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Pattern separation and pattern completion in early childhood

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Pattern separation, or distinguishing similar experiences from one another, and pattern completion, in which components of an experience prompt retrieval or forgetting of an event pattern as a unit, are essential components of episodic memory. However, these two components are sometimes described as opposite ends of a continuum and sometimes described as independent processes. Here, we examined the relations between the two processes for the same events in children between 4 and 7 y. Mnemonic discrimination (the behavioral signature of pattern separation) improved with age; holistic recollection (the behavioral signature of pattern completion) did not change in this age range. Crucially, the two behaviors were unrelated, controlling for the effect of age, and even when examining their relations at the fine-grained level of memory for individual events.

memory | development | childhood | hippocampus

Significance

Episodic memory is how we remember our lives. To create accurate memories, we must be able to both distinguish similar experiences from one another, a process called pattern separation, and recollect the multitude of components of each life event as a unified whole, a process called pattern completion. We examined the relations between these two processes. We found no relation between the behavioral signatures of these processes in early childhood. Our results suggest that these two foundational components of episodic memories are independent.

Imagine a scenario where Angelica, a young child, went to a picturesque lake while on vacation with her family. While there, she saw a sheep separated from the flock. She also found a distinctive mug along the path by the lake. When she later remembers this moment on her vacation, is her highly detailed memory for the lake accompanied by a strong association between the components of her experience: the sheep, the lake, and the mug? In other words, do the different characteristics of a given memory, namely the cohesiveness between all its component parts and the detailedness of those parts, go hand in hand? These characteristics are often referred to as holistic recollection (1, 2) and mnemonic discrimination (3) and they are fundamental components of episodic memories. Holistic recollection is closely related to relational binding, and yet distinct in important ways. Relational binding refers to memory accuracy for any given pairwise association from an experience [e.g., sheep and mug (1, 2)]. Holistic recollection refers to the degree to which several different parts of an event are remembered or forgotten together as an interwoven unit or pattern. In other words, relational binding involves accuracy of memory for individual associations whereas holistic recollection refers to interdependence of memory or forgetting for all associations that make up an episode. It has also been called "retrieval dependency" (1, 2).

Some theorists propose that the processes underlying holistic recollection and memory discrimination are competing components of episodic memory (4–7). On the one hand, Angelica must distinguish the lake that she saw from other similar lakes. Such discrimination is thought to rely on pattern separation (3, 5). On the other hand, Angelica must bind together the lake–sheep–mug experience such that in the presence of one cue (e.g., the lake), she can retrieve the other parts of the same event (e.g., the sheep and the mug). This ability, holistic recollection, is thought to rely on pattern completion (3, 5). The two processes are at computational odds. One can either differentiate between similar memoranda (pattern separation) or relate them as a cohesive unit (pattern completion) (5).

Both pattern separation and pattern completion are hippocampal-dependent processes. However, they are distinct neurocomputations that play complementary roles in episodic memory (3, 7, 8). Pattern separation distinguishes one memory from partially overlapping memories via the dentate gyrus which codes similar inputs as sparse uncorrelated patterns of activity (4, 7, 9, 10). In contrast, pattern completion, which allows for holistic representations of experiences, is believed to rely on the hippocampus's CA3 subfield, whereby activating one part of an event causes the other components to simultaneously activate (6, 7, 11). Although the processes and their neural underpinnings are well defined, we do not know how the two processes relate for a given memory, or whether the relationship changes during development.

Mnemonic discrimination has been found to improve between the ages of 4 and 6 y (12–14). Using the Mnemonic Similarity Task, Ngo et al. (12) showed children and adults a series of object images. Following this, in the test phase, some test items were identical or completely dissimilar to those seen at encoding. Importantly, some test items were similar exemplars to the studied objects. Participants were instructed to judge whether

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each test item was identical, similar, or new compared to those seen during the study phase. Four-year-old children had a strong tendency to confuse similar lures and previously seen objects. This tendency—a hallmark of pattern separation failure—disappears by age six. This effect has been replicated (13, 15) and extended to the range of 3 to 8 y (14, 16, 17).

There are fewer data on the development of holistic recollection in early childhood (2, 18, 19). Two studies found that holistic recollection is already evident at age 4 (2, 18), reviewed in ref. 20. That is, 4-y-old children already tend to remember (or forget) an experience as an integrated whole. If one association is successfully retrieved, other associations from the same episode are also likely to be successfully retrieved. Nonetheless, the degree of holistic recollection increases from age 4 to adulthood (2, 18).

Previous studies of the relation between mnemonic discrimination and holistic recollection have been done on the interindividual differences level. In one study, after learning a set of multielement episodes (e.g., lake–sheep–mug; playground–cat–chair), mnemonic discrimination was assessed for a subset of the episodes (e.g., two similar lakes), and holistic recollection on another subset (e.g., playground–cat–chair). Young adults' detailed memories *did not* relate to their likelihood of remembering or forgetting episodes as integrated units (21).

The second set of relevant findings comes from developmental studies investigating the relationship between children's mnemonic discrimination and relational binding. Unlike holistic recollection, relational binding refers to retrieval accuracy of pairwise associations (e.g., lake–sheep) irrespective of whether they come from the same event. A series of studies show that individual differences in mnemonic discrimination and relational binding were unrelated in 4- and 6-y-old children (12, 13), suggesting that the development of these two abilities is decoupled in early childhood.

