, once this key is pressed, Passive Group participants will watch a screen-captured video of the yoked Active Group participant's prior exploration through the relevant room. Once the video concludes, Passive Group participants will self-report their interest before progressing to the next trial.

Analysis Plan

Measures

Our analyses will depend on the following measures. Where applicable, the sections below detail any pre-processing steps involved in obtaining a particular measure.

1) Pre-room curiosity ('Curiosity', self-reported along a 10-point Likert-type scale; see Method). Responses along Likert-type scales can be influenced by individual differences in response styles (Kreitchmann, Abad, Ponsoda, Nieto, & Morillo, 2019) as well as cultural biases (Lee, Jones, Mineyama, & Zhang, 2002). In effort to minimize such influences, this measure will be centred around each individual participant's mean curiosity score. We will treat curiosity as a continuous predictor; in Cen et al. (2024), we had originally wondered whether it might be preferable to treat it as ordinal, but found that doing so increased computation times without meaningfully influencing the results.

2) Post-room interest ('Interest', self-reported along a 10-point Likert-type scale; see Method). As above, this measure will be centred around each individual participant's mean interest score. Note that interest is not central to our hypotheses; however, we have included this measure so that we can fully replicate the analyses conducted by Cen et al. (2024).

3) Roaming Entropy (RE). As in Cen et al. (2024), we will quantify two types of RE: *Path RE*, which reflects spatial exploration through the location data from participants' on-screen avatars, and *Head-Direction RE*, which reflects visual exploration through participants' mouse-guided adjustments to their onscreen viewing angle (i.e., the movement of their virtual avatar's 'head'). As above, note that Head-Direction RE is not central to our hypotheses; however, we have included this measure so that we can fully replicate the analyses conducted by Cen et al. (2024).

   To calculate Path RE, we will down-sample the area of each room into a 32x32 grid, then label each cell according to whether it is accessible in virtual space (i.e., not blocked by furniture). Participants' exploration trajectories will be projected onto this grid, and Path RE will be calculated as the entropy of the probability distribution of the participant (*i*) visiting a given grid cell (*j*) at a given time (*t*), as below (where *k* is the number of accessible grid cells in a given virtual room):

$$PathRE_{i,t} = -\sum_{j=1}^{k} \frac{p_{i,j,t} \log_2 p_{i,j,t}}{\log_2(k)}.$$

   To calculate Head-Direction RE, we will project the participant's mouse-guided viewing angle (their avatar's 'head' direction) onto an 18 x 36 grid spanning -180° to 180° horizontally and 0° to 90° vertically. Head-Direction RE will then be calculated as the entropy of the probability distribution of the participant (*i*) facing a given cell (*j*) at a given time (*t*), as below (where $k = 648$, the number of head-direction grid cells).

$$Head-directionRE_{i,t} = -\sum_{j=1}^{k} \frac{p_{i,j,t} \log_2 p_{i,j,t}}{\log_2(k)}.$$

4) Room drawing memory test performance. As in Cen et al. (2024), two independent raters will score participants' room drawings along four key dimensions. Each dimension will be measured along a 1 (Poor) to 5 (Excellent) scale with 0.5 step increments. Overall memory test performance will be calculated according to the sum total of all four dimensions. The dimensions themselves are as follows:

Object Presence: Scores along this dimension are determined according to the presence and accuracy of key objects recalled from the virtual room. Scoring depends on the inclusion of major, layout-defining objects (e.g., furniture, windows, staircases) rather than smaller decorative items (e.g., dishware, books). A score of 1 indicates the inclusion of few or no major objects, while a score of 5 indicates the inclusion of (nearly) all major objects.

Spatial Distortion and Rotation of Features: Scores along this dimension are determined according to the size, shape, and rotation of individual objects. A score of 1 indicates a high degree of misalignment and/or size distortion relative to the virtual room, while a score of 5 indicates good alignment with little or no distortion.

Relative Positioning: This dimension indexes whether objects are accurately placed relative to one another. A score of 1 indicates that no objects are correctly positioned (i.e., that positioning is random), while a score of 5 indicates that (nearly) all objects are correctly positioned.

