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A Time and Place for Everything: Developmental Differences in the Building Blocks of Episodic Memory

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Abstract

This research investigated whether episodic memory development can be explained by improvements in relational binding processes, involved in forming novel associations between events and the context in which they occurred. Memory for item-space, item-time, and item-item relations was assessed in an ethnically diverse sample of 151 children aged 7 to 11 years and 28 young adults. Item-space memory reached adult performance by 9½ years, whereas item-time and item-item memory improved into adulthood. In path analysis, item-space, but not item-time best explained item-item memory. Across age groups, relational binding related to source memory and performance on standardized memory assessments. In conclusion, relational binding development depends on relation type, but relational binding overall supports episodic memory development.

Keywords

episodic memory; space; time

Episodic memory, the capacity to remember the past in specific detail, is a fundamental aspect of cognition. It not only supports our ability to face daily challenges, such as remembering where we last placed our phone but also provides the foundation for autobiographical memory (Nelson & Fivush, 2004), and building connections among past, present, and future states (Coughlin, Lyons, & Ghetti, 2014). Episodic memory improves substantially during childhood, and the implications of this development are far-reaching. For example, the episodic component of memory for a passage of text seems to reflect the degree of integration of ideas from that text more so than do other memory components, such as familiarity (Mirandola, Del Prete, Ghetti, & Cornoldi, 2011). Furthermore, measures

of episodic memory are part of standardized assessments of intellectual ability (Woodcock and Johnson, 1989). Finally, the development of episodic memory is impaired following even mild forms of acquired neurological insult due to cerebral hypoxia or ischemia (e.g., De Haan, 2012; Ghetti et al., 2010), or in common mental health conditions such as depression (e.g., Whalley, Rugg, Smith, Dolan, & Brewin, 2009), and anxiety (Airaksinen, Larsson, & Forsell, 2005). Overall, it is critical to understand the mechanisms underlying typical episodic memory development, given its importance for cognition, as well as its susceptibility to impairment across various conditions.

Episodic memory is known to improve during childhood (Ghetti & Lee, 2011). Its rise can be explained in part by improvements in strategic, or controlled, aspects of memory (Bjorklund, Dukes, Brown, 2009; Ghetti & Angelini, 2008; Ghetti, Castelli & Lyons, 2010; Shing, Werkle-Berhner, & Linderberger, 2008). However, based on research with adult humans and non-human animals (e.g., O'Reilly & Rudy, 2001), we know that episodic memory also fundamentally depends on the additional capacity to bind the arbitrary features of an experience into an integrated episodic representation (e.g., Eichenbaum & Cohen, 2001; Tulving, 1985). Although the capacity for episodic memory depends on the ability to bind the arbitrary features of an experience into an integrated episodic representation, relatively few studies have examined the possibility that basic binding mechanisms continue to develop late into childhood (e.g., DeMaster & Ghetti, 2013; Guillery-Girard et al, 2013, Lee, Ekstrom, & Ghetti, 2014).

Initial research suggested that binding mechanisms reached adult-like functioning by early childhood (e.g., Lloyd Doydum, & Newcombe, 2009; Sluzenski, Newcombe & Kovacs, 2006). However these initial studies did not directly manipulate binding operations; instead they varied the extent to which controlled encoding (i.e. incidental vs intentional) or controlled retrieval processes (i.e. recognition vs free recall) were engaged to successfully remember bound representations. Relative maturity of binding operations in early childhood was inferred from lack of age-related differences under conditions minimizing controlled processes. If binding mechanisms are truly age-invariant beyond early childhood, then the improvements in episodic memory observed into adolescence would not depend on changes in the nature of episodic representation, but rather on the extent to which children can mobilize cognitive resources or strategic processes to support the formation or retrieval of these episodic representations.

However, the possibility that binding operations contribute to the development of episodic memory during childhood has not been fully addressed, raising the question of whether the nature and quality of memory episodes continue to change during this period. In the present research, we addressed this gap in the literature and directly manipulated variables that are most relevant for binding operations.

Relational Binding Mechanisms and the Development of Episodic Memory

The rich experience associated with episodic memory, the sense of retrieving numerous details and mentally being in the past could not be achieved without mechanisms that integrate information about an event itself with information about where the event happened

(spatial binding; Ekstrom, Copara, Isham, Wang, & Yonelinas, 2011; Lloyd et al., 2009), when it happened (temporal binding; Eichenbaum, 2013; Friedman, 1991), and in the presence of what other events it co-occurred (associative binding; Russell, Cheke, Clayton, & Meltzoff, 2011; Giovanello, Schnyer, & Verfaellie, 2004), and also those mechanisms which integrate the other features of our experience, which include thoughts, intentions, and emotions. Without these binding mechanisms, the elements of episodic experiences would be fragmentary and could not be retained.