Here, we investigated whether the two properties of episodic memory, highly detailed memory and holistic recollection, are coupled *for the same episode*. We designed a task in which we assess the componential behavioral outcomes of pattern separation and pattern completion in 4- to 7-y-old children. First, children were shown multielement events, such as the lake–sheep–mug event (Fig. 1*C*: Encoding). After that, we measured both the specificity with which they remember the components of the event (e.g., the specific lake they saw; Fig. 1*C*: Mnemonic discrimination test) and their ability to use any one item as a cue for both of the other two (Fig. 1*C*: Holistic recollection test). This design provides the behavioral indices of *both* mnemonic discrimination and holistic recollection for the same events in the same children. By testing memory for aspects of the same events, we will be able to determine that potential differences between the two components are not due to changes in attention or encoding, but rather differences in the computations underlying these behaviors.

Results

We examine mnemonic discrimination and holistic recollection for the same memoranda such that we can tie the ability to remember which particular lake was experienced to the ability to recall or forget the lake–animal–object event. Furthermore, we examine the relationship between these components of episodic memory in children, thus allowing us to probe for changes

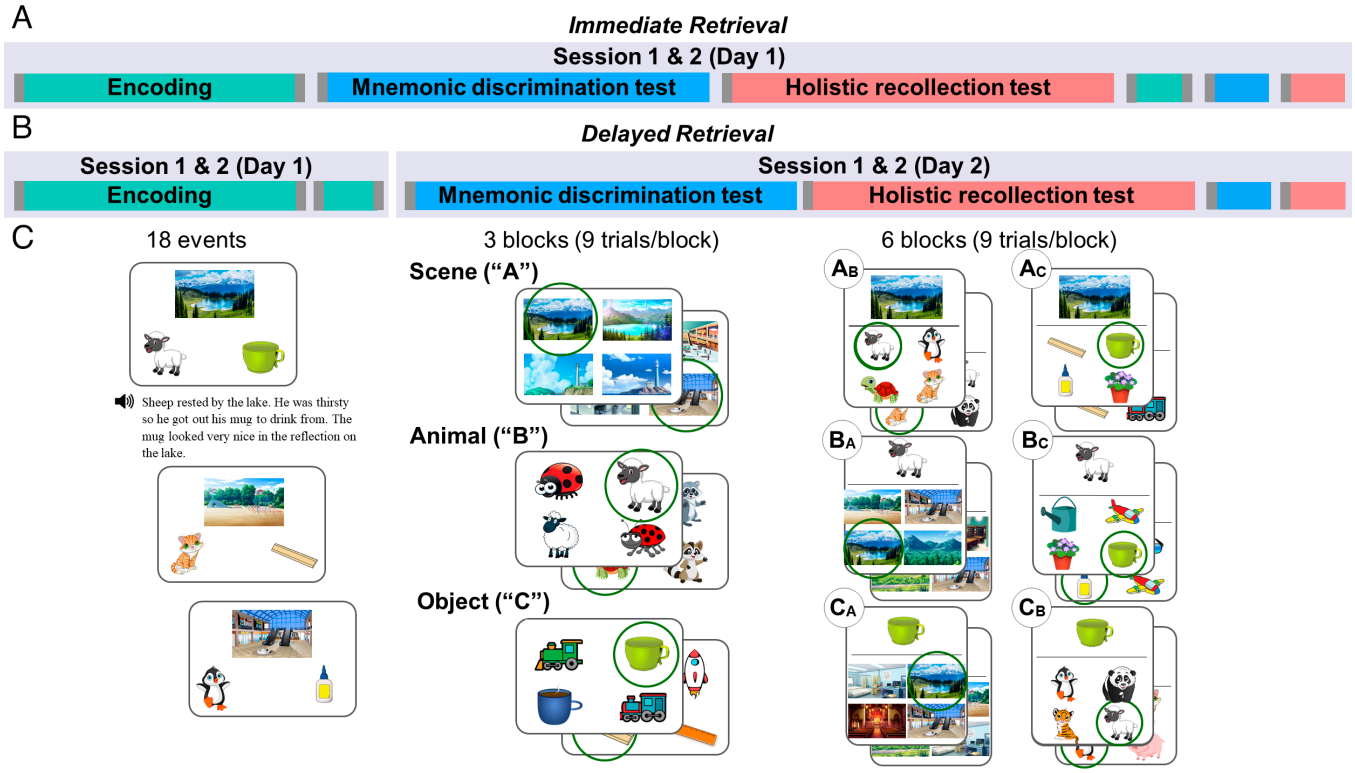

Fig. 1. A schematic depiction of the task procedure for the immediate (*A*) and delayed (*B*) retrieval groups. (*A*) For the immediate retrieval group, the entirety of Sessions 1 and 2 occurred on the same day. (*B*) For the delayed group, encoding for Sessions 1 and 2 was done on Day 1, and the mnemonic discrimination and holistic recollection tests were performed on Day 2, on average 1 wk later. (*C*) For both groups, each session consisted of encoding event triads composed of a scene, an animal, and an object. Each event was accompanied by an audio narrative. The event triads in each session were flanked by four example triads at the beginning and end of the encoding phase (represented as gray bars in *A* and *B*). These examples were then used to instruct the mnemonic discrimination and holistic recollection tests (instruction indicated by gray bands). In each four-alternative forced choice (4AFC) trial in the mnemonic discrimination test the four options included the correct target, a similar lure, and two exemplar foils. In each 4AFC trial in the holistic recollection test, the cue was presented on top and the four options for the to-be-retrieved element were presented on the bottom of the screen. Scenes, animals, and objects are denoted as elements A, B, and C, respectively. Green circles indicate the correct option and are shown here for visual illustration.

