# Supplemental Methods and Results

## 1 Item and Source Memory

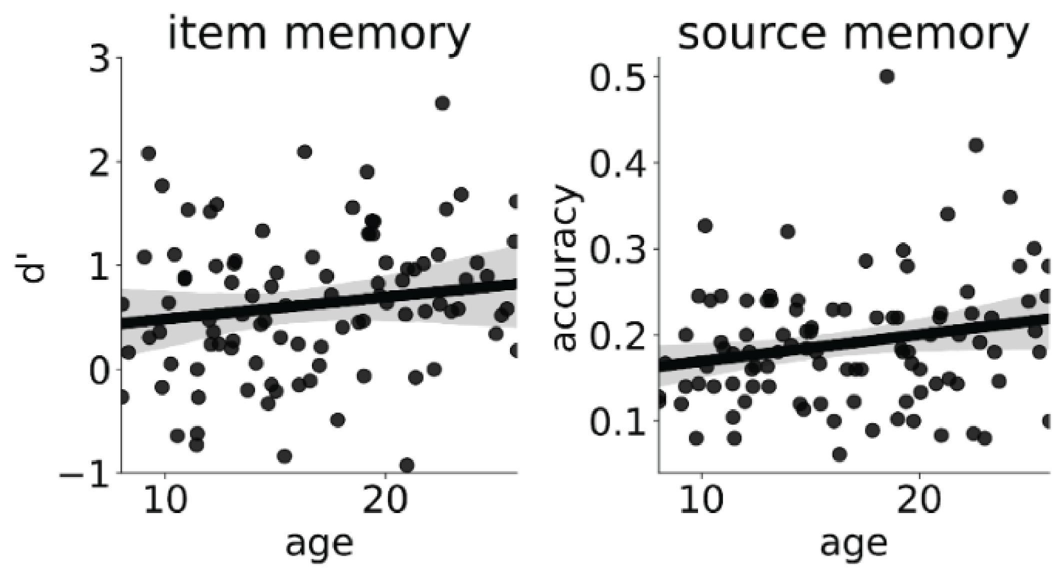


Figure S1: **Item and source memory do not improve with age. A. Item memory.** Recognition memory of probe objects, as measured by d', did not change with age ($\rho(104)$ =0.079 , p=.42). **B. Source memory.** Similarly, accuracy on source memory trials also did not increase with age ($\rho(104)$ =0.14, p=.15).

## 2 Mnemonic Similarity Task

### 2.1 Task

The task was split into an incidental encoding and test phase and was performed in a separate session from the memory and decision-making task (Figure 2A). During the encoding phase, participants performed a cover task in which they were shown an object and while it remained on screen, were asked to identify it as belonging indoors by pressing the 'v' or outdoors by pressing the 'n' on their keyboard. 64 objects were presented sequentially in a randomized order for 2 seconds each followed by a 500 ms inter-stimulus interval.

During the test phase, participants were informed that they would be shown some objects they had previously seen and some objects that were novel. When an object was displayed, they had 3 seconds to decide if the object was identical to one from the encoding phase ('old'), similar to one they had seen before ('similar'), or a novel object dissimilar to any objects encountered during the encoding phase ('new'). 32 old objects, 32 similar lures, and 32 new foils were presented in a randomized order and each choice was followed by a 500 ms inter-stimulus interval. Participants responded using their keyboard, pressing 'v' for old, 'b' for similar, and 'n' for new. We selected images from the Stark lab database (https://github.com/celstark/MST/tree/master/Set%206) based on our subjective assessment of children's familiarity with the objects. Lure images belonged to five bins of varying similarity as rated by a separate group of adult participants.