It is currently unknown whether spatial, temporal, and associative binding develop uniformly, or whether their development differs as a function of the type of relation. Adjudicating between these possibilities is important for at least two reasons. First, this knowledge would elucidate the nature of episodic memory difficulties during childhood: while it is known that episodic memory develops substantially during this period, it is possible that children experience particular difficulty with certain aspects of their episodic memories. This would have implications for the content of episodic memory throughout childhood. Second, this knowledge could provide a richer understanding of binding operations, as detailed below.

By one account, binding operations encode spatial, temporal, and associative relations equivalently (Konkel & Cohen, 2009). Consistent with this view, Konkel and colleagues found that adults with hippocampal lesions are equally impaired on spatial, temporal, and associative binding, when these abilities are concurrently assessed in over short memory delays (Konkel, Warren, Duff, Tranel & Cohen, 2008). Similar age-related differences of spatial, temporal, and associative binding would be consistent with the hypothesis that binding operations are equivalent irrespective of the type of relation being bound. The paradigm developed by Konkel et al. (2008) has substantive strengths, and we have adapted this paradigm for use with children in order to examine age-related differences in episodic binding

Alternative accounts point to functional dissociations among these types of binding (e.g. Ekstrom et al., 2011). For example, memory for space and time seem to involve separable cognitive processes (Tolentino, Pirogovsky, Luu, Toner, & Gilbert, 2012; van Asselen, van der Lubbe, & Postma, 2006), and different brain networks (Ekstrom & Bookheimer, 2007; Staresina & Davachi, 2009). If the children seem to improve at different rates depending on type of relational binding, we would conclude that there may be distinct and separable binding mechanisms.

Extant developmental research makes it difficult to draw firm hypotheses about potential differences in developmental trajectories, because all of these binding operations have never been compared within the same task, and with procedures that do not encourage the contribution of additional memory processes, including verbal strategies as further discussed in upcoming paragraphs. Nevertheless, this research does consistently suggest that robust age-related improvement is evident across all types of relations. For example, memory for spatial relations seems to improve into early adolescence (e.g., Lorscheid & Reimer, 2005) despite basic skills being observed in the toddler years (Newcombe, Huttenlocher, & Learmonth, 1999). Likewise, memory for temporal order is shown to improve from early to

later childhood (Friedman & Lyon, 2005), despite a rudimentary capacity to retrieve arbitrarily ordered sequences of actions in late infancy (e.g., Bauer & Leventon, 2012). Similar findings hold for item-item associations (e.g., Shing et al., 2008). Overall, while these results indicate that memory for item-space, item-time, and item-item relations all undergo substantial development during childhood, they necessarily cannot provide comparative information about potential differences in developmental trajectories. We know of no studies that directly compared binding by type of relation during infancy or early childhood. However, several studies do hint at the possibility that distinct trajectories may be observed. In two cross-sectional studies examining memory for both item-space and item-time relations, memory for item-space relations was superior to memory for item-time relations in early middle-childhood (Picard, Cousin, Guillery-Girard, Eustache, & Piolino, 2012), but item-time memory may improve substantially in late-childhood (Guillery-Girard et al., 2013) and adolescence (Picard et al., 2012). These results are in line with evidence that memory for temporal order of autobiographical memories seems particularly fragile until at least middle childhood (Pathman, Doydum, & Bauer, 2013), despite being present in infancy (Bauer & Leventon, 2012; Riggins, 2012).

Even less is known about how the developmental trajectory of item-item relations compares to that of memory for item-space and item-time relations. Behavioral studies have reported protracted age-related trajectories in memory for paired associates (e.g., Kee, Bell, & Davis, 1981), but no comparisons were made with memory requiring binding of items in their spatial and temporal relations. By providing initial evidence for distinct trajectories, this prior research has laid an important foundation for the present work. However, the evidence is not conclusive because, even when testing the same children across tasks, these studies used different materials and procedures to test each relation (e.g., Guillery-Girard et al., 2013; Picard et al., 2012), reducing the opportunity for a direct comparison. Furthermore, these studies employed materials that could be easily encoded verbally, providing an opportunity to apply semantic and other organizational memory strategies, which are known to robustly develop into adulthood and support the formation and retrieval of episodic memories (Bjorklund, et al., 2009). For example, controlled retrieval strategies may leverage semantic categorical information to guide retrieval searches (e.g. There were several vegetables that I saw, which were they?), or infer relations through semantic relations (e.g., I saw a fork and frying pan together because both are found in the kitchen). The opportunity to rely on these additional verbal and organizational strategies may obscure true age-related differences in the binding of arbitrary relations. In the present study, we addressed these limitations with an assessment of each type of binding within the same paradigm, and with materials that cannot be easily verbalized.

On the other hand, it is also important to show that relational binding performance is relevant to performance in more typical episodic memory tasks that are known to benefit from verbalization, strategies or other forms of controlled processes, and relate to the types of memory in which children typically engage, for example in school settings (e.g., Mirandola et al., 2011). In the present study, we examined whether performance in relational binding predicted episodic memory, as assessed with completely different materials and procedures.