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in their relationship with increasing age. First, we will examine changes in mnemonic discrimination, relational binding, and holistic recollection with age, and then we will probe the potential for a relationship between these memory components. We began by examining memory immediately after encoding (*immediate* group), but after encountering unexpected ceiling effects, rendering it impossible to determine whether holistic recollection was due to performance, we tested the remainder of the sample's memory after a 1-wk delay (*delayed* group). This presented us the opportunity to examine the potential effect of delayed retrieval on mnemonic discrimination and holistic recollection. Results are reported separately for each group where they differ.

Mnemonic Discrimination. Given the time-dependent nature of memory accuracy (22–24), it comes as no surprise that the delayed recall group had significantly worse memory discrimination than the immediate group. They selected the target item significantly less than the immediate group ($t(79.50) = -8.41$, $P = 1 \times 10^{-12}$), and selected the lure and foil items significantly more than the immediate group (both P's $< 1 \times 10^{-6}$). We will therefore examine results separately for the two conditions.

In both conditions, the rate of target selection significantly increased with age (immediate: $r(32) = 0.38$, $P = 0.03$; delayed: $r(49) = 0.54$, $P = 5 \times 10^{-5}$), and the rate of foil selection significantly decreased with age (immediate: $r(32) = -0.37$, $P = 0.04$; delayed: $r(49) = -0.53$, $P = 7 \times 10^{-5}$). While the rate of lure selection significantly decreased with age in the delay group ($r(49) = -0.35$, $P = 0.01$), this effect was only trending in the immediate group ($r(32) = -0.33$, $P = 0.06$), perhaps due to lack of power (Fig. 2). When examined in 1-y bins spanning our age range, all ages selected targets and rejected foils and lures at a rate greater than that suggested by chance in a 4AFC task (indicated by a dashed line in Fig. 2; all P's < 0.001).

Using a generalized linear mixed model, with repeated measures for each participant, we found a three-way interaction between retrieval delay, age, and item selected (lure vs. foil) ($\beta = 0.04$, SE = 0.02, $P = 0.04$). A post hoc examination of this interaction indicates that although there is a trending interaction between age and delay for foil selection ($\beta = 0.04$, SE = 0.02, $P = 0.05$), there is no interaction between age and delay for lure selection ($P = 0.9$). This pattern of results suggests that with a delay younger children forget the item identity entirely and are therefore more likely to select the foil then the lure. However, despite this, all ages, examined in 1-y bins, selected either the target or the lure more frequently than the foil (all P's $<$ 0.001), and when they made mistakes, they selected the lure at a relatively more frequent rate (all P's < 0.05, except for 6-y-olds, $P = 0.1$).

Finally, we examined whether target–lure similarity influenced mnemonic discrimination performance. We found only a marginal relationship between target–lure similarity and mnemonic discrimination performance ($\beta = -0.08$, SE = 0.04, $P = 0.05$). Indicating that participants tend to perform slightly, although not significantly, worse when targets and lures are more similar.

Relational Binding and Holistic Recollection.

Relational binding. Again, as expected, the number of pairwise associations remembered significantly decreased after a 1 wk delay ($t(52.42) = -7.71$, $P = 3 \times 10^{-10}$). We will therefore examine results separately for the immediate and delayed recall conditions. Aligning with our mnemonic discrimination results, in both conditions the number of pairwise associations remembered significantly increased with age (immediate: $r(25) = 0.59$, $P = 0.002$; delayed: $r(39) = 0.34$, $P = 0.03$; Fig. 3).

We next examined whether the order of cue–item pairs affected relational binding (e.g., did subjects perform better on object–location pairs if they were presented after location–object pairs). Linear mixed effects models revealed no effect of order on accuracy after controlling for the effect of age (all P's > 0.3).

Holistic recollection. Aligning with previous work suggesting that holistic recollection is a time and accuracy-invariant memory process (25), we found no effect of delay on recollection dependency ($P = 0.9$). Furthermore, replicating previous findings in children (2), we found that when examined in 1-y bins spanning our age range, all ages had retrieval dependency significantly above zero (all P's < 0.009) and dependency did not change with age for either the immediate or delayed retrieval condition (all P's > 0.1; Fig. 3). This result indicates that even for our youngest participants, although some individuals have fragmentary memories, for a majority of children events are remembered or forgotten as an integrated whole and that the degree of holistic recollection does not vary as a function of age.