Spatial Proportions: This dimension indexes whether objects are accurately distanced from one another. A score of 1 indicates strong distance distortion (e.g., extreme degrees of compression and/or expansion of the space between objects), while a score of 5 indicates highly accurate distance representation.

Importantly, these dimensions do not incorporate any judgements of artistic ability [indeed, participants are encouraged to draw simple boxes with the appropriate labels (e.g., ‘chair’) rather than needing to draw the objects themselves]. However, because all four measurements are subjective, we also plan to assess a more objective measurement of participants’ room drawings: their hit rates. For each drawing, hit rate will be calculated as the number of objects correctly included in the drawing, divided by the number of objects that were actually present in the room [# correctly included objects / (# correctly included objects + # objects missed)]. Note that hit rate was not calculated in Cen et al. (2024), and is not central to our research questions; however, for posterity, we plan compare the results of our critical memory test analysis (see below) with the results of an otherwise identical analysis that uses hit rate (rather than summed performance across the above four dimensions) as the dependent measure. If the results of these analyses do not meaningfully differ, then we will conclude that rater subjectivity is unlikely to have biased our results.

The two raters will meet regularly to calibrate their scoring and to discuss and resolve any discrepancies. All coding will be done via the bespoke coding system developed by Cen et al. (2024), which is accessible via map-scoring.vercel.app. This system is advantageous because it allows raters to organize their own scoring records, and because it allows immediate access to all scoring information.

Statistical Analyses

All statistical analyses will be conducted in R (Version 4.2.2; R Core Team, 2023), with Bayesian multi-level models fit via the *brms* package (Bürkner, 2017, 2018). For each individual model (see below), we will use Bayesian estimation methods for parameter inference, with multiple chains (N = 4) and iterations (N = 4800) to promote convergence. Results will be interpreted according to the Bayes Factors (BFs) calculated from marginal likelihoods in accordance with our prespecified criteria for compelling evidence for or against a given effect (BF > 10 or BF < .10, respectively; see Method). To ensure robustness, we will conduct the same posterior predictive checks and sensitivity analyses as in Cen et al. (2024), including comparing model predictions to observed data as well as assessing the influence of alternate priors and model specifications. Across models, and because our predictions surrounding the magnitude and direction of critical effects are nonspecific, we will employ conservative priors centred on 0 for all main effects and interactions.

Across models, the random effects for individual participants will be nested within yoked participant pairs (1|Participant/Yoked_Pair). Participants will only be excluded from our analyses if they did not complete the full experimental procedure (in which case an additional participant will be run in their stead).

Our critical analysis concerns the influence of curiosity within the Passive Group, relative to the influence of curiosity within the Active Group; that is, our primary theoretical interest is in the potential two-way interaction between experimental condition (Active vs. Passive) and pre-room curiosity as predictors of memory test performance (note that our stopping criteria also depend on this interaction; see Method). However, in order to properly interpret such an interaction, we will also (1) determine whether the effects of curiosity observed in Cen et al. (2024) replicate within the Active Group participants, and (2) control for other variables that could potentially influence memory test performance (such as post-room interest; Cen et al., 2024).

In Cen et al. (2024), we found that higher pre-room curiosity was predictive of higher Path RE. In turn, both pre-room curiosity and Path RE were predictive of memory test performance. Before assessing whether these effects differ as a function of experimental condition, we will first ask whether they replicate within the Active Group. To do so, we will evaluate two statistical models, as detailed below:

1) *How does curiosity shape exploration among the Active Group?* Here, we expect to replicate our previous finding (Cen et al., 2024) that higher pre-room curiosity predicts greater Path RE within the Active Group (note that the Passive Group will not be included in this analysis because the RE that they experience depends on the Active Group participants to whom they are yoked). To assess this question, we will fit a Bayesian bivariate multilevel model with Path RE and Head-Direction RE as the two outcome measures. Pre-room curiosity and post-room interest will be entered as predictors, and duration spent exploring each room will be controlled as a potential confound. Our main theoretical interest is whether pre-room curiosity is predictive of Path RE [though other effects will also be reported in effort to replicate Cen et al. (2024)].

2) *Does curiosity directly benefit memory?* In Cen et al. (2024), curiosity and Path RE were positive predictors of spatial memory. Here, we aim to replicate these findings, as well as to determine whether active exploration predicts better cognitive map formation relative to passive exploration.

