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Prior Spatial Knowledge Differentially Impacts Learning in Children and Young Adults

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Abstract

Previous work suggests that established memories can both facilitate and interfere with new learning in adults. We predicted that children may not show these same effects of prior knowledge, as there is emerging evidence that they are less likely to relate new experiences to existing memories. To test this hypothesis, we had children (4-11 years) and young adults (17-33 years) complete a spatial learning task inspired by rodent model paradigms. Subjects first formed strong memories for object-location maps and then learned new locations, some of which could be incorporated into a learned map. We found that same-day prior spatial knowledge had a different impact on learning in children and adults: Adults demonstrated marginal proactive interference while children showed slight proactive facilitation, if anything. Our results suggest there are developmental differences in the effects of prior knowledge on learning, perhaps due to immature associative memory formation and/or activation mechanisms in children.

Keywords: Spatial learning; Proactive interference; Proactive facilitation; Development

Introduction

When we learn something new, past related experiences may either help ground that new knowledge or compete with it. These opposing phenomena can be referred to as proactive facilitation and interference, respectively. The impact of prior knowledge on learning has been broadly demonstrated in a variety of tasks in humans (Anderson, 1981; Ghosh & Gilboa, 2014; van Kesteren et al., 2012), as well as using spatial learning paradigms in rodents (Tse et al., 2007; Tse et al., 2011). In these rodent studies, animals are given extensive multi-day training with a map of flavour-location pairs, such that they form a “schema”, or well-established spatial map. In addition to illuminating neural mechanisms with precision, these studies have shown that rodents can rapidly learn novel flavour-location pairs when they are incorporated into an established spatial map (Tse et al., 2007; Tse et al., 2011). More recent studies using similar spatial learning tasks with adult humans have reported parallel findings (Guo & Yang, 2020; He et al., 2021; Sommer, 2017; van Buuren et al., 2014). These results suggest that knowledge of a spatial context, such as the relative locations of various landmarks, helps learners anchor new locations in memory.

Though prior knowledge can facilitate learning, it can also hinder learning in what is called proactive interference. There

are many factors that may result in proactive interference (Kliegl & Bauml, 2021) instead of facilitation, including the degree of conflict or overlap between previous and new information (Chanales et al., 2017; Craig et al., 2013; He et al., 2021). For instance, He et al. (2021) found that learning new spatial navigation routes was facilitated when these routes were within a familiar spatial context – perhaps because they could be incorporated into an existing map – but impeded when they overlapped with previously learned paths. Additional factors that could prompt interference include the temporal proximity of initial and new learning (Kincaid & Wickens, 1970), strength of initial learning (Hayes-Roth, 1977), and lack of testing on initial learning before new learning begins (Wahlheim, 2015).

Though eliciting opposite behavioural effects, proactive facilitation and interference may both be the result of retrieving related memories during new learning. Kuhl et al. (2011) found that reactivation of competing memory traces at retrieval was associated with interference in memory performance. In contrast, reactivation of related memories can benefit learning when new information is then integrated into established knowledge (van Kesteren et al., 2012). Thus, recalling previously learned landmarks during new spatial learning may be one mechanism by which established knowledge can alternately facilitate (via integration) or interfere with (via competition) learning. In the brain, these behavioural phenomena may depend on connections between the hippocampus and various cortical regions. Specifically, hippocampal connections to the posterior cortex for initial reinstatement of related memory contents (Kuhl, Bainbridge, & Chun, 2012; Kuhl & Chun, 2014), and the hippocampal-prefrontal (PFC) circuit for resolving overlap between current and recalled information (Oren et al., 2017; Schlichting & Preston, 2017; van Kesteren et al., 2012). Indeed, previous work has emphasized the role of hippocampus-PFC connections for enabling integration of new and prior knowledge (Gilboa & Marlatte, 2017; Preston & Eichenbaum, 2013; Sommer, 2017).