Next, we examined the association between relational binding and holistic recollection. By design, holistic recollection should be an accuracy-invariant measure of memory as it measures the extent to which events are entirely remembered or forgotten (1). Therefore, it comes as no surprise that in the delayed recall group, there was no significant correlation between holistic recollection and relational binding ($P = 0.3$). However, there was a significant relationship in the immediate recall group ($r(24) = -0.47$, $P = 0.02$). This unexpected result is no longer significant when controlling for age ($P = 0.06$), indicating that it may in part be driven

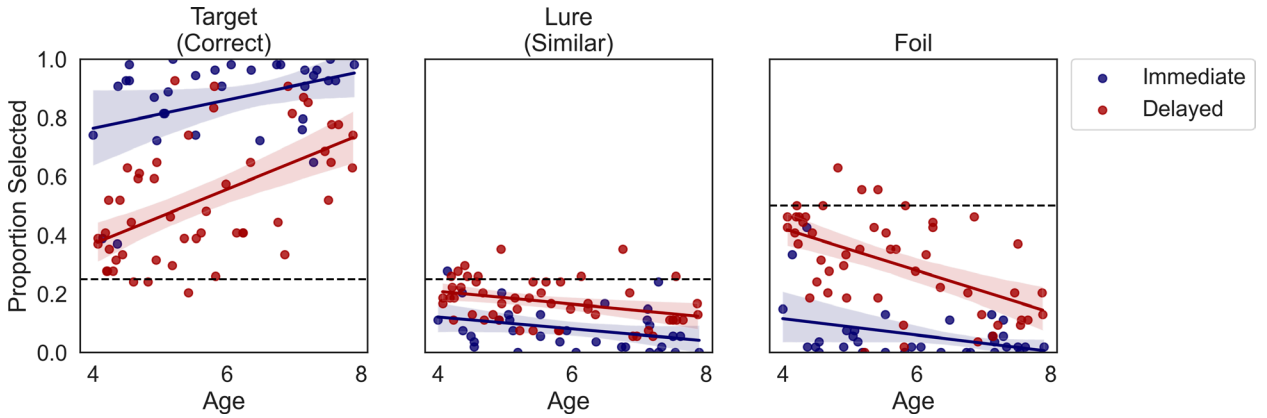

Fig. 2. The proportion of Target (*Left*), Lure (*Middle*), and Foil (*Right*) selected (*y* axis) is related to participants' age (*x* axis). The dashed line in each plot indicates the proportion of each item that would be selected if a participant were randomly guessing.

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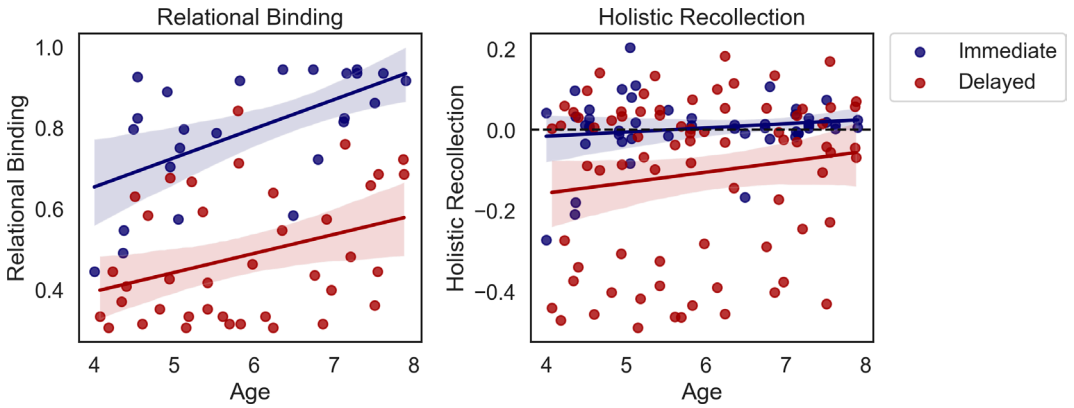

Fig. 3. While relational binding increases with age in both immediate and delayed groups, holistic recollection does not vary with age.

by the large number of school-aged children who have near-ceiling performance in this group.

Mnemonic Discrimination's Relationship with Relational Binding and Holistic Recollection.

Mnemonic discrimination and relational binding. We first examined the relationship between two general episodic memory abilities: the ability to select a previously experienced target item from similar lures and distracting foils (mnemonic discrimination), and the ability to remember which pairs of items were previously associated (relational binding). Prior results are mixed. On the one hand, we previously found a significant relationship in young adults, indicating that these two abilities are related (21). On the other hand, we also previously found that in children there was no significant relationship between mnemonic discrimination and relational memory after controlling for age-related memory improvements (12). Here, we find a significant relationship between mnemonic discrimination, whether measured as target, lure, or foil selection rate, and relational binding whether controlling for age or not (all P's < 0.008; Fig. 4).

Echoing these results, we also found a significant correlation between mnemonic discrimination and relational binding when each component is assessed on the same event (same trial and same participant; all P's < 0.008). These results indicate that whether measured across participants or across events, there is a significant link between these two fundamental components of episodic memory in children.

Holistic recollection and mnemonic discrimination association. Finally, following previous research that examined mnemonic discrimination and holistic recollection in adult participants on an interindividual differences level (21), we predicted that individual variations in these two indices would be unrelated. Uniquely, we also examine the association between mnemonic discrimination and holistic recollection on the event-specific level. This feature of the design departs from previous studies. Extending previous findings in young adults (21), we find that mnemonic discrimination, when measured as target selection rate, is unrelated to holistic recollection on the individual child level (immediate: r = −0.19, P = 0.2; delayed: r = 0.02, P = 0.9). Similarly, lure and foil selection rates are also unrelated to mnemonic discrimination (all P's > 0.1). This pattern of results remains when controlling for age (all P's > 0.2). These findings suggest that children who remember individual elements with high details do not necessarily have the tendency to remember or forget events holistically.

As stated previously, our paradigm uniquely allows us to examine whether mnemonic discrimination and holistic recollection are related in *the same multielement event episodes*. For this analysis, we implemented the application of a retrieval dependency analysis at the event level to estimate the degree of holistic recollection on a per-event basis (*Materials and Methods*). Here, echoing our across-participants results, we find that mnemonic discrimination, when measured as target selection rate, is unrelated to holistic recollection at the individual event level (z = −1.06, P = 0.3). This association is also nonsignificant between holistic recollection and lure and foil selection rates (all P's > 0.2; see Fig. 5 which illustrates the z-value of the relationship as black stars relative to the null distribution derived from permuting event-wise holistic recollection across all participants 100 times). These findings suggest that these two characteristics of memory for a given event, detailedness and cohesiveness, are unrelated to each other.

Discussion

We examined two fundamental components of episodic memory in early childhood: pattern separation and pattern completion. We collected a large sample of children, 4 to 7 y of age, who were exposed to several events consisting of a location, an animal, and an object. We found that regardless of the interval between encoding and retrieval, the ability to identify which particular item was seen previously (i.e., mnemonic discrimination, the behavioral output of pattern separation), improved with age. However, the ability to recollect or forget experiences holistically (i.e., holistic recollection, the behavioral output of pattern completion), did not change in this age range. Holistic recollection was present even in our youngest participants and remained consistently strong. Finally, similarly to mnemonic discrimination, relational binding, the ability to remember pairwise associations between event elements, also improved with age.

The unique feature of this study is that we were able to examine the behavioral outputs of pattern separation and pattern completion in not only the same subjects, as has been done previously in adults, but also within the same events. This was possible because both aspects of memory were examined for the same memoranda. By examining the relationship between these properties at such a fine-grained level we were able to demonstrate that not only are mnemonic discrimination and holistic recollection unrelated within individual subjects, but further, even at the level of individual events, the two properties are unrelated. This indicates that children's ability to precisely remember their experiences is not tied to their tendency to holistically associate or forget the component parts of those experiences as an integrated whole. Further, our findings show that events that are remembered or forgotten as a coherent whole are not the same as the events whose components are remembered with specificity.

The finding that mnemonic discrimination and holistic recollection are dissociated at the level of individual events extends

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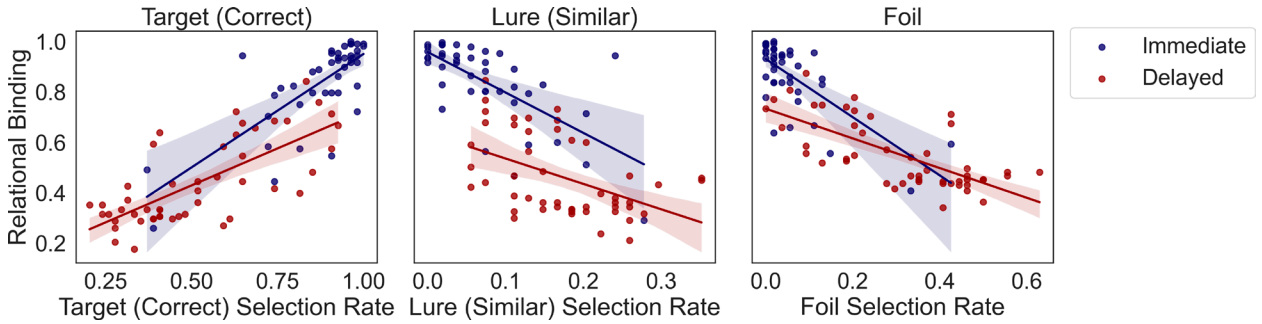

Fig. 4. The relationship between mnemonic discrimination and relational binding for both the immediate (blue) and delayed (red) retrieval groups.

previous evidence that these two properties of episodic memory are unrelated. Ngo et al. (21) implemented a similar task in adults. However, in this study, they did not associate mnemonic discrimination and holistic recollection at the level of events, but rather only at the level of subjects (21). Here, they too found that these properties are unrelated within individual participants (21). We have extended this finding to young children, showing that even in a time of tremendous growth in episodic memory ability broadly, the underlying components are still dissociated (26).

Our findings also suggest that younger children can perform pattern completion to the same extent that older children can, although we should remember that Ngo et al. (2, 13, 15) found that young adults showed greater pattern completion than 4-y-olds. By contrast, pattern separation ability improves more continuously and clearly with age. This pattern may suggest that younger children are relatively more biased toward a state of connecting previously learned experiences rather than encoding new ones (5, 27). Likewise, younger children may encode less precise memories, although they are subsequently able to recollect the gist of their experience. A tendency toward a more general representation, rather than one focused on the details, may be a part of what helps younger children extract the schemas about their world that are essential for their development (26, 28).

This dissociation may in part be due to the distinct neural foundations of the processes underlying these behaviors: pattern separation and pattern completion. It may be that the hippocampal subfields supporting these processes develop on different timelines, thus rendering the two properties unrelated (29, 30). It is additionally possible that the inputs to hippocampal subfield CA3, which can perform both computations depending on the nature of the input, also develop at relatively different rates (6). The recurrent collaterals within CA3 that support pattern completion may be relatively stronger in younger children, thus biasing them toward pattern completion rather than pattern separation. Speculatively, since cholinergic activation supports the process of pattern separation, acetylcholine may be relatively more subdued in younger kids and exert a stronger influence with age (6, 31, 32).