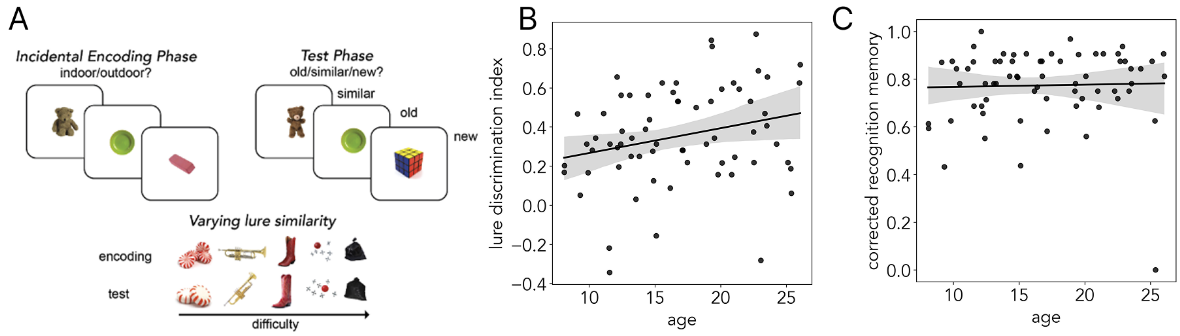


Figure S2: **Mnemonic Similarity Task. A. Task.** Participants completed two phases: an incidental encoding phase and a test (retrieval) phase. During the incidental encoding phase, participants perform a cover task in which they are sequentially shown 64 object images and are asked to indicate whether the object belongs indoors or outdoors. During the test phase, participants were presented sequentially with 96 object images and asked to respond whether they saw an object in the previous phase ("old"), saw a similar but not identical object ("similar"), or the object was completely novel ("new"). 32 test objects were target images (identical to an image shown during the encoding phase), 32 were lures (highly similar to objects shown during the encoding phase), and 32 were foils (images that were dissimilar to any encoding phase objects). Lure objects varied in similarity, falling into 5 bins of discrimination difficulty. **B-C.** Results. Lure discrimination significantly improved with age ($\rho(65) = 0.25$, p=.04) while corrected recognition memory did not ($\rho(65) = 0.13$, p=.29). Markers indicate individual estimates of lure discrimination index/corrected recognition memory plotted against age. Shaded regions indicate 95% confidence intervals.

### 2.2 Analysis

We used the lure discrimination index (LDI) as a measure of an individual's pattern separation abilities or memory precision. It was computed as the difference between the rate of "similar" responses given for lure items and "similar" responses given to foils. We also computed a general recognition memory score (REC). This was taken as the difference between the rate of "old" responses given for repeat items and "old" responses given to foils.

### 2.3 Results

We tested for age-related changes in memory precision as measured by the lure discrimination index (LDI). More specifically, LDI indexes an individual's ability to recognize an item as distinct from a highly similar, previously encountered item. LDI scores can range from -1 to 1 with positive values indicating successful discrimination, negative values indicating a response bias towards reporting that items are "similar", and 0 indicating chance performance. Participants across our age range demonstrated well-above-chance discrimination (mean LDI=0.35, SD=0.25, one sample t-test against 0 (t(66)=11.52, p¡.001). However, older participants tended to have higher LDI scores (Figure 2B; $\rho(65) = 0.25$, $p$ =.04). As a baseline memory measurement, we also calculated participants' recognition memory (REC) scores for only the dissimilar items, with a range of -1 to 1 and positive values indicating better performance. Participants again performed well above chance (mean REC=0.77, SD=0.15; $t$(66)=40.75, $p$ <.001), however, REC scores did not significantly increase with age (Figure 2C; $\rho(65) = 0.13$, $p$ =.29).

## 3 The Two Step Task

### 3.1 Task

In a separate session, participants completed a version of the original task (Daw et al. 2011) adapted for developmental populations (Decker et al. 2016), specifically for online data collection (Nussenbaum et al. 2020).