Though established in adults, the ability to form and utilize well-learned associative memory networks, or schemas, to scaffold new learning may not be in place earlier in development. The hippocampus and prefrontal regions hypothesized to be critical to schema formation and updating undergo a prolonged development (Calabro et al., 2020; Gogtay et al., 2004; Tang, Shafer, & Ofen, 2018). As such,

children may still be honing the ability to build associative knowledge structures from their experiences. Indeed, Pudhiyidath et al. (2020) found that children and adolescents were not able to learn temporal schemas, i.e., regularities in event sequence, to the same degree as adults. Additionally, research on the development of associative learning suggests that children tend to store memories for related experiences separately, rather than integrate them into a larger structure (Bauer et al., 2020; Shing et al., 2019). For example, Shing et al. (2019) had children and adults learn overlapping associative pairs and then make inferences across indirectly related items. They found that children were much slower at making inferences than adults, suggesting they may not integrate related experiences until directly prompted (Shing et al., 2019). Similarly, Bauer et al. (2020) had children and adults learn a series of overlapping associations and found that when prompted with one item, adults spontaneously looked to its indirectly related item while children did not. These results suggest that adults may store related experiences in a shared memory structure even before it is necessary for the task, while children do not (Bauer et al., 2020). Recent neuroimaging work also suggests that children may store related memories separately in part because, unlike adults, they do not reactivate related memories while learning new associations (Schlichting et al., 2021). Therefore, children may not be impacted by related memories during new learning in the same way as adults.

In the current study, we aimed to address whether children and adults differ in the influence of prior spatial knowledge on new learning. We also aimed to determine whether spatial memories can support new encoding on a more rapid (same-day) timescale than shown with previous spatial learning paradigms, given demonstrations of such rapid integration in associative learning tasks (Zeithamova, Dominick, & Preston, 2012). We first had subjects learn maps of object-location pairs to criterion. The maps then served as prior knowledge when participants learned new locations that either could or could not be integrated into one of the maps. This paradigm was designed to parallel previous tasks used in rodents and adults (Sommer, 2017; Tse et al., 2007), but instead of days of training, subjects learned initial and new associations on the same day. In addition to addressing whether past observations generalize to a shorter timescale, this design allowed us to compare learning between children and adults largely isolated from imbalances in real-world knowledge; all relevant “prior knowledge” was acquired during the experiment and immediately before new learning. We hypothesized that adults would show facilitated learning when new object locations could be incorporated into a recently learned spatial context compared to when they could not. In contrast, we predicted that children would not be impacted by prior task knowledge when learning new information, due to immature associative memory-updating abilities.

Methods

Participants

Participants were 59 young adults (15 male, 43 female, 1 unknown; 17-33 years old, $M_{age}=19.7$ years, $SD_{age}=2.7$) and 51 children (19 male, 32 female; 4-11 years, $M_{age}=7.4$ years, $SD_{age}=1.7$). All were English speakers with no known or suspected history of mental illness, neurological disorder, or learning difference. All were able to meet the learning criterion and complete all experimental phases. Participant data was collected and analyzed as per the preregistration (<https://osf.io/mc6u4>). However, data collection for the child group was halted prior to reaching the planned sample size ($N=150$) due to inability to collect in-person data at our main data collection venue, the local science museum. All subjects provided informed consent/assent prior to participating in the experiment and were compensated. Permission was obtained from the parent or guardian of all child participants. All procedures were approved by the ethics committee at our university.

Stimuli & Procedure

Participants learned arrangements (“layouts”) of object-location pairs through a virtual card game on an iPad/tablet (Fig. 1). First, they learned object locations in two layouts (A and B). Then they learned additional locations in layout A as well as in a novel layout C. Finally, subjects were tested on their memory for initially learned locations. The experiment included animations between layouts to indicate that they existed in different “worlds” of a game.

Stimuli. Stimuli were virtual playing cards distributed face-down across simple colourful backgrounds. Each playing card within a layout had a unique everyday object illustrated on one side. These objects were chosen to be familiar to children (Fig. 1B). To match task difficulty across age groups, children learned up to fourteen object locations per layout while adults learned up to twenty. The three different card layouts that subjects learned throughout the experiment (A, B, and C) took place in different worlds in the game (pink, yellow, blue), where world determined the background colour and the spatial organization of cards. Hereafter, we refer to layouts based on their experimental role. For the initial learning phase, subjects learned a subset of locations in layouts A and B (denoted with a subscripted 1; A_1 , B_1). The remaining locations in these layouts were not visible to participants. In the new learning phase, subjects were presented with the remaining cards in layout A (A_2), while the previously learned locations (A_1) were visible in gray but could not be flipped over. Subjects also learned a matching number of new locations in a novel layout (C_2), which were similarly interspersed with gray cards to parallel the appearance of A_2 . However, the gray cards did not correspond to any prior learning. Thus, locations in A_1 and