These conjectures rely on the assumption that our tests of pattern separation and pattern completion are process pure, but of course, it is possible that aspects of each task rely on the other component memory process. For instance, our mnemonic discrimination task contains the target item as well as a similar lure. It is possible that seeing the similar lure causes the participant to recall the target via a process of pattern completion since the lure may remind the participant of the previously seen item (33). This contrasts with the mnemonic similarity task that is often used in tests of mnemonic discrimination (12). One might also argue that, because our holistic recollection task prompted participants to select among several items they saw during encoding, they had to perform a process of pattern separation to reject the incorrect associations. Although our holistic recollection task is conceptually identical to previous studies (1, 2), the construct could potentially be tested via recall or cued-recall rather than recognition, thus potentially yielding a purer, albeit more difficult, task (1).

These limitations aside, our results are exciting for both the fields of development and memory research more broadly. Our findings may help us better understand the phenomenon of developmental amnesia (26). We found that younger children can holistically represent an experience while they simultaneously forget the specifics of that experience. This blurring of specific details, especially evident a week after encoding, may in part explain why episodic memories are less faithfully encoded in young children. Instead, they may be focused on encoding a more generalized summary of the events of their lives and, for instance, the animals, objects, and locations within them. It is well known that while younger children form relatively less episodic memories than their older peers, they can acquire semantic knowledge. This tendency toward pattern completion rather than pattern separation may help support the preferential acquisition of this general world knowledge.

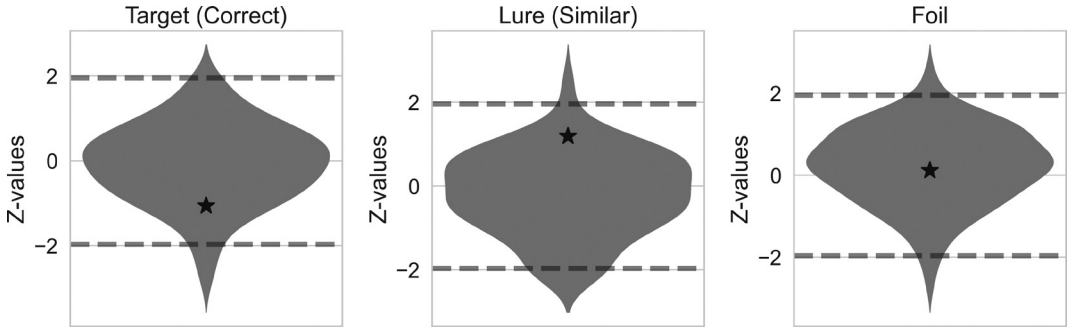

Fig. 5. A comparison between the actual z-value for the relationship between how often the target, lure, or foil was selected on a given event and the holistic recollection for that event (black star) and possible z-values from permuted distributions (gray violin plots). Permuted distributions were derived by permuting event-wise holistic recollection across all children 100 times. Values outside of the border of the dashed lines indicate significant z-values at the 0.05 level.

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Materials and Methods

Participants. A total of 95 4- to 7-y-old children participated in the current study. Of these children, one was excluded due to poor language proficiency, seven did not return for the second session when their memory was tested, and four participants are missing because their data were improperly recorded due to experimenter error. The final sample included 83 children (5.77 ± 1.21 y, range = 4.0 to 7.9 y, 52 female, 31 male) provided useable behavioral data and were included in the analyses; 33 of these participants (40%) recalled the memoranda immediately after encoding (*immediate* retrieval group, described below) and 50 participants (60%) recalled the memoranda after a 1 wk delay (*delayed* group; see below). The delayed group was introduced due to the large proportion of participants who were at ceiling for the holistic recollection task in the immediate group (7/33 participants, or a little over 20%). The interval between encoding and retrieval was between four and 20 d for the delay group (on average 7.42 ± 2.25 d). Children were recruited from a major metropolitan area in the United States through recruitment events and online advertisements. Children were enrolled in a larger, ongoing, longitudinal study on memory and brain development in accordance with and approved by the Institutional Review Board at Temple University. Prior to enrollment, children were screened via parental report to ensure they were proficient in English, had not been diagnosed with a psychiatric, neurological, or developmental disorder, had no known metal in their body, and exhibited normal or corrected-to-normal vision and hearing. Informed consent was obtained from parents, and written assent was obtained for 7-y-old children. Most of the sample identified as white, from middle- to higher-income households.

Materials. The stimuli came from 216 child-friendly cartoon images used in a previous study (21). Of these stimuli one-third were scenes (e.g., a lake), one-third were animals (e.g., a sheep), and one-third were objects (e.g., a mug). Each category of stimulus included 18 exemplar pairs (e.g., two similar images of lakes). Children encoded 18 unique scene–animal–object triads (e.g., lake–sheep–mug). The assignment of an item to a triad was predetermined based on the criterion that items with a potential pre-experimental semantic association (e.g., library and notebook) would not be assigned to the same triad. Following the methods of prior research in this age range (2), three-sentence audio narratives were created for each triad, with each sentence highlighting one association within the triad. For example, the lake–sheep–mug triad was accompanied by the following narrative: "Sheep rested by the lake. He was thirsty so he got out his mug to drink from. The mug looked very nice in the reflection on the lake." The order of the associations in the narrative (scene–animal, animal–object, object–scene) was consistent across all triads. All narratives were audio-recorded with a child-friendly female voice and were 15 s long. Following prior research in children (2), these narratives were used to maximize task engagement and the likelihood that comparable attention was drawn to each item within a triad.

Procedure. All children were tested individually in a room with an experimenter present and stimuli displayed on a 14-in. MacBook Pro laptop screen. The task was divided into two sessions. Each session consisted of an encoding phase, the mnemonic discrimination test (to assess pattern separation), and the holistic recollection test (to assess relational binding and pattern completion), administered in a fixed order. The two sessions were procedurally identical but with completely nonoverlapping stimuli (nine event triads/session). Children in the immediate retrieval group did encoding and retrieval for the first session immediately followed by encoding and retrieval for the second session (Fig. 1*A*). Children in the delayed retrieval group did encoding for both sessions on their first lab visit and retrieval for both sessions on their second visit (Fig. 1*B*). This order was consistent for all children in their respective retrieval group.

Encoding. Children were invited to play a "story game" about animals who went to places with objects. The encoding phase consisted of nine events. The items and events in nine were subsequently tested on. Four additional stories served as examples and subsequent test practice material: one was shown at the beginning of the encoding phase to acquaint children with the procedure, and three were shown at the end to be used as practice material for the mnemonic discrimination test. In each event, a predesignated scene, animal, and object appeared simultaneously on the top, bottom left, and bottom right of the screen, respectively. Each event was presented for 15 s with a 0.5-s intertrial interval. A corresponding prerecorded narrative accompanied each encoded event. The same session order and event order was administered to all children. The encoding phase for each session, including the example events, took approximately 4 min.

Mnemonic discrimination test. Either immediately after the corresponding session's encoding phase (*immediate* group, Fig. 1*A*) or 1 wk later (*delayed* group, Fig. 1*B*), children played the "which one" game wherein the experimenter wanted to know how well they had remembered the stories. We tested children's memory discrimination for each item seen in each story with a self-paced four-alternative-forced choice (4AFC) task. This test phase was divided into three blocks per session: scene, animal, and object (27 trials per session, nine items per item category). The session order, block order, and within-block trial order were identical for all children.

In every test trial, children were shown four image options from a given item category (e.g., four scene images) and were asked to choose the same image that they had seen previously by pointing to it. The four options included a target: the same image that appeared at encoding (e.g., the same lake), a lure: a similar exemplar of the target (e.g., a different lake), and two foils: similar exemplars of an unstudied place (e.g., two lighthouses). In a previously published study, an independent group of 31 young adults rated the level of similarity of each target–lure pair on a 7-point-Likert scale, ranging from 1-completely different, to 7-identical to each other in Qualtrics (21). During our study, the experimenter recorded the child's selection with a mouse click. The screen positions of the targets and lures were approximately equally distributed within each block and across the entire test phase. The mnemonic discrimination test phase for each session took on average 5.0 ± 2.0 min.

Note that the test phase for each session was preceded by a brief practice phase that introduced all three kinds of mnemonic discrimination test trials: scene, animal, object. In this practice phase, children were tested on items from the example events that were presented during the end of the encoding phase.

Holistic recollection test. The holistic recollection task for each session immediately followed the mnemonic discrimination task and was introduced as the "Go-together" game. In this game, children were instructed to choose the item that was previously presented in the same event as the cue. To estimate holistic recollection (defined in the Holistic Recollection Calculation), we tested children on all possible cue–item pairs for each three-item event (e.g., retrieving the object that belonged to the same event as the animal cue). This resulted in six different retrieval types per event (see Fig. 1*C* for illustration). The six different retrieval pairs were separated into blocks with nine trials per block for a total of 54 trials per session. To maintain attention, there was a self-paced break between each block. All children were tested in the same pseudorandomized block order so that bidirectional test types did not occur in succession (e.g., A_B following B_A, where B and A come from the same event).

On each test trial, a cue and four options were presented simultaneously (Fig. 1*C*). The four options consisted of one target: the correct item associated with the same event as the cue, and three lures: same-category elements from different events in the same session. The position of the target was counterbalanced across the test phase. Each item served as a lure an equal number of times across all trials within each block and across the entire test phase. Given that holistic recollection is based on the accuracy of test trials that share the same cue (e.g., A_B and A_C) or the same to-be-retrieved item (e.g., B_A and C_A), we counterbalanced how often the lures on these trials overlapped in their membership. Across all nine events in each session, any given two test trials that had overlapping cue items (e.g., A_B and A_C, where the A's are the same scene), or tested items (e.g., B_A and C_A, again, where A is identical across pairs), or were bidirectional (e.g., A_B and B_A, where A and B are identical) only shared one lure with one another. For example, for the A_B test trial for event 1, the lures included the B elements from events 2, 3, and 4, whereas for the A_C trial for event 1, the lures included the elements from events 3, 5, and 7. Thus, only one B and one C lure both belonged to the same event (event 3). The holistic recollection test phase for each session took on average 8.0 ± 2.3 min.

As in the mnemonic discrimination test phase, a brief practice session preceded the holistic recollection phase for each session. In the practice phase, children were shown an example event and immediately tested with three example trials where each item served as the cue or as a to-be-retrieved item once (e.g., cue: scene–retrieve: animal; cue: object–retrieve: scene; and cue: animal–retrieve: object).

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Holistic Recollection Calculation. Following previous work (1, 2, 21), we estimated the degree to which people remembered (or forgot) all of the pair-wise associations within the same event while controlling for their overall associative memory accuracy in the holistic recollection task. We therefore calculated two values: 1) the proportion of joint retrieval, and 2) the independent model. Both are described below. The difference between the proportion of joint retrieval and the independent model yielded a measure of *holistic recollection* or *retrieval dependency*. Positive values indicate that children's memories are more holistic than we would expect due to chance, zero values indicate that there is no difference between the joint retrieval in a child's data and that indicated by the independent model, and negative values mean that children's episodic memories are more fragmentary than we would expect given their overall associative memory accuracy.

The proportion of joint retrieval. The proportion of joint retrieval is measured individually for each participant. It measures whether remembering (or misremembering) an item when cued by another item from the same event was associated with remembering (or misremembering) the same item when cued by the third item from the event. For example, it calculates if remembering a scene when cued by its associated object is associated with remembering the same scene when cued by the animal. Thus, we calculated the frequency with which each participant correctly remembered or forgot each possible pair of cue–item pairs (either A_BA_C, a common cue, or B_AC_A, a common to-be-retrieved item) from the same event. For each event, this was done separately for all six possible cue–item pairs, and then these values were averaged across all events and all pairs. Eq. **1** shows this equation for an example cue–item pair:

$$\frac{\sum_{i=1}^{N} \delta_i}{N} = \frac{\sum_{i=1}^{N} [(X_i \wedge Y_i) \vee (\rightharpoonup X_i \wedge \rightharpoonup Y_i)]}{N}, \qquad [\mathbf{1}]$$

where N is the total number of events, X_i are events where the cue successfully cues one item, Y_i are events where the cue successfully cues the other item, $\wedge$ is the logical "and," and $\vee$ is the logical "or," and $\rightharpoonup$ is the logical "not." δ_i is 1 if X_i and Y_i are both 1 or 0.

The independent model. To calculate a measure of the overall likelihood of remembering (or forgetting) any given cue–item pair, regardless of whether that pair belongs to the same event, we calculated the independent model based on previous work (1). For this calculation, the probability of remembering any scene–object pair is deemed independent of remembering any scene–animal pair. For each participant, we calculated average accuracy for one cue–item pair across all events and multiplied this value by the average accuracy for the other cue–item pair across all six possible situations with either a common cue or a common to-be-retrieved item, and then averaged these values across all pairs. The independent model is illustrated in Eq. **2** for an instance in which item A cues items B and item C:

$$P_{AB} * P_{AC} + (1 - P_{AB}) * (1 - P_{AC}), \qquad [\mathbf{2}]$$

where P_{AB} is the probability of A successfully cuing B across all events, and P_{AC} is the probability of A successfully cuing C across all events.

The measure of holistic recollection for each participant is the proportion of joint retrieval in their data minus the value calculated for their independent model (Eqs. **1** and **2**), thus controlling for overall pair-wise retrieval accuracy in a world in which someone is no more likely to jointly retrieve pairs from the same event than can be explained by accuracy alone. Since the variance of holistic recollection is dependent upon overall retrieval accuracy, we removed participants whose overall accuracy values on the holistic recollection task (relational binding) were within 5% of ceiling (above 95% accuracy; seven children from immediate group: three 5-y olds, one 6-y old, and three 7-y olds) or within 5% of floor (below 30% accuracy on a 4AFC task; 11 children: one 4-y old from the immediate group, and 10 from the delay group: nine 4-y olds and one 5-y old). These participants were removed from all results involving relational binding and holistic recollection and included in analyses involving mnemonic discrimination in isolation.

Per-event holistic recollection. Given our aim of relating mnemonic discrimination to holistic recollection within the same events, we computed holistic recollection, also known as retrieval dependency, on an event-by-event level. For this calculation, the independent model is calculated for each cue–item pair (as described above), and this value is then subtracted from the joint-retrieval value for each cue–item pair in each event (1 for jointly remembering or forgetting both pairs, or 0 for remembering one and forgetting the other). The six resultant dependency values for the cue–item pairs within each event are then averaged within each event, yielding an event-specific value for holistic recollection, also known as retrieval dependency, for every participant.

Per-event mnemonic discrimination. For each of the three items in each event, the rate at which targets, lures, and foils are chosen within that event yields a value of target, lure, and foil selection rate per-event.

Statistical Tests. For two-sample *t* tests that compare groups of different sizes, Welch's *t* tests were used as they allow for comparisons between groups with unequal variances. The degrees of freedom for Welch's *t* tests are determined by the Welch–Satterthwaite equation and are reported to two decimal places.

A linear mixed effects model was run to determine whether the order of cue–item pairs had an influence on relational binding accuracy.

The relationship between event-wise mnemonic discrimination and holistic recollection was calculated using a generalized linear mixed model with the repeated measure of participants (who are repeated across all 18 events). To determine where our results fall within a null distribution, the z-value of the relationship between mnemonic discrimination and holistic recollection was compared to permuted z-values where each participant's event-wise holistic recollection was permuted across all participants 100 times. All analysis code used in this manuscript is available on GitHub at https://github.com/samsydco/PSPC.

Data, Materials, and Software Availability. Anonymized (h5 file and .csv) data have been deposited in GitHub (https://github.com/samsydco/PSPC) (34).

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