   Additionally, and critically, we will ask whether these relationships are moderated by experimental condition (Active vs. Passive Group). To assess this question, we will fit a Bayesian multilevel model with memory test performance as the outcome measure[2]. Experimental condition (Active vs. Passive Group, dummy-coded such that the Active Group serves as the reference point), curiosity ratings, interest ratings, Path RE, and Head-Direction RE will all be entered as predictors, alongside all two-way interaction terms involving experimental condition, a two-way interaction term involving curiosity and Path RE, and a three-way interaction term involving experimental condition, curiosity, and Path RE. Duration spent exploring each room will be controlled as a potential confound.

If (1) we obtain a significant main effect of pre-room curiosity [meaning that, among participants in the (dummy coded) Active Group, higher curiosity predicts better memory], and (2) we do *not* obtain any significant higher order interactions involving experimental condition, then we will conclude that the effect of pre-room curiosity does not meaningfully differ across experimental conditions: in other words, curiosity directly benefits memory even without the ability to actively engage in curiosity-guided exploration.

Alternatively, if (1) any significant main effect of pre-room curiosity is qualified by a higher order term involving experimental condition, and (2) the nature of the interaction is such that pre-room curiosity has no effect (or a significantly weaker effect) within the Passive Group, relative to the Active Group, then we will conclude that the benefits of curiosity are (at least partially) dependent on the ability to actively engage in curiosity-guided exploration.

[2] As described above (see Measures), we will also compare the results of this model to an otherwise-identical model that uses hit rate (rather than subjectively-scored memory test performance) as the outcome measure. Although not central to our research question, comparison across these two models will help us ensure that rater subjectivity has not biased our results.

Study Design Template

Question	Hypothesis	Sampling plan	Analysis Plan	Rationale for deciding the sensitivity of the test for confirming or disconfirming the hypothesis	Interpretation given different outcomes	Theory that could be shown wrong by the outcomes
Preliminary Research Question 1 (PRQ1): Does curiosity predict higher Path RE?	Among the Active Group, we expect to replicate Cen et al.'s (2024) finding that higher state curiosity predicts greater Path RE (i.e., greater variability in spatial locations explored)	Our sample size will be determined according to a modified Sequential Bayes Factor design ("Sequential Bayes Factor with maximal n"; Schönbrodt & Wagenmakers, 2018). We will recruit to a maximum of 120 participants ($N = 60$ in each of the Active and Passive Groups), *or* until our prespecified stopping criteria are reached. We will begin analysing our data at $N = 30$, and will reanalyse the data after every 6 additional participants, *unless* the Bayes Factor corresponding to the two-way interaction between experimental condition and curiosity is > 10 or < .10. At that point, the Bayes Factors for all effects of interest will be	As in Cen et al. (2024), we will fit a Bayesian bivariate multilevel model with Path RE and Head-Direction RE as the two outcome measures. Random effects for individual participants will be nested within yoked pairs. Curiosity ratings and interest ratings will be entered as predictors, and duration spent exploring each room will be controlled. Note that, while we are attempting to replicate Cen et al.'s findings in full, only the effect of curiosity on Path RE is critical for our research question (all other effects will still be reported in the interest of determining their replicability)	Bayes Factors (calculated from maximal likelihoods) > 10 will be considered compelling evidence for a meaningful effect, while Bayes Factors < .10 will be considered compelling evidence for the absence of an effect. Bayes Factors not meeting these criteria will still be interpreted; however, our Stage 2 submission will specify that they did not meet our prespecified evidentiary thresholds. .	If we do not replicate the effect of curiosity on Path RE, we will consider (1) the possibility that curiosity does not reliably induce exploration (it could plausibly interact with other factors, such as spatial anxiety, that might prove promising for future research), as well as (2) the possibility that the virtual exploration paradigm may not reliably induce curiosity in laboratory settings.	Among both humans and nonhuman animals, spatial exploration has long been assumed to reflect curiosity (Berlyne, 1966; O'Keefe & Nadel, 1978; Tolman, 1948); however, very few studies have directly investigated this claim. If we find evidence for the null, then these findings would suggest that existing theories surrounding how curiosity influences exploration may need further refinement: for example, curiosity might interact with other motivational factors and/or with task characteristics in order to determine exploration patterns.