Participants were tasked with collecting as much space treasure as possible from aliens residing on different planets (Figure S3B). Each trial consisted of two decision stages. At the first stage, participants chose between two spaceships that would probabilistically transition to a red or purple planet. Each spaceship had a planet it would more commonly transition to (70% versus 30% of the time). Participants were informed that some transitions between spaceships and planets would be more frequent, but they were not informed of the exact transition structure, requiring them to learn this through experience. Once on a planet, they would then select one of two aliens to ask

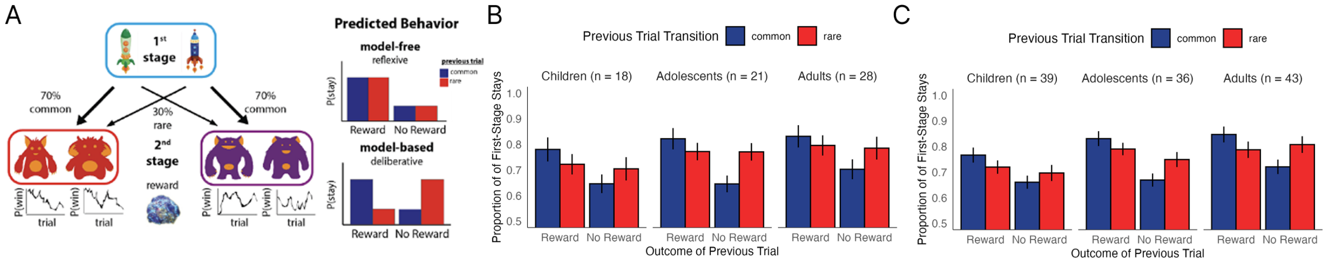


Figure S3: **Two step Task. A. Task.** Participants completed 200 trials. On each trial, they made two choices. At the first stage, they chose between two spaceships that would travel to one of two planets with differing frequency. On a planet at the second stage, they would then choose between two aliens, each with a unique drifting probability of reward. This task allows for the dissociation between model-free and model-based behavior. A model-free learner would be more likely to repeat their first stage action from the last trial if it led to reward, regardless of the transition structure. **B-C.** Results. Proportion of first-stage choice repetitions ("stays") as a function of the previous trial's outcome and transition type, shown separately for each age group. Children were younger than 13 years; adolescents were 13–18 years. In the subset of 67 participants, the reward × transition × age interaction was not significant ($b_{reward\,X\,transition\,X\,age}$=-0.30, SE=0.23, $p$ =.19), but the interaction emerged as significant in the full sample of 118 participants ($b_{reward\,X\,transition\,X\,age}$-0.34, SE=0.17, $p$ =.045).

for treasure (the second-stage decision). Aliens provided treasure with some probability that slowly changed over time. Participants completed 200 of these trials.

### 3.2 Analysis

Using a previously described analytical approach (Nussenbaum et al. 2020), we examined participants' use of model-free and model-based strategies by running a mixed effects logistic regression predicting choice from the transition type (common vs. rare) and reward received on the previous trial. If using a model-free strategy, a participant should be insensitive to the previous trial's transition type. On the next trial, they should be more likely to repeat their previous first-stage choice if it led to reward and switch to the other option if it did not. In contrast, a participant using a model-based strategy would be sensitive to transition type. They should be more likely to repeat their first-stage choice under two scenarios — if it was common transition trial and they received a reward or it was a rare transition and they did not receive reward. If the opposite of either scenario occurred, then they should be more likely to switch their choice. Thus, we used the random slopes of the reward x transition type interaction effect as a measure of individuals' model-based strategy use.

### 3.3 Results

We aimed to replicate findings from prior work demonstrating age-related changes in model-based strategy use (Decker et al. 2016; Nussenbaum et al. 2020). Across our sample, we observed both a main effect of reward and an interaction effect between reward and transition type, suggesting that participants used both model-free and model-based strategies throughout the task ($b_{reward}$=1.45, SE=0.17, $p$ <.001; $b_{reward\,X\,transition}$=-1.52, SE=0.24, $p$ <.001). Older participants were not significantly more likely to repeat their first stage choices regardless of the previous outcome ($b_{age}$=0.19, SE=0.12, $p$ =.11). Importantly, we did not find an age by reward interaction effect ($b_{age\,X\,reward}$=0.27, SE=0.17, $p$ =0.11), suggesting that model-free learning did not vary with age. Finally, and of primary interest, we tested whether model-based strategy use changed with age. Contrary to previous findings, we did not observe significant age-related change, (Figure S3B; $b_{reward\,X\,transition\,X\,age}$=-0.30, SE=0.23, $p$ =.19). This divergent finding may potentially be a consequence of our exclusion criteria in the memory and decision-making task, which places high demands on attention, learning, and memory. Excluding participants based on these criteria may have left only particularly high-performing younger participants that exhibited higher levels of model-based strategy use. Consistent with this, when we include all participants (N=118), we do find a significant reward by transition by age interaction (Figure S3C; $b_{reward\,X\,transition\,X\,age}$=-0.34, SE=0.17, $p$ =.045). Many of the other effects remain the same ($b_{reward}$=1.25, SE=0.12, $p$ <.001; $b_{age}$=0.15, SE=0.088, $p$ =.096; $b_{reward\,X\,transition}$=-1.27, SE=0.17, $p$ <.001), however, we do find age-related changes in model-free learning ($b_{age\,X\,reward}$=0.24, SE=0.11, $p$ =0.037).

# 4 Relationships between memory-guided decision making, memory precision, and forward planning

For the regressions reported in this section, we extracted the random slopes from the logistic regression model described in the main text, but first, we re-estimated the model with age and its interactions excluded. We omitted age from this model so that we could examine how age interacted with our predictors of interest (e.g., the influence of the probed trial's reward).

**Tables 1-3**

Results from separate linear regressions predicting individuals' random slopes for (S1) the "average reward across the probed context", (S2) "reward on probed trial", and (S3) "choice on probed trial". Each regression included an intercept term and a fixed effect of lure discrimination index.

| term | estimate | SE | p-value |
|---|---|---|---|
| Intercept | -0.09 | 0.06 | 0.16 |
| LDI | 0.30 | 0.14 | 0.04 |

Table 1: Predicting the influence of probed context

| term | estimate | SE | p-value |
|---|---|---|---|
| Intercept | -0.01 | 0.03 | 0.70 |
| LDI | 0.05 | 0.06 | 0.45 |

Table 2: Predicting the influence of reward on probed trial

| term | estimate | SE | p-value |
|---|---|---|---|
| Intercept | 0.08 | 0.06 | 0.18 |
| LDI | -0.23 | 0.14 | 0.10 |

Table 3: Predicting the influence of choice on probed trial

**Tables 4-6**

Results from separate linear regressions predicting individuals' extent of forward planning. Each regression included an intercept term,fixed effects of age and one of the random slopes from Table S1-3 (S4: probed context, S5: probed trial reward, S6: probed trial choice), as well as an interaction term.

| term | estimate | SE | p-value |
|---|---|---|---|
| Intercept | 0.31 | 0.04 | 0.00 |
| probed context | 0.19 | 0.13 | 0.14 |
| age | 0.06 | 0.04 | 0.12 |
| probed context*age | 0.14 | 0.15 | 0.36 |

Table 4: Predicting the extent of forward planning

| term | estimate | SE | p-value |
|---|---|---|---|
| Intercept | 0.31 | 0.04 | 0.00 |
| probed trial reward | 0.59 | 0.31 | 0.07 |
| age | 0.05 | 0.04 | 0.20 |
| probed trial reward*age | 0.81 | 0.38 | 0.04 |

Table 5: Predicting the extent of forward planning

| term | estimate | SE | p-value |
| --- | --- | --- | --- |
| Intercept | 0.32 | 0.04 | 0.00 |
| probed trial choice | 0.03 | 0.14 | 0.85 |
| age | 0.05 | 0.04 | 0.20 |
| probed trial choice*age | 0.26 | 0.14 | 0.06 |

Table 6: Predicting the extent of forward planning