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Authors
Wang, Jiangmeng
Gao, Mengcun
Sloutsky, Vladimir

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Examination of Developmental Changes in Complexity of Memory Structures

Jiangmeng Wang (wang.15066@buckeyemail.osu.edu)
Cognitive Development Lab, 1835 Neil Ave
Columbus, OH 43210

Mengcun Gao (gao.643@buckeyemail.osu.edu)
Cognitive Development Lab, 1835 Neil Ave
Columbus, OH 43210

Vladimir M. Sloutsky (sloutsky.@psy.ohio-state.edu)
Cognitive Development Lab, 1835 Neil Ave
Columbus, OH 43210

Abstract

Episodic memory proves fragile and undergoes a protracted development, as it often requires a combination of multiple elements, during which interference occurs as different sets of learned information partially overlap. One way of preventing interference is a complex representation that links together multiple components of an experience (i.e., three-way binding between items and context). The present study aimed to examine the developmental trajectory of the ability to form complex memory structures. Seventeen 5-year-olds and 26 adults participated in this study and performed a memory task that required binding two items to a context. The results showed that adults were able to form three-way binding; however, 5-year-olds exhibited difficulties in both three-way binding and binding between two items. Moreover, 5-year-olds did not benefit from extra learning opportunities, indicating that their difficulty in forming complex binding structures did not result from insufficient learning, but from a property of immature episodic memory.

Keywords: memory binding; memory structures; memory development; interference

Introduction

It's been widely acknowledged that memory is critical for human beings to function in the world. It allows people to distinguish the familiar from the new, to obtain, maintain and employ knowledge, to connect their past experience with present situations, and to make predictions about the future based on what has happened (Kumaran & McClelland, 2012; Brainerd, Reyna, & Ceci, 2008; Brainerd, Kingma, & Howe, 1985). However, memory, as an important function of ours, is proven to be fragile throughout preschool years and undergoes a protracted development (Bauer, Wenner, Dropik, Wewerka, & Howe, 2000; Drummey & Newcombe, 2002; Ghetti, & Bunge, 2012; Richmond & Nelson, 2007). It's especially true in the case of episodic memory, which involves remembering multiple components of an event such as what, where, and when it happened, and that is much more complicated than remembering an isolated item.

The Importance of Encoding on Memory

To form memory traces correctly, it's essential and important to encode elements correctly to make those memory traces distinct from each other (Canada, Ngo, Newcombe, Geng, & Riggins, 2019). An example of a memory combining a few elements would be a child seeing a toy armadillo (A) in a box (B) in Room 1, and then in a chest (C) in Room 2. It's easy to tell that these pairs (A-B, A-C) overlap because they both have the armadillo (A) as a common element, which makes the two traces less distinct and less separate. If the armadillo works as a cue, it can trigger two potential responses, and they will compete with each other, making accurate retrieval more difficult. However, if the child binds the armadillo not only to the container (B/C) but also to the respective room (X/Y), thus forming two complex memory representations that requires three-way binding (A-B-X, A-C-Y), these memory traces should be sufficiently different from each other, although they both involve the armadillo. This process of transforming similar memory traces into distinct ones is called pattern separation (McClelland, McNaughton, & O'Reilly, 1995; Bakker, Kirwan, Miller, & Stark, 2008).

To sum up, interference occurs when different sets of information we learnt partially overlap and we fail to achieve pattern separation to form distinct representation for similar experiences. That is, in order to prevent interference, a complex or configural representation needs to be formed and bind together multiple components of an experience. Such complex representations can effectively reduce overlap between things that bear similarity, and thus improve the accuracy of memories.

The Protracted Development of the Ability to Form Complex Memory Traces

Over the past few decades, developmental and cognitive psychologists have been interested in the ability to form memory bindings and whether it has a different developmental trajectory than single-item recognition. In

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early childhood, children show the ability to integrate multiple units of the same event in memory and retrieve them as a whole (Ngo, Horner, Newcombe, & Olson, 2019).

Developmental changes in memory binding have been found between younger children and older children and between older children and adults
(Ngo, Newcombe, & Olson, 2018; Benear, Ngo, Olson, & Newcombe, 2021; Darby, Sederberg, & Sloutsky, 2022; Darby & Sloutsky, 2015; Ngo, Horner, Newcombe, & Olson, 2019). Moreover, adults and children showed different learning rates when learning the relationship between multiple elements. Unlike adults who were able to quickly acquire the relationship between different elements and achieve high memory accuracy in binding task, children exhibited slower learning rates and were more prone to interference from similar learning materials (Yim, Dennis, & Sloutsky, 2013; Darby & Sloutsky, 2015; Ngo et al., 2019;).