		interpreted and data collection will conclude.				
Preliminary Research Question 2 (PRQ2): Do curiosity and Path RE predict better memory among the Active Group?	Among the Active Group, we expect to replicate Cen et al.'s (2024) finding that higher state curiosity and higher Path RE each predict better memory test performance.	See above	We will fit a Bayesian multilevel model with memory test performance as the outcome measure. Experimental condition, curiosity ratings, interest ratings, Path RE, and Head-Direction RE will all be entered as predictors (alongside all two-way interaction terms involving experimental condition, the two-way interaction term involving Path RE and curiosity, and the three-way interaction term involving curiosity, Path RE, and experimental condition). Duration spent exploring each room will be controlled. Note that we have included Head-Direction RE and interest ratings as predictors for the sake of fully replicating Cen et al. (2024); however, these measures are not central to our research question. Their effects will still be reported for the sake of determining replicability. In evaluating PRQ2, we will	See above	If we do not replicate Cen et al. (2024), then we will consider the possibility that curiosity and/or Path RE might not reliably predict memory for explored environments. Their effects on memory could also plausibly be moderated by other factors, such as spatial anxiety, that might prove a promising direction for future research.	Curiosity is often assumed to facilitate exploration, which is in turn assumed to facilitate cognitive map formation (e.g., Tolman, 1948; Wang & Hayden, 2021); however, these assumptions have rarely been empirically tested (c.f., Cen et al., 2024). If we obtain evidence for the null, then our findings would suggest a need to refine existing theories surrounding whether and how curiosity influences cognitive map formation.

			consider the evidence for main effects of curiosity and Path RE (each of which pertain to the Active Group, which will be dummy-coded as the reference point).			
Preliminary Research Question 3 (PRQ3): Does active exploration predict better memory than passive exploration?	Based on prior research surrounding the benefits of active learning (e.g., Craddock, Martinovic, & Lawson, 2011; Wang & Simons, 1999), we expect that the Active Group will display better memory test performance than the Passive Group.	See above	See above. In evaluating PRQ3, we will consider the evidence for a main effect of experimental condition (as qualified by any higher order interaction terms involving experimental condition, if strong evidence for such interactions is obtained).	See above	If we do not observe a main effect of experimental condition, we will consider the possibility that the benefits of active exploration may be moderated by motivational factors such as curiosity (e.g., Passive Group participants may benefit from their own curiosity, and/or may use their curiosity to engage in subtler forms of exploration – such as eye movements – that nonetheless benefit memory).	Although active exploration often benefits memory over and above passive exploration (e.g., Craddock, Martinovic, & Lawson, 2011; Wang & Simons, 1999), these effects are inconsistent (Gaunet, Vidal, Kemeny, & Berthoz, 2001; Wilson, & Péruch, 2002). If we do not observe a benefit of active exploration, we will ask whether our data support that motivational states (specifically, curiosity) might moderate the relationship between active exploration and memory, thus leading to theoretical refinement.
Critical Research Question: Does the effect of curiosity differ as a function of condition (Active vs. Passive Group)?	We do not have specific predictions concerning the magnitude or direction of the potential interaction between experimental condition and curiosity.	See above	See above. In evaluating our critical research question, we will consider the evidence for a two-way interaction between experimental condition and	See above.	Compelling evidence for the *absence* of an interaction between experimental condition and curiosity would suggest that curiosity directly promotes memory.	At present, we are not aware of any prior work asking whether the benefits of curiosity depend on the ability to actively engage in curiosity-driven exploration; as such, our data (specifically involving the Passive Group)

			curiosity (as qualified by any higher order interaction terms involving experimental condition and curiosity, if strong evidence for such interactions is obtained.)		Compelling evidence for the *presence* of an interaction between experimental condition and curiosity (such that the benefit of curiosity is stronger in the Active Group relative to the Passive Group) would suggest that the benefits of curiosity are at least partially dependent on the ability to actively engage in curiosity-guided exploration.	will aid in refining existing theories surrounding the conditions under which curiosity benefits memory.

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