The Present Study

The main goal of the present research is to examine age-related differences in spatial, temporal, and associative binding operations with a within-subject paradigm adapted from Konkel et al. (2008). This paradigm has several strengths. First, it employs a single encoding procedure across types of relations in a within-subject design. This helps ensure that all items and their relations are initially processed in the same way, which increases comparability across conditions within each individual. Second, the paradigm employs novel visual stimuli that are resistant to easy verbal labeling and fully arbitrary relations. In Konkel et al. (2008), these stimuli included complex, abstract shapes that may pose undue processing challenges for children. We adapted the task to include concrete, yet unknown, objects, so as to reduce the possibility that age-related differences in performance reflect differences in the use of semantic-based organizational strategies (Bjorklund et al., 2009), or unitization (Diana, Yonelinas, & Ranganath, 2008; Quamme, Yonelinas, & Norman, 2007), while minimizing visual processing demands. Third, the paradigm assesses item memory in addition to relational memory to help account for age differences in the capacity to encode and retrieve item features that contribute to memory requiring binding. Fourth, the paradigm employs a recognition memory paradigm with a short delay between encoding and retrieval to reduce the contribution of age-related differences in long-term storage capacity and retrieval search demands.

We predicted that distinct age-related differences would be found for memory requiring item-space, item-time, and item-item binding, which would suggest heterogeneity in the underlying binding operations. Specifically, we predicted that age differences in performance between children and adults would be greater for item-time binding compared to item-space binding. This hypothesis was based on evidence that younger children remember item-space relations much better than item-time relations (Picard et al., 2012), which suggests a more protracted course of development in the latter. In addition, despite the paucity of research examining the development of item-item binding, we also predicted that this type of relation will result in age differences that will continue into adulthood. This prediction is based on a small set of developmental studies (e.g., Kee et al., 1981), and the fact that adults show lower performance on an item-item binding condition as compared to item-space and item-time conditions (Konkel et al., 2008).

We argued that the use of a task in which participants are required to retain arbitrary relations among visually novel items allows us to identify and compare age-related differences in the binding operations that are at the core of episodic memory. However, it is important to show that performance on this binding task is predictive of performance on other tasks that are traditionally used to assess episodic memory. Thus, one final goal of the present study was to verify that performance in the binding task predicts performance on a source memory task (e.g., Cycowicz, Friedman, Snodgrass, & Duff, 2001), which is a type of measure that is typically used in the laboratory to examine episodic memory (Tulving, 1985), as well as on a standardized measure of memory functioning, the Wide Range Assessment of Memory and Learning, Second Edition (WRAML-2; Sheslow & Adams, 2003).

Method

Participants

A total of 158 children aged 7 to 11 years (81 female), and 32 college-age adults (17 female) participated in this experiment. We examined children aged 7 to 11 years because prior evidence suggests that there are substantial improvements in memory and cognition during this period (e.g., Waber et al., 2007). Child participants were recruited from the Sacramento metropolitan area via authorized flyers distributed through elementary schools to parents, whereas adults were undergraduate students recruited through UC Davis. Child participants received monetary compensation and adult participants received class credit for their participation. Data were collected from December of 2011 to June of 2014.

Participants came from a diverse racial and ethnic background: 7.3% identified themselves as African-American, 8.4% Asian, 40.2 % Non-Hispanic Caucasian, 8.9% Hispanic Caucasian, 0.6% Native American, 1.1% Pacific Islander, and 21.2% of Mixed race, while 12.3% of participants declined to identify a race. Children and adults were ineligible for participation if there was a history of learning disability, neurologic disease, or psychological issue requiring medications, which was assessed at the time of recruitment.

Materials

Triplet Binding Task (TBT)—The TBT is a memory task adapted from Konkel et al. (2008) for use with child participants. The TBT is designed to assess the capacity to remember item-space, item-time, and item-item relations, as well as item-recognition memory.

Each memory type (item-space; item-time, item-item; item) was assessed over two testing sessions. Within each testing session, the four memory types were assessed in blocks to minimize age-differences in switching costs that could influence performance. Assessment order was counterbalanced across participants. Within each assessment block, five mini encoding-retrieval phases were administered. Retrieval immediately followed encoding and consisted of three test probes. Across the two testing sessions, these procedures yielded 30 test probes for each memory type (i.e., 15 targets and 15 lures) respectively. Stimuli were administered on a laptop and included color images of novel real-world, obscure objects (Figure 1) likely to be impede semantic-based organizational memory strategies, the use of which is known to improve with age and contributes to the development of episodic memory (e.g. Bjorklund et al., 2009).

Wechsler Abbreviated Scale of Intelligence (WASI)—The Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999) is a measure of IQ for individuals aged 6 to 89 years. Full-scale IQ scores (FSIQ-2) were acquired using two subtests (Vocabulary and Matrix Reasoning).