Substantial research has been conducted to look into the psychological and neurobiological mechanisms underlying the development of memory representations. Some researchers linked it to the maturation of hippocampus, which is still developing into adulthood (DeMaster, Pathman, Lee, & Ghetti, 2014). Others have found that the development of the medial temporal lobe (Ghetti, DeMaster, Yonelinas, & Bunge, 2010) and dorsolateral prefrontal cortex (Drummey & Newcombe, 2002) as well as the interaction between these two regions (Ofen, Chai, Schuil, Whitfield-Gabrieli, & Gabrieli, 2012; Tang et al., 2020) play important roles in memory development.

Accordingly, children's inability to form complex memory binding may result from protracted development of brain areas that are involved in episodic memory. However, it is also possible that children just learn more slowly than adults. In other words, the ability to encode complex structures may have already emerged in early childhood, and it will transpire when children get sufficient learning opportunities. If this is true, then we would expect young children to benefit from more learning time and learning opportunities.

To examine whether (a) the ability to form complex memory binding (i.e., three-way binding) undergoes substantial increase during development due to immature brain development, in which case no additional amount of learning would help, or (b) the ability to form complex memory binding is present in early development but limited since the rate of learning in children appears to be slower compared to adults. In this case, children's memory binding performance can be improved by simply having more learning opportunities, we conducted the current study with 5-year-old children and adults. We selected the 5-year-old age group to investigate because 5 years of age is a major transitional period for memory development (Yim, Dennis, & Sloutsky, 2013; Darby & Sloutsky, 2015) and 5-year-olds were old enough to understand instructions and successfully complete the task.

Hypotheses about Children's Ability to Form Three-way Binding

The goal of the present study is to examine children's ability to form three-way binding, using a memory task developed in a previous study conducted by Darby and Sloutsky (2015). We hypothesized that early in preschool years, memory would be driven primarily by simpler representations, such as item familiarity and item-item binding; the primary developmental change would be the improvement in the ability to form increasingly complex memory representations that prevent interference and support memory retention. In addition, we predicted that young children would not benefit from an additional learning block.

Method

Participants

Seventeen 5-year-olds (M_{age} = 5.21 years, SD_{age} = 0.19, 9 females, 8 males) were included for the current study. They came from local preschools or elementary schools in the United States. Five additional young children participated in the experiment but were excluded from data analyses due to only completing one block of training and testing. Another 26 adults (M_{age} = 19.04 years, SD_{age} = 2.22, 16 females, 10 males) participated in the experiment. They came from introductory psychology classes at a university in the United States, and earned partial course credit for participation. All of them completed two blocks of training and testing.

Materials

The experiment was adopted from a previous study and presented with OpenSesame software (Darby & Sloutsky, 2015; Benear et al., 2021). Adult participants made responses on a computer monitor, whereas children made responses on a touchscreen. The learning materials included a pair of shape and color and a cartoon character (X in Figure 1). In each trial, participants were supposed to associate a certain pair of shape and color with a given character (Figure 1). We selected individual shape and color blobs as stimuli because shape and color are two important features when it comes to item recognition, and previous work has shown that tasks involving shape and color as stimuli are a valid measure for memory binding performance (Darby & Sloutsky, 2022).

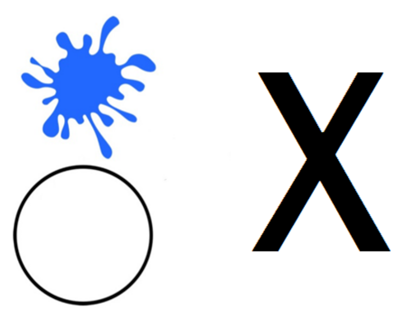

Figure 1: Stimuli of the memory task.

There were two sets of materials for participants to learn (Figure 2). In set A, there were four different pairs of shapes and colors, and they belonged to either Mickey Mouse (referred to as character X in the paper and figures) or Pooh Bear (referred to as character Y in the paper and figures). In set B, there were another four pairs of shapes and colors. Two pairs of shapes and colors that showed up and were bound with one character in set A were repaired and associated with another character in set B. These were referred to as Overlapping Trials, in which case three-way binding was required (as elaborated in the later sections). As for the other two pairs of colors and shapes in set A and B, they were completely different from any other color or shape pairs (sharing no common features) among these two sets of stimuli. These were referred to as Unique trials.