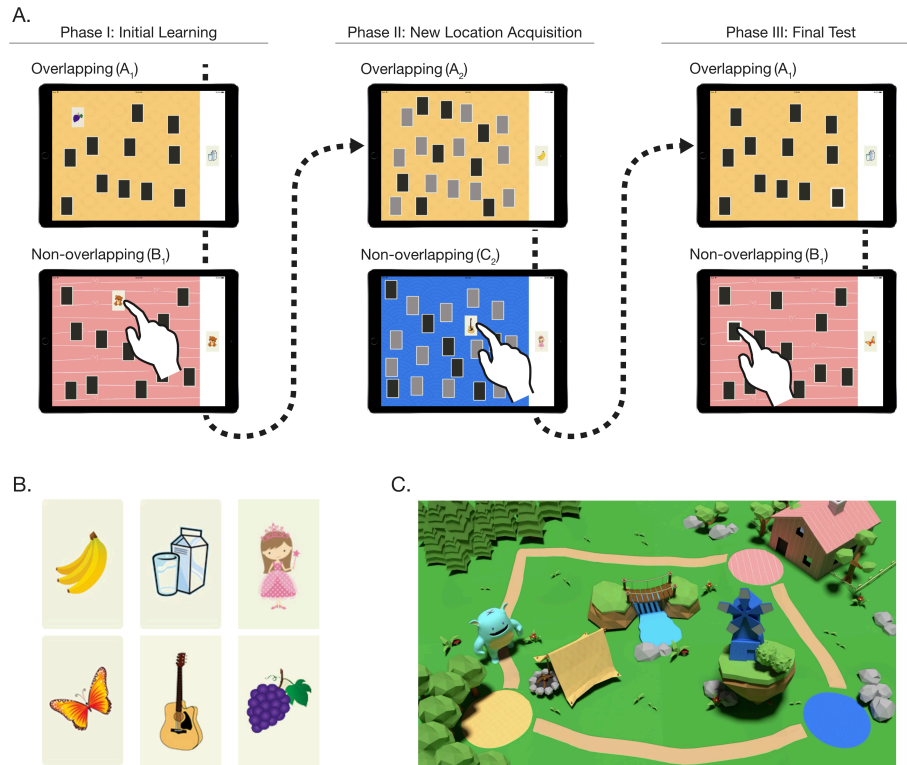


Figure 1: Experimental Procedure. A. Example of an adult subject’s progression (dashed arrow) through learning the layouts. Background colours indicate the “world”. B. Example cards seen in layouts. C. Screenshot of the animation shown between layouts where a blue monster walks to the appropriate world, indicated by the corresponding yellow, blue, or pink landmark.

A₂ existed the same map (“overlapping”), while B₁ and C₂ were unrelated (“non-overlapping”) controls.

Initial Learning Phase. The aim of the initial learning phase was to ensure that subjects had strong memories for the learned object locations (A₁ and B₁). For each layout, learning was done in repetitions. On a single repetition, the subject had to locate every object one by one in random order (12 cards for adults, 8 for children). For each trial, they were prompted to find a particular target object, displayed on the right side of the screen, by tapping cards in the layout to flip them over. Trials were self-paced, so subjects had as much time as they needed to locate the target object among the cards. After they located every object with a single tap for two consecutive repetitions, they moved on to the next layout.

New Learning Phase. The goal of the new learning phase was to assess learning when it could be anchored by existing knowledge compared to when it was completely novel. Subjects learned new object locations in layout A (A₂) as well as a matched number of locations in a novel layout (C₂), in the same manner as the initial learning phase. For this phase, learning was restricted to the new (black) cards in the layouts (8 cards for adults, 6 for children). With this design, participants learned more total locations in layout A across the experiment than either control layout B or C (as in past approaches, e.g., Sommer, 2017; Tse et al., 2011). This was

central to our manipulation because it allowed us to (1) match the number of locations learned across conditions for each phase and (2) avoid potential interference in our control condition by having separate layouts for Phase I and II.

Memory Test. Finally, subjects were tested on their memory for the object locations learned in the initial layouts (A₁ and B₁) in the order the layouts were first learned. The goal of this test was to assess whether overlapping learning for layout A had any retroactive impact on memory for the initially learned locations. For each memory test, the cards were displayed as in the initial learning phase. Subjects were prompted to locate each object in random order by tapping on the correct card. They had as much time as they needed to locate each object but only one try to do so. They received no feedback on their performance (i.e., the cards did not flip over to reveal the selected object).

Counterbalancing. The order in which subjects learned the layouts in each phase (initial: A₁, B₁; new: A₂, C₂) was counterbalanced across subjects. Additionally, the three layouts were assigned to different worlds across participants, e.g., layout A could be set in either the pink, yellow, or blue world. However, due to a technical error, the assignment of worlds to layout A (overlapping condition) was not balanced across participants. To account for potential differences in learning rate across the worlds which may have impacted our

results, we ran analyses that confirmed world identity (yellow, pink, or blue) did not interact with overlapping versus non-overlapping condition to affect the rate of new learning (all $F_{(1,104)} < 2.6$, all $p > 0.08$). Additionally, we reran all the main analyses including a predictor for world identity to confirm that results remained similar when accounting for this factor.

Analyses

To address our question, we compared learning rate for the overlapping and non-overlapping layouts. Learning rate for a layout was computed by fitting performance (defined as the number of cards per trial that a subject touched before locating the goal object) with an exponential function. The number of touches per trial should decrease over learning until there is exactly 1 touch per trial for the last two repetitions, i.e., perfect performance. Before fitting the exponential function, number of touches was converted to proportion of touches (touches divided by number of cards in the layout) to correct for differences in the number of cards across age groups. The following decreasing exponential function was fit for each subject:

$$\frac{\text{touches}}{\# \text{ cards}}(r) = \frac{1}{\# \text{ cards}} + \alpha * e^{-\beta * (r-1)}$$

where proportion of cards touched per trial is modeled as a function of repetition number (r). The beta (β) parameter was allowed to vary during fitting and was used to quantify learning rate for a given layout. A larger beta corresponds to a steeper exponential decrease in proportion of touches, i.e., more rapid learning. Beta parameters were log-transformed for use in analyses because they did not follow a normal distribution. The alpha (α) parameter was also allowed to vary during fitting and reflects the starting point of the learning curve when added to the minimum possible proportion of touches. In contrast to beta, the alpha parameter was fit at the learning phase level for each subject, rather than for each layout within a phase. This was done so that alpha was the same for both the overlapping and non-overlapping layout in a phase to ensure the only differences in the learning curves between conditions were the beta values. Figure 2 depicts an example subject's trial-by-trial performance in the new learning phase as well as the results of fitting an exponential function to their performance on each layout.

After calculating learning rates for each participant on each layout, we ran a linear mixed model in R (*lme4::lmer* package; Bates et al., 2015) to test whether learning rates differed between layouts and age groups. We ran parallel analyses for the initial and new learning phases. For each phase, we ran a statistical model that predicted learning rate as a function of layout condition (overlapping or non-overlapping), age group (child or adult), and their interaction, with subject-specific intercepts (i.e., learning rate ~ condition * age group + (1|subject); separately for Phase I and II). A two-way ANOVA was used to test the significance of predictors in each model.

Age Differences Among Children. We ran a model with age as a continuous predictor to test for differences among the children. However, the variability among our child sample was low with 33/51 participants within a 3-year age range (6-8 years old). We therefore also interrogated whether there were differences across younger and older children in the sample using a median split approach. Children were split into those 7 years or younger ($N=26$; $M_{age}=6.0$ years, $SD=0.9$) and those older than 7 years ($N=25$; $M_{age}=8.8$ years, $SD=1.0$).

Differences in Memory. To test whether there were differences in memory for the initial layouts, we ran linear mixed models for the final memory test. In separate linear models, trial-wise accuracy and log-transformed reaction time (correct trials only) on the memory tests were predicted as a function of initial layout condition (overlapping or non-overlapping), age group (child or adult), and their interaction. Participant was included as a random effect.

Results

No Differences in Initial Learning Across Layouts

We first ensured there were no differences in initial learning across the conditions, as overlapping information had yet to be introduced. Consistent with these expectations, age group (child or adult), layout (A_1 or B_1), and the interaction between group and layout did not significantly affect initial learning rate (all $F_{(1,108)} < 0.7$, $p > 0.4$). These results also suggest that child and adult learning rates were successfully equated by having children learn fewer cards. In addition to effects of layout condition, we found there were no differences in

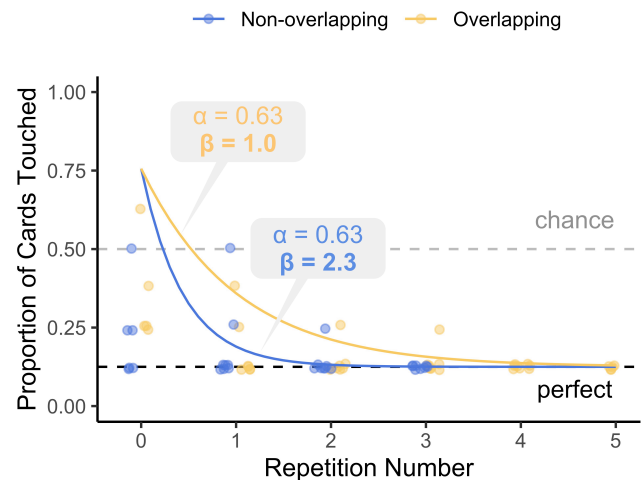


Figure 2: Example learning curves in new learning phase. Trial-wise performance from one adult displayed behind fitted exponential functions. Annotated with learning rates (β) and starting values (α) for each curve. Black dashed line indicates perfect performance, gray dashed line indicates chance.

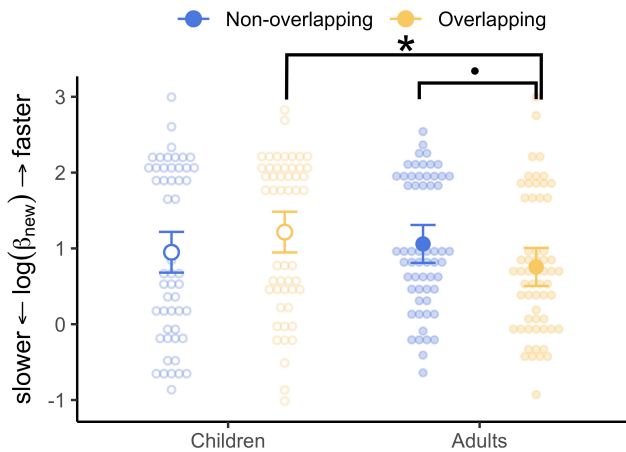


Figure 3: Child and adult log-transformed learning rates (β) in new learning phase according to layout condition.

Interaction effect: $F_{(1,108)}=5.38, p=0.02$.

• $p<0.1$; * $p<0.05$

learning rate according to whether the layout was learned first or second, in either age group (all $F_{(1,108)}<1.2, p>0.2$), suggesting no significant impact of task experience on performance.

Impact of Prior Knowledge on New Learning Differs Between Children and Adults

We primarily aimed to investigate how pre-existing spatial knowledge impacted new learning, and whether this effect was different in children and adults. Consistent with our expectation of developmental differences, we found a significant interaction between layout condition and age group on new learning rate (condition \times age group: $F_{(1,108)}=5.38, p=0.02$; no main effects, all $F_{(1,108)}<1.6, p>0.2$; see Fig. 3). However, this difference was in the opposite direction of our predictions. We expected that adults would benefit from overlap with prior knowledge, but instead we found that they showed a statistical trend consistent with proactive interference. Specifically, adults had marginally *slower* learning on the overlapping than non-overlapping layout (two-tailed $p=0.07$), while for children the difference was numerically (not significantly; $p=0.14$) in the opposite direction. Moreover, interrogating differences across development within each condition revealed learning rate was significantly slower in adults than children on the overlapping layout ($p=0.015$), while the difference was not significant for the non-overlapping layout ($p=0.56$). This suggests that learning may be impeded in adults when they have overlapping spatial knowledge, while it is largely unaffected, or slightly facilitated, in children. All effects were similar when we controlled for individual learning rates on the associated initial layouts (layout condition \times age group: $F_{(1,103.5)}=5.30, p=0.02$; no main effects, all $F_{(1,103.2)}<1.6, p>0.2$; condition for adults: $p=0.075$; condition for children: $p=0.14$; age group for overlapping layouts: $p=0.015$; age

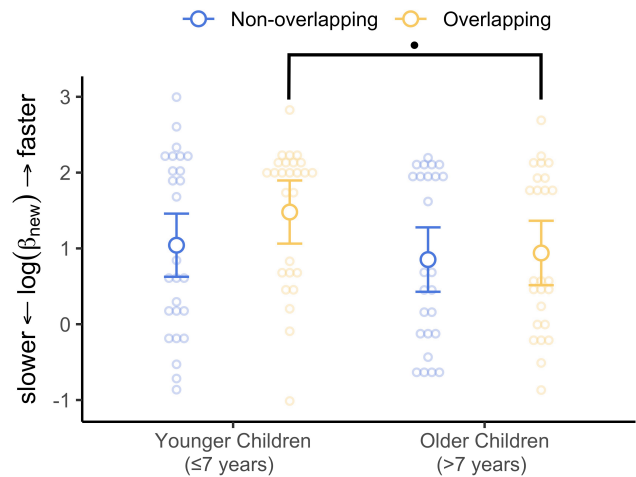


Figure 4: Younger and older children log-transformed learning rates (β) in new learning phase. Child group effect for overlapping layout: $p=0.075$.

• $p<0.1$

group for non-overlapping layouts: $p=0.56$). This suggests that our findings are not due to differences in initial learning. Moreover, we found no effect of layout learning order on new learning rate (all $F_{(1,108)}<1.6, p>0.2$).

We also looked at whether there were developmental differences within the children across conditions. When age was included as a continuous predictor, we found no significant effect of child age, layout condition, or their interaction (all $F_{(1,49)}<1.6, p>0.2$). When children were split into older (>7 years) and younger (≤ 7 years) groups, younger children had marginally higher learning rates ($F_{(1,49)}=2.96, p=0.09$; no layout condition or interaction effects, $F_{(1,49)}<1.6, p>0.2$). This overall effect was driven by a trend-level difference on the overlapping ($p=0.075$; see Fig. 4), but not the non-overlapping layout ($p=0.53$). Additionally, learning rate was numerically (not significantly; $p=0.15$) faster on the overlapping than the non-overlapping condition in the younger age group. This suggests that differences within the child group were limited and if anything, learning may have been slightly facilitated by overlapping spatial knowledge for younger but not older children.

Initial Memory Unaffected by New Learning

We also investigated whether memory for initially learned locations was retroactively disrupted by new learning in the same spatial context. Any difference in memory for the initially learned locations (A_1 and B_1) would reflect the impact of new overlapping learning on memory for A_1 locations. Overall, accuracy was high on the memory tests (adults: $M_{acc}=0.92, SD=0.10$; children: $M_{acc}=0.84, SD=0.25$). Interrogating performance as a function of layout condition (overlapping versus non-overlapping) revealed no significant differences (all $F_{(1,116.5)}<1.0, p>0.3$); however, we caution against over-interpretation of this result given many

participants (roughly 50% of each age group) performed perfectly. When we considered developmental differences, children were significantly less accurate on the final memory tests than adults ($F_{(1,109.1)}=5.78, p=0.018$). Additionally, for both age groups, performance was better on the second memory test (always also the second layout learned) compared to the first ($F_{(1,121.9)}=15.9, p<.001$; no interaction with age group: $F_{(1,121.9)}=0.68, p=0.41$). This may simply reflect a bias for the most recently learned layout or for the layout acquired when subjects were more familiar with the task. Response time analyses mirrored the accuracy results (age: $F_{(1,113.5)}=26.6, p<.001$; order: $F_{(1,122.8)}=29.2, p<.001$; layout condition, age \times condition: all $F_{(1,106.0)}<0.03, p>0.8$).

Discussion

We set out to test whether prior knowledge differentially impacts new learning in children and adults using a spatial learning task. In accordance with our developmental predictions, we found that new learning was differently affected by relevant spatial memories in adults and children. However, rather than enhancing new learning in adults, recent prior knowledge seemed to proactively interfere with their ability to learn new object-location pairs within the same spatial context. In contrast, learning in children, especially younger children, was potentially facilitated by previous experience with a spatial layout. There was no evidence for retroactive impact of new learning on initial memory.

In contrast to studies with rodents and humans using similar paradigms (Sommer, 2017; Tse et al., 2007; van Buuren et al., 2014), adults here did not benefit from prior overlapping knowledge when acquiring new spatial information. This deviation from previous findings may be due in part to the much shorter time frame of our experiment. To investigate whether more recent memories could facilitate new learning, our subjects learned initial and new locations within an hour, rather than across multiple days (Tse et al., 2011; van Buuren et al., 2014; van Kesteren, Brown, & Wagner, 2018). Thus, the interference effect seen here may point to the importance of time and/or sleep for consolidating initial spatial memories into a structure that can facilitate new learning (Lewis & Durrant, 2011; Tse et al., 2007; Wang & Morris, 2010; see however Cai et al., 2016; Zeithamova & Preston, 2017). It could also signal the importance of extensive initial training; previous work suggests that stronger initial spatial memories support more facilitation (van Kesteren, Brown, & Wagner, 2018). Further, some associative learning studies have even reported that medium strength initial memories compete (i.e., interfere) with new learning (Hayes-Roth, 1977), suggesting there may not be a simple monotonic relationship between prior knowledge and new learning (Ritvo, Turk-Browne, & Norman, 2019).

Additional potential factors driving the discrepancy between our findings and previous work may include high individual variability and our choice to focus on learning rate rather than later memory. First, there may be high variability in whether adults integrate related memories that are formed on the same day (Schlichting, Mumford, & Preston, 2015;

Schlichting & Preston, 2014). If this kind of variability were to exist in our sample, it would be difficult to see consistent effects of prior knowledge on new learning. Second, many studies reporting proactive facilitation effects focus on later memory benefits for newly learned information (Guo & Yang, 2020; Sommer, 2017; van Kesteren, Brown, & Wagner, 2018), rather than the acquisition rates measured here. Future research could investigate whether later memory for associations that overlap with prior spatial knowledge may be enhanced, despite proactive interference during learning. Combining initially competing experiences in memory, though perhaps a slow process in this case, may result in later protection from forgetting (Anderson & McCulloch, 1999; Radvansky, 2005).

We predicted that children would not be impacted by prior knowledge in the same manner as adults, as brain regions important for utilizing related memories during new learning undergo prolonged development (Calabro et al., 2020; Gogtay et al., 2004; Schlichting et al., 2017). Our results suggest that the effects of prior spatial knowledge on new learning in children is indeed limited, which may seem to contradict prior research suggesting children should be equally, if not more, prone to proactive interference than adults (Darby & Sloutsky, 2015; Robert et al., 2009). However, work characterizing interference over development largely focuses on memory retrieval, rather than encoding. The lack of interference for children here may indicate that they do not retrieve related (competing) memories during new learning (Schlichting et al., 2021) and may store related memories separately (Bauer et al., 2020; Shing et al., 2019). Thus, the proactive interference effects typically seen in children may be due to later post-learning processing, as memories are consolidated or retrieved. As for the slight facilitation seen in younger children (4-7 years old), we are hesitant to interpret this effect too strongly, given it did not reach statistical significance. Future work will be needed to confirm whether the effect would emerge or disappear with a larger sample of children. While the former outcome might suggest that young children can use recent spatial memories to scaffold new learning, the latter possibility could reflect that there is high individual variability amongst children in whether they integrate related memories from same-day learning, similar to adults (Schlichting, Mumford, & Preston, 2015; Schlichting & Preston, 2014). Future research will investigate these possibilities and pinpoint the age at which performance in children mirrors that of adults.

The current study provides evidence for a developmental shift in the impact of prior memories on new learning. While recently formed memories may interfere with the acquisition of new spatial knowledge in adulthood, children do not seem to experience this interference. This may be because they do not activate or prior knowledge during new learning. The current work improves our understanding of learning over development and the ways in which it differs from adults. Further research can illuminate how best to support child learners in educational settings, where it is often critical to integrate new learning with recently acquired knowledge.

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