Wide Range Assessment of Memory and Learning (WRAML-2)—WRAML-2 is a standardized battery of measures of an individual's immediate and delayed memory and learning abilities, standardized for individuals aged five years and older (Sheslow & Adams, 2003). This battery produces a normalized General Memory Index (GMI) score representing

an individual's overall memory ability. One of the components of the GMI is the Verbal Memory Index which reflects a person's ability to learn and retrieve verbal information, and can be used as an index of an individual's ability to use language in the service of remembering.

Source Memory Task—The task consisted of three interleaved encoding-retrieval phases. Each encoding phase presented participants 48 item-scene pairs to remember. Each retrieval phase included 64 line drawings, 48 of which had been presented during the prior encoding phase, and the remaining 16 of which were new drawings. This procedure yielded a total of 144 old and 48 new probes. Source memory was computed as the number of correctly identified sources divided by the number of drawings that the participant correctly identified as old.

Procedure

The assessments for the present study took place over two testing sessions, separated by approximately one week. In the first session, participants completed the WRAML-2, the WASI and the TBT task as described below. In the second session, participants completed the source memory task.

TBT Encoding phase—Each encoding phase included three unique trials. Each trial consisted of a triplet sequence of unique images, each individually presented for one second at one of three locations on the screen and appearing immediately after the last (Figure 1a). All three locations were used on each trial, and locations were equidistant from the center of the computer screen. Between each trial, a one second inter-trial fixation was presented. Once all three trials in the encoding phase were presented, the three trials were presented a second time in duplicate. This gave each participant two chances to encode the relations in each triplet sequence. Encoding procedures were identical for each type of memory assessment. Prior to each condition block, participants were instructed and tested on their understanding of the instructions, the relation to be remembered, and the trial structure (i.e. the triplet grouping in each trial) using practice encoding and retrieval phases. Participants were reinstructed as necessary.

TBT Retrieval Phase—After the end of an encoding phase, memory for item recognition or for item-space, item-time, or item-item relations was tested, depending on the current block (Figure 1). In a retrieval phase, memory was tested with three probes, including targets and lures.

Item recognition: In the item-recognition condition participants determined whether all images were studied. Three images simultaneously appeared in a horizontal line across the center of the screen. On target trials, three studied images from the same encoding phase were presented. On lure trials, one image was studied and two were novel (Figure 1b).

Item-space binding: In the item-space binding condition, participants determined whether images were in their original locations or not. Images from one encoding sequence appeared

together on the screen. In target trials, all images appeared at their original locations. In lure trials, two images switched locations (Figure 1c).

Item-time binding: In the item-time binding condition, participants determined whether images appeared in their original order or not. Images from one encoding sequence appeared sequentially in the center of the screen; thus none of them appeared in the original locations. In target trials, all images were in their original sequential order. In lure trials, two images switched ordinal position within the sequence (Figure 1d).

Item-item binding: In the item-item binding condition, participants determined whether all images appeared together in the same encoding triplet. Three images simultaneously appeared in a horizontal line across the center of the screen, with no image appearing in one of the three original locations. In target trials, all images appeared from the same encoding triplet. In lure trials, one image was replaced by an image from an encoding triplet from the same encoding-retrieval phase within the block (Figure 1e).

Source Memory Task—The source memory task took place in an MRI scanner one week following administration of the other tasks. Analysis of neuroimaging data is not presented in the current report. The task consisted of three interleaved encoding-retrieval phases. On each encoding trial, a park, farm, or a city scene was presented for one second. A line drawing was then placed at the center of the scene for 2 seconds during which participants had to make a semantic judgment about whether the drawing belonged to that scene by pressing a “belongs” versus “does not belong” button on a key board. In the test phase, for drawings previously studied participants were to identify the scene with which the item had appeared (park, farm, or city), or to indicate that the scene could not be recalled by pressing one of 4 corresponding buttons on the right hand keyboard. If participants thought the drawing had not been previously studied, they were to press the Novel button on the left hand keyboard.

Results

Preliminary Analyses

Based on inclusion criteria established prior to data collection, participants were excluded from primary analyses if they failed to discriminate old from new items on the item-recognition memory condition (i.e. hits - false alarms = 0). Application of this criterion resulted in the exclusion of 13 participants (5 female; $M = 9.29$ years, $SD = .93$, range = 7.26 - 10.68). Two 9-year-old male participants failed to complete the TBT task and were thus excluded from analyses. One additional child participant was excluded from analysis because of an incidentally discovered brain abnormality from data collected as part of a larger longitudinal study.

Preliminary analyses of TBT performance revealed no main effect of gender ($ps > .74$) or interaction between gender and age or binding condition ($ps > .12$). Therefore, we excluded gender as a factor in our primary analyses. Additionally, preliminary analyses revealed no main or interactive effect involving counterbalancing condition ($ps > .19$). Thus, we collapsed across counterbalancing conditions in subsequent analyses.