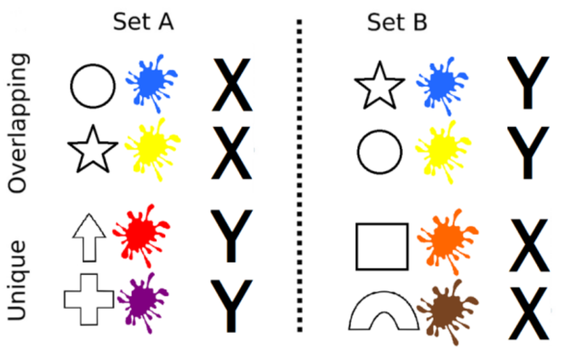

Figure 2: Example of a complete set of stimuli

Procedures

The experiment consisted of two blocks, and each block included two learning phases (32 trials each) and a binding test (16 trials each). Specifically, in the first learning phase, participants learned one set of contingencies (i.e., Set A in Figure 2, Left) with feedback, and then learned another set of contingencies with feedback in the second learning phase (i.e., Set B in Figure 2, Right).

In each of the learning phases, participants learned which character the given pair of shape and color belonged to, Mickey Mouse (character X) or Pooh Bear (character Y). After they made a response by touching (adults by clicking) one of the two characters on the touchscreen (adults on computers), the computer would give them feedback on whether their answer was correct. There are two trial types for each learning phase: Overlapping and Unique trials (as shown in Figure 2). Overlapping trials contained features that were presented in both sets, and therefore, associated with both characters when paired with a different feature. For example, the color of blue was associated with character X when paired with the circle shape but associated with character Y when paired with the star shape. Unique trials, on the other hand, contained features that were only presented in one set and only associated with one character. For example, the color of red was only presented in the first learning phase (Set A), and was only associated with the character Y.

In the binding test, participants were presented with a forced choice recognition task. On every trial, participants saw one of the characters (cue character) presented with a cue feature (i.e., a shape or a blob of color), and they were asked to choose which of five options was paired with the cue feature and as a shape-color pair, associated with the cue character. Same as the learning phases, there were two trial types: Overlapping trials and Unique trials. Trial types were dependent on the cue feature: trials were Overlapping trials if the cue feature was an Overlapping trial feature in the learning phases and were Unique trials if the cue feature was a Unique trial feature in the learning phases.

As for the options on each trial, only one of the five options was correct (referred to as Correct Feature), and the remaining four were incorrect features and were referred to as Overlapping Feature, Unique Same Character Feature, Unique Different Character Feature, and Novel Feature. Overlapping Features were features that belonged to both characters but paired with different features. For example, the star shape in Figure 3 (top) was an Overlapping Feature because it belonged to Character X when paired with the color of yellow but belonged to Character Y when paired with the color of blue. Unique Same Character Features were features that belonged to the cue character of the trial but were never paired with the cue feature. For example, when the cue character was X, and the cue feature was the color of blue in Figure 3 (top), the square shape is a Unique Same Character Feature because it belonged to X (as shown in Figure 2) but was never paired with the color of blue. Unique Different Character Features were features that belonged to a different character and were never paired with the cue feature. For example, the cross shape in Figure 3 (top was a Unique Different Character Feature because it belonged to Character Y (instead of the cue character, X), and it was never paired with the color of blue (the cue feature). Last but not least, Novel Features were features that were never presented during the learning phases (diamond shape in Figure 3, top).

We used different types of distracters (incorrect options) to test the complexities in adults' and children's binding structures and whether children would show substantial improvement in more complex minding structures when given extra learning opportunities. First, three-way binding (the most complex binding structure tested in the paper) must be present for people to distinguish Correct features from Overlapping features on Overlapping trials. Specifically, given that the overlapping features on each trial were paired with both the cue feature and the cue character in the learning phases, simply forming two-way bindings (i.e., item-item binding and item-context binding, see the following paragraph for more details) was insufficient to exclude Overlapping Features on Overlapping trials. Instead, three-way-binding (item-item-context) was needed. Therefore, one of our major focuses was on adults' and children's proportion differences between choosing the Correct Feature and the Overlapping Feature on Overlapping Trials. Larger differences indicated a more mature three-way binding structure.

In addition to three-way binding, children may also have less efficient two-way binding structures compared to adults. There were two different two-way binding structures tested in the study: item-item binding (e.g., the color of blue and the star shape), and item-context binding (e.g., the color of blue and the character X). Forming item-item binding structure allowed participants to rule out the feature option that was never paired with the cue feature. In our design, mature item-item binding structure of participants could be demonstrated by their large proportion differences between choosing the Correct Feature and the Overlapping Feature on Unique Trials, and between choosing the Correct Feature and the Unique Same Character Feature on both Overlapping and Unique Trials. Given that these features were never paired with the cue feature in previous learning phases, participants with mature item-item binding structure should easily rule them out.

Moreover, another type of two-way binding, item-context binding would enable participants to reduce false-alarms on Unique Different Character Features because they were never paired with the cue feature or the cue character in the previous learning. It's worth noting that given that Unique Different Character Features could also be ruled out if participants formed item-item binding, low choosing proportion of Unique Character Features did not necessarily demonstrate mature item-context binding. However, failure to rule out Different Character Features was strong evidence for immature item-context binding.

Last but not least, Novel Features were used to examine participants' recognition of single items in the study. If they have formed memory traces for single items (shapes and colors), they should rarely false alarm on Novel Features since these features were never presented in the learning Phase.

In sum, the purpose of the design was to investigate whether there were age differences in different levels of memory binding structures and whether children could benefit from extra learning opportunities (or experiences with learning stimuli).

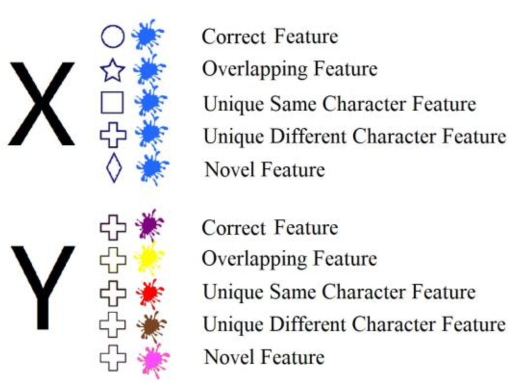

Figure 3: Example of choices in binding test

Results

Training Results

First, we conducted a series of One-Sample *t*-test to examine whether adults and children show above-chance accuracy during learning phases for all trial types. As shown in the Figure 1, adults showed significantly above chance accuracy on both Overlapping and Unique trials across stimuli sets and learning phases, all *ps* < 0.001, all *d*s > 2.87. Similar to adults, children showed significantly above chance accuracy for all types of trials, *ps* < 0.05, all *d*s > 0.53, except Overlapping trials of set B in the second learning phase, which was marginally significant, $p = 0.056$, all $d = 0.50$.

Then, to compare children's learning to adults', we conducted a mixed ANOVA with age (Adults vs. Children) as the between-subject independent variable, learning phase (Phase 1 vs. Phase 2), set (Set A vs. Set B), and trial type (Overlapping vs. Unique) as within-subject independent variables. According to the results, there was a significant main effect of age, $F(1, 41) = 14.18$, $p < 0.001$, $\hat{\eta}^2_G = 0.115$, with adults ($M = 0.80$, $SD = 0.18$) showing higher overall accuracy compared to children ($M = 0.67$, $SD = 0.20$). There was also a significant main effect of trial type, $F(1, 41) = 11.10$, $p < 0.01$, $\hat{\eta}^2_G = 0.023$, as participants were more accurate on unique trials ($M = 0.78$, $SD = 0.20$) compared to overlapping trials ($M = 0.72$, $SD = 0.20$). In addition, there was a significant interaction between block and trial type, $F(1, 41) = 4.65$, $p = 0.037$, $\hat{\eta}^2_G = 0.004$. Specifically, participants were more accurate on unique trials in the second learning block compared to the first learning block, but less accurate on overlapping trials. Last but not least, there was a marginally significant three-way interaction between age, block, and trial type, $F(1, 41) = 3.40$, $p = 0.073$, $\hat{\eta}^2_G = 0.003$, suggesting that the interaction between block and trial type was primarily due to children's performance.

Results of the learning phase provided preliminary evidence that there were developmental changes in recognition. To gain more insights into how developmental changes differed across complexities of binding structures, we conducted multinomial logistic regression models on adults' and children's binding task performance and present the results in the following section.

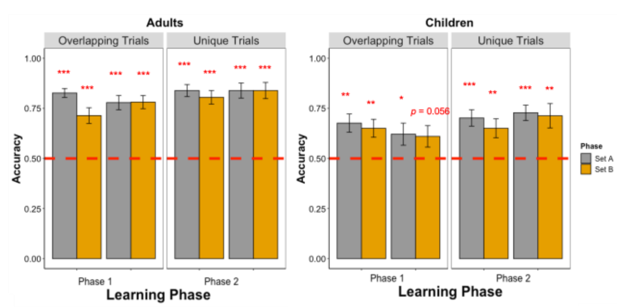

Figure 4: Children and adults' accuracy in the training phase, broken down by sets, trial types, and blocks.

Binding Task Results

To analyze adults' and children's performance in the binding task, we conducted multinomial logistic regression analyses using the multinom function from R nnet package (Venables & Ripley, 2011). First, we ran multinomial logistic regression models for Overlapping and Unique trials separately. The models were employed to examine how age (adults vs. children), learning phase (phase 1 vs. phase 2), and their interactions affected participants' choosing proportions among different feature options, while accounting for the random effects of individual participants.

Next, we particularly focused on children and ran multinomial logistic regression analyses for children's Overlapping and Unique trials. The model included learning phase as a main effect and participant as random effect with a goal to directly examine whether children gained improvement in any memory binding structures in the later learning phase. The referent category for feature option in all models was the Correct Feature.

The results of the multinomial regression models were presented in Table 1, 2, 3, and 4. USC in all tables stood for Unique Same Character Features, and UDC represented Unique Different Character Features. None of the Odds Ratios for the interaction between age and learning phase was significant, and therefore, were not included in the tables.

Table 1. Multinomial Logistic Regression Results in Odds Ratios for Overlapping Trials across ages.

Age (Children)	Odds Ratio	95% CI
Overlapping	1.813	[1.011, 3.252]
USC	3.870	[1.967, 7.614]
UDC	1.627	[0.790, 3.349]
Novel	6.699	[2.774, 16.173]
Phase (Phase 2)		
Overlapping	0.911	[0.570, 1.455]
USC	0.685	[0.344, 1.366]
UDC	0.896	[0.499, 1.611]
Novel	1.030	[0.400, 2.652]

Table 2. Multinomial Logistic Regression Results in Odds Ratios for Unique Trials across ages.

Age (Children)	Odds Ratio	95% CI
Overlapping	3.637	[1.966, 6.728]
USC	4.881	[2.243, 10.621]
UDC	2.813	[1.509, 5.246]
Novel	10.820	[4.020, 29.126]
Phase (Phase 2)		
Overlapping	0.977	[0.565, 1.690]
USC	1.115	[0.527, 2.356]
UDC	0.459	[0.244, 0.863]
Novel	1.071	[0.350, 3.274]

Table 3. Multinomial Logistic Regression Results in Odds Ratios for Overlapping Trials for children.

Phase (Phase 2)	Odds Ratio	95% CI
Overlapping	0.804	[0.397, 1.625]
USC	1.067	[0.527, 2.157]
UDC	1.520	[0.686, 3.364]
Novel	1.033	[0.471, 2.268]

Table 4. Multinomial Logistic Regression Results in Odds Ratios for Unique Trials for children.

Phase (Phase 2)	Odds Ratio	95% CI
Overlapping	0.776	[0.403, 1.493]
USC	0.880	[0.416, 1.858]
UDC	0.629	[0.309, 1.278]
Novel	0.632	[0.282, 1.415]

According to the results, for children, the odds ratio of choosing all the incorrect options except Unique Different Character Feature over the Correct Feature option were significantly more than 1 (as indicated by 95%) when compared to adults on both Overlapping and Unique trials. The results indicated substantial developmental changes in all levels of memory binding structures from 5 years of age to adulthood. Interestingly, the age difference in choosing between the Correct and the Overlapping Feature were more salient on Unique Trials compared to Overlapping Trials, indicating a larger age difference in two-way item-item binding than three-way binding. Such results might seem counterintuitive; however, previous studies have shown that even adults may have difficulties with three-way binding (Darby & Sloutsky, 2022), but their two-way binding is relatively mature (Ngo et al., 2019; Darby & Sloutsky, 2022). On the other hand, for children, both of their three-way binding and two-way binding structures were at an early stage of development. The reduced age difference in three-way binding might due to lower-than-expected adults' performance.

Unlike age differences, learning phases had no effects on the odds ratio of choosing any incorrect options over the Correct Feature option (1 was within the 95% Confidence Interval for both Overlapping and Unique Trials). In addition, as stated earlier, no significant interaction between age and learning phase was found in the models, suggesting that the effect of learning phase did not differ between adults and children.

Although no significant interaction between age and learning phase was found, we still decided to run multinomial logistic regression models for children alone, with learning phase being the only main effects to provide further evidence that more learning experience had no influences on children's binding structures. As shown in Table 3 and Table 4, for children, learning phase indeed had no effects on the odds ratio of choosing any incorrect options over the Correct Feature option (1 was within the 95% Confidence Interval for both Overlapping and Unique Trials).

To sum up, our results indicated that there were substantial developmental changes in all levels of binding structures, consistent with previous findings (Rudy, Keith, & Georgen, 1993; Darby & Sloutsky, 2015; Ngo, Newcombe, & Olson, 2018; Benear et al., 2021; Darby & Sloutsky, 2022). More importantly, our finding that children's memory binding did not improve in the later learning phase provided novel evidence that children's deficits in memory binding was not simply due to not having sufficient learning experience for binding to transpire. Nevertheless, it is worth noting that, it is possible that our study did not provide enough learning opportunities for young children. Actually, as shown in the Figure 5, children indeed showed an increasing trend (yet non-significant) of choosing the Correct Feature over the Overlapping Feature in the second learning phase. Therefore, it remains possible that when given excessive learning time and opportunities, children will eventually form more advanced and complex binding and reach adult-level performance. Future investigations are expected to test this possibility and further examine the effects of learning time/opportunities on shaping and improving children's memory binding structures.

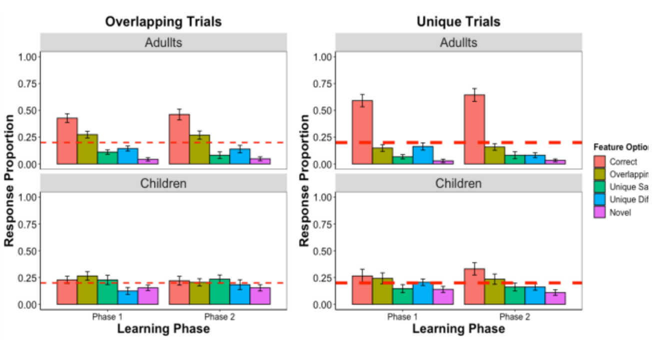

Figure 5: Children and adults' choice proportion among feature types on Overlapping (left) and Unique (right) trials in the binding test phase.

Discussion

The results from this study showed that adults outperformed young children in memory binding, in the sense that adults were more likely to identify the correct option out of the five options, while children had more false alarms on new combinations of shape-color-character, exhibiting an inability to form distinct and complex memory traces and showing deficits in all the levels of memory binding compared to adults. These results provided further evidence for the phenomenon that young children's ability to discriminate among similar components of episodes undergoes protracted development (Ngo, Newcombe, & Olson, 2018).

Our results indicated that unlike adults who exhibited three-way bindings between items and context, 5-year-olds not only failed to form three-way binding, but also experienced more difficulties binding two items and forming memory traces of single features compared to adults. Our results were consistent with the results from previous studies, which also showed that interference effects in memory binding decreased with age (Darby & Sloutsky, 2015) while recognition improved as children grow up (Bauer, 2009).

Moreover, we found that simply doubling the learning trials did not help children reach adults' performance, suggesting that the ability to form complex memory structures in episodic memory was not due to lack of learning opportunities or familiarity with stimuli being stored. Instead, the ability needs to undergo protracted development to mature (Canada, et al., 2019). However, that could also be possible that doubling the blocks might still be insufficient for children to learn and form complex memory binding, which may be one limitation of our study. One future direction is to increase the experiment blocks even more to examine whether 5-year-old can benefit from those.-Another future direction can be to investigate the developmental trajectory of this ability by studying older children.

Conclusion

To investigate whether young children's difficulty with complex and distinct memory binding is due to insufficient learning or reflect substantial developmental changes, we conducted the current study in which both adults and young children were given two training blocks to learn different shape-color-character bindings. Our findings showed that unlike adults who were able to form complex three-way binding, children were struggling with all levels of memory bindings. Such age differences explain why children were more likely to be interfered by memories that share similar components. Also, the finding that young children's performance did not improve when given extra learning opportunities indicated that the ability to form complex and distinct memory traces undergoes protracted development and cannot be compensated simply by more learning opportunities or longer learning times.

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