For our primary analyses, five child groups were created based on age (Quintile I, $n = 29$, $M = 7.98$, $SD = 0.34$, range 7.10 – 8.39 years; Quintile II, $n = 28$, $M = 8.61$, $SD = 0.14$, range 8.39 – 8.86 years; Quintile III, $n = 29$, $M = 9.32$, $SD = 0.23$, range 8.88 – 9.66 years; Quintile IV, $n = 27$, $M = 10.11$, $SD = 0.23$, range 9.74 – 10.47 years; Quintile V, $n = 29$, $M = 11.02$, $SD = 0.48$, range 10.47 – 11.99 years), which created child age groups of similar size to the adult-sample. For convenience, Quintiles I thru V are referred to as 8-year-olds, 8½-year-olds, 9½-year-olds, 10-year-olds, and 11-year-olds, respectively corresponding to the average age in each quintile.

Age-related Differences in Item-Space, Item-Time, and Item-Item Binding

Hit and false alarm rates for each age group are reported in Table 1. We conducted a 6 (age group: 8, 8½, 9½, 10, and 11-year-old children, and adults) $\times$ 3 (condition: item-space, item-time, item-item) by two (trial-outcome: hit, false alarm) repeated measures Multivariate Analysis of Covariance (repeated measures MANCOVA) with item-recognition discrimination (proportion hits minus proportion false alarms on the item-recognition memory condition) entered as a covariate. Results revealed a significant main effect of trial-outcome, and interactive effects of trial-outcome with age and binding condition, $F_s = 6.31$, $p_s = .01$, captured in an overall age $\times$ condition $\times$ trial-outcome 3-way interaction, $F(10, 332) = 2.24$, $p = .02$, Wilks' $\lambda = .88$, $\eta_p^2 = .06$. We note that there was also a significant trial-outcome $\times$ condition $\times$ item-recognition covariate three-way interaction, $F(2, 166) = 7.35$, $p = .01$, Wilks' $\lambda = .92$, $\eta_p^2 = .08$; this further justifies the need to account for item-recognition since item-recognition might be more strongly associated with performance to binding some types of relations than others, and is investigated further in a later analysis.

Further inspection suggested that this three-way interaction was driven by the typically found pattern of age-related increase in hit rates and age-related decrease in false alarm rates. Examination of hits and false alarms separately in two 6 (age group) $\times$ 3 (condition) repeated measures MANCOVAs with item-recognition hits or false alarms (respectively) entered as a covariate did not reveal significant age group $\times$ condition interactions for hits, $F(10, 332) = 1.39$, $p = .18$, Wilks' $\lambda = .92$, $\eta_p^2 = .04$, or for false alarms, $F(10, 332) = 1.63$, $p = .10$, Wilks' $\lambda = .91$, $\eta_p^2 = .05$. Therefore, to simplify subsequent analyses, memory discrimination scores were computed by subtracting false alarm rates from hit rates separately for each condition. We then proceeded to examine age-related differences in discrimination scores separately for each type of condition. Thus, we conducted three one-way ANCOVAs with item-recognition discrimination entered as a covariate in each separately examining the effects of age on item-space, item-time, and item-item discrimination scores. In all of these analyses, post-hoc comparisons of age effects were conducted with Bonferroni corrected p-values (Figure 2).

In the item-space condition ANCOVA, a statistically significant main effect of age was observed, $F(5, 167) = 3.45$, $p = .01$, $\eta_p^2 = .09$. Adults performed significantly better on item-space discrimination than 8½-year-old children, Mean Difference = .20, $p = .02$, 95% CI [.02, .39]. No other age differences in marginal means reached statistical significance, $p = .07$. We note that there was also a main effect of the item-recognition discrimination covariate,

$F(1,167) = 31.27, p < .001, \eta_p^2 = .16$, which further justifies the need to account for this factor.

In the item-time condition ANCOVA, a significant main effect of age was observed, $F(5,167) = 8.70, p < .001, \eta_p^2 = .21$. Adults performed significantly better than 8-year-olds, 8½-year-olds, 9½-year-olds, and 10-year-olds; Mean Differences .22, $ps < .01$, 95% CIs [.03, .42]. Additionally, 11-year-old children performed significantly better than 8½-year-olds, Mean Difference = .22, $p = .01$, 95% CI [.03, .41]. No other comparison of marginal means reached statistical significance, $p > .06$. A significant main effect of the item-recognition covariate was also observed in the ANCOVA, $F(1,167) = 16.02, p < .001, \eta_p^2 = .09$.

Finally, in the item-item condition ANCOVA, a significant main effect of age was observed, $F(5,167) = 8.89, p < .001, \eta_p^2 = .21$. Adults performed significantly better than 8-year-olds, 8½-year-olds, 9½-year-olds, 10-year-olds, and 11-year-olds; Mean Differences .21, $ps < .01$, 95% CIs [.04, .37]. No other comparison of marginal means reached statistical significance, $p > 0.09$.

The influence of the interaction between item recognition and binding condition on parameter estimates is likely small and, if anything, results in more conservative effect size estimates and no increase in Type I error (Maxell & Delaney, 2004, p. 468). Nevertheless, we tested whether the condition x trial-outcome x age group interaction would be replicated if we were to assess the effect of item recognition as a between-subject factor. To this end, we dichotomized item-recognition scores to identify high and low performers based on a median split within each age group. A 2 (Dichotomized item-recognition: high, low) $\times$ 6 (age group: 8, 8½, 9½, 10, and 11-year-old children, and adults) $\times$ 3 (condition: item-space, item-time, item-item) x Trial-Outcome repeated measures MANCOVA fully replicated the condition x trial-outcome x age group interaction, $F(10, 322) = 1.95, p = .038, \eta_p^2 = .06$. Item-recognition interacted with trial-outcome, $F(1, 162) = 9.56, p = .002, \eta_p^2 = .06$, such that high item-recognition performers were associated with lower false alarm rates, $F(1, 162) = 9.16, p = .003, \eta_p^2 = .05$, but not greater hit rates, $p = .231, \eta_p^2 = .009$, and was potentially subsumed in a three-way interaction with condition, $p = .057, \eta_p^2 = .035$: Lower false alarms in high item-recognition performers were observed for item-space and item-time binding, $F(1, 162) = 7.44, p = .007, \eta_p^2 = .044$, but not for item-item binding, $p = .22, \eta_p^2 = .009$. Item-recognition did not interact with age group, $ps > .259, \eta_p^2 > .037$.

All effects of the primary analyses retained statistical significance if item discrimination was not entered as a covariate. Additionally, the age x condition x trial-outcome 3-way interaction was virtually identical to those reported above if WRAML-2 Verbal Memory Index was additionally entered as a covariate in the MANCOVA to control for verbal memory ability, $F(10, 330) = 2.43, p = .008, \eta_p^2 = .07$, if IQ was additionally entered as a covariate $F(10, 330) = 2.20, p = .017, \eta_p^2 = .06$, or if counter-balancing condition was entered as an additional between-subjects factor, $F(10, 296) = 1.95, p = .04, \eta_p^2 = .06$. We also note that the age group x condition x trial-outcome interaction was not sensitive to the particular child age group definition. For example, this interaction was fully replicated when age groups corresponded to age as an integer, $F(10, 332) = 2.09, p = .025, \eta_p^2 = .06$, to

tertiles, $F(6, 336) = 2.77, p = .012, \eta_p^2 = .05$, underscoring the robustness of our central result.

Condition-Related Differences—The interaction between age and condition justifies a further examination of whether level of performance on the different binding conditions differs within age groups. This analysis can provide additional information about predicted functional differences among these conditions. In adults, memory for item-space relations and memory for item-time relations were virtually identical and each was significantly better than memory for item-item relations (Mean Difference = .22, $p < .001$, 95% CI [.14, .29], Mean Difference = .22, $p < .001$, 95% CI [.13, .31], respectively). In contrast, in children overall, item-space memory was significantly better than item-time memory, Mean Difference = .15, $p < .001$, 95% CI [.10, .19], which in turn was better than item-item memory, Mean Difference = .15, $p < .001$, 95% CI [.10, .20]. To examine these differences in detail, differences in item-space, item-time, and item-item discrimination were compared within each age group using Benjamini-Hochberg (Benjamini & Hochberg, 1995) corrected p -values to control the false discovery rate, ($\alpha = .05$, 18 comparisons, 3 per age group). Within each age group, item-space, item-time, and item-item discrimination significantly differed in every comparison, Mean Differences = .11, $ps = .024$, 95% CIs [min = .02, max = .45] as subsumed by the general analysis. The only exceptions were that (a) item-time discrimination did not statistically differ from item-item discrimination in 8½-year-olds, Mean Difference = .03, $p = .62$, but each differed from item-space, and (b) item-space and item-time did not differ in adults, Mean Difference $< .01$, $p = .96$, but each differed from item-item.

Item-item discrimination seems particularly difficult for younger children despite acceptable levels of performance on the item-space and item-time associations. One might therefore wonder whether reliable item-item discrimination ability is conserved in the context of this paradigm. Therefore we report whether item-item discrimination was reliably greater than zero: 8-year-old, Mean Difference = .03, 95% CI [−.06, .11], $p = .52$; 8½-year-old, Mean Difference = .12, 95% CI [.026, .11], $p = .02$; 9½-year-old, Mean Difference = .07, 95% CI [−.005, .15], $p = .08$; 10-year-old, 11-year-olds, and adults each performed significantly different from zero, Mean Differences = .13, 95% CIs [.06, .52], $ps = .001$. Also, we note that eight-year-olds performed reliably different from zero on all other conditions, Mean Differences = .08, 95% CIs [.08, .42], $ps = .001$, as did all older age groups, $ps = .002$. In an earlier section, we showed that there were no age-differences in performance on item-item condition among children. Failure to fully differ from chance in 8-year-olds and 9½-year-olds suggests increased individual variability in these age groups. Individual differences were examined next.

Individual Differences in Relational Binding—An individual difference approach may be helpful to further explore the relation among binding of event features. In the previous analysis, memory for item-item relations seemed to exhibit the most distinct pattern of age-related differences compared to memory for item-space and item-time, with the latter failing to improve during childhood. Thus, we asked whether in children this feature would be more weakly related to the space and time event features.

We conducted a path analysis of the child data by first estimating the saturated model which accounted for age and item-recognition. We then progressively removed paths which failed to significantly change model fit, as estimated by maximum likelihood method. Zero order correlations among these variables in children are shown on Table 2(a). As a result, the paths from item-recognition, age, and item-time binding towards item-item binding were removed, $\beta_s < |.14|$, $SEs = .09$, $\chi^2(1) = 2.76$, $ps = .10$. All other paths led to significant changes in model fit, $\beta_s = .16$, $\chi^2(1)s = 9.61$, $ps < .01$. The final model is depicted in Figure 3, which demonstrated good fit, $\chi^2(3) = 4.88$, RMSEA = 0, SRMR = .04, CFI = 1.00. Thus, in children, item-space binding was a reliable predictor of item-item binding, while item-time binding was not a reliable predictor.

We note that the adult sample was insufficient to attain reliable parameter estimates, and we also chose not to collapse the adult data with the child data because of the absence of data from 12- thru 17-year-old participants and because we wanted to focus on individual differences in childhood. We reported zero-order correlations in adults in Table 2(b).

Relation to Source Memory and WRAML-2 Assessments—In a final analysis, we examined the degree to which overall binding performance on the TBT was predictive of performance on a source memory measure of episodic memory, and the WRAML-2, a standardized measure of memory functioning. All 174 child and adult participants included in the TBT analyses completed the WRAML-2 memory assessment and IQ assessments; however, 13 children (8 female), and 1 adult (0 female) did not elect to participate in the source memory task. Performance on these two tasks was normative. Descriptive statistics are reported for illustration purposes in Table 3 using the age groups with which we have conducted the previous analyses. GMI is standardized by age, and as would be expected, age groups did not reliably differ, $F(5, 168) = 0.96$, $p = .44$. Age-related improvements in source memory accuracy are typically reported (e.g., Cycowicz et al., 2001), and consistent with earlier findings, source memory accuracy differed as a function of age, $F(5, 154) = 12.3$, $p < .001$, $\eta_p^2 = .29$.

A composite binding score was computed across participants by averaging z-scores of item-space, item-time, and item-item discrimination scores. In two multiple regressions, we regressed source memory accuracy and WRAML-2 GMI scores onto the entered composite binding score, age, and WASI IQ. We included IQ because it has been shown to be substantively correlated to performance on WRAML assessments (e.g., Hartman, 2007) and to diminish the possibility that a significant relation between binding performance and WRAML performance would be due to language or fluid reasoning abilities. Both source memory accuracy and GMI were predicted by the composite binding score; results are summarized in Table 4. Relations between binding and episodic memory did not substantively differ if separately analyzing children and adults. The reliability and pattern of results are virtually unchanged if IQ is not entered as a predictor, (GMI: $\beta = .30$, $p < .001$; Source memory accuracy: $\beta = .26$, $p = .003$).

In summary, the results show that age-related differences in binding differ as a function of the type of relations being bound. Item-space memory reached adult levels by age 9 years, item-time memory reached adult levels by age 11 years, and item-item memory was

consistently lower in children than in adults. In adults, item-space binding and item-time binding were comparable and superior to item-item binding, but in children, item-space binding was superior to item-time binding, which in turn was superior to item-item binding. In contrast to item-time binding, item-space binding was a reliable predictor of item-item binding in the path analysis of the children's data. Finally, across children and adults, relational binding was related to two other measures of memory, a source memory task, and the standardized WRAML General Memory Index.

Discussion

Episodic memory critically depends on operations that bind the arbitrary features of experience into an integrated episodic representation of an experience (e.g., Eichenbaum & Cohen, 2001; Tulving, 1985). Episodic memory is known to improve in middle childhood (Ghetti & Lee, 2011) and its development has implications for a variety of domains including autobiographical memory (Nelson & Fivush, 2004), connecting past with the future (Coughlin et al., 2014), and capacities important to school performance (Mirandola et al., 2011). While part of that improvement is due to development in strategic, or controlled, processes supporting memory (e.g., Bjorklund, et al., 2009; Ghetti & Angelini, 2008; Ghetti et al., 2010), here we provide evidence that improvements in episodic memory also depend on binding operations specific to the basic capacity to form relational memories between fundamental features of our experience: items within space, within time, and with other items in the episode. Initial research suggested that binding mechanisms reached adult-like functioning by early childhood (e.g., Lloyd et al. 2009; Sluzenski et al., 2006), but these conclusions were made on the basis of manipulating controlled processes, not binding. We addressed this gap in the literature and directly manipulated variables relevant to binding using an experimental procedure that also controlled the contribution of strategic and other controlled memory processes, and provided a common foundation for direct comparison of relational binding across feature type and across age groups.

The Development of Relational Binding Operations

We predicted that age-related improvements in memory for item-space, item-time, and item-item relations would be observed, and that these age-related improvements would differ as a function of type of relation being bound. Consistent with predictions, age-related improvements in accuracy were observed for all types of relations but these improvements differed by type of relation, implicating the development of binding operations to account, at least in part, for the development of episodic memory in middle and late childhood. While initial research had suggested that binding reached adult-like operation in early-childhood (Lloyd et al. 2009; Sluzenski et al., 2006), manipulating the episodic representation was associated with robust and diverging age-related improvements in memory, despite using methods that should have substantially reduced the use and efficacy of controlled processes (e.g., encoding strategies; e.g., Bjorklund et al., 2009; Ghetti & Angelini, 2008); the predominate explanation of developmental improvements in episodic memory. These results are consistent with prior neuroimaging research which suggests a developing functional role of the hippocampus to binding operations (e.g., DeMaster & Ghetti, 2013; Guillery-Girard et al, 2013; Lee et al., 2014). Together these data support the hypothesis that binding

operations substantively contribute to episodic memory development in middle and late childhood.

We further predicted item-space relations would pose the least challenge to younger children, and that item-space binding would achieve adult levels of performance before item-time binding. Consistent with these predictions, memory for item-space relations reached adult levels of performance by 9½ years, while memory for item-time relations reached adult levels at 11 years. This pattern of results is consistent with that reported by Guillery-Girard et al. (2013), albeit the comparison in that study was made using two different behavioral tasks.

Guillery-Girard and colleagues suggested that the observed pattern of age-related differences in memory for time were due to developmental improvements in language and organizational strategies (Romine and Reynolds, 2004); these capacities could assist in producing linguistic temporal markers useful for event segregation and other reconstructive processes thought to be critical to memory for temporal order (e.g., Friedman & Lyon, 2005). While these processes may be in part responsible for their results, we note that memory for temporal order is present even in pre-verbal infants (e.g., Bauer & Leventon, 2012), and in the present study, verbal reconstructive processes are not likely to contribute due to the use of stimuli that should impede easy verbalization. Despite the common attribution to under-developed language concepts for time information (e.g., Conway, Pisoni, Anaya, Karpicke, & Henning, 2011), the present results suggest that children's poor memory for time may also depend on non-verbal episodic binding operations. Despite these differences in age effects between item-space and item-time binding, and prior evidence that spatial and temporal information are supported by separable brain networks in adults (e.g., Ekstrom & Bookheimer, 2007), our analysis of individual differences also suggests that these forms of binding may not be entirely unrelated, which is consistent with their shared dependence on the hippocampus (Konkel et al., 2008).

In addition, we had tentatively predicted that memory requiring item-item binding would be more difficult for children and later developing than memory requiring item-space or item-time binding, based on adults' lower performance in the item-item condition in Konkel et al. (2008), and on evidence that memory requiring item-item binding exhibits age-related improvements after childhood. Consistent with these predictions, item-item binding did not reach adult accuracy levels in any of the child age groups tested, and while item-space and item-time memory levels were similar in adults, these differed in children, again underscoring distinct trajectories for these types of relations.

One might ask whether an older child capable of remembering temporal order has all the information necessary to remember item-item relations. For example, if a child remembers that item B immediately followed item A, then the child should be able to infer that those items occurred in the same event. However, the results from the item-item condition do not support this hypothesis; not only was item-item binding more difficult, but age-related differences in this condition differed from those in the other binding types. One possible explanation is that item-time binding was not achieved by relating the order between items, but by relating items to an ordinal position within the trial episode (i.e. temporal tagging;

Pathman & Gheetti, 2014). If so, then the capacity to remember items with their ordinal position within triplet would not necessarily contribute to order retention across triplets and consequently to item-item binding performance. What then might explain the age-related difficulties in establishing that a set of items occurred within the same episode? One possibility is that when items appear at different moments within an episode, as items do in the present study, additional hippocampally mediated binding mechanisms are necessary to bridge the temporal gaps between related item representations (Staresina & Davachi, 2009; Tulving, 1985). These mechanisms may include those engaged in distinguishing between features occurring within an episode or across episodic boundaries (Davachi & DuBrow, 2015) and may be supported by specific populations of hippocampal neurons (e.g., Time Cells in CA1 subfield) thought to encode a distinct, temporally structured representation of the episode (MacDonald, LePage, Eden, & Eichenbaum, 2011). A direct comparison of item-item binding across different temporal gaps and stimulus durations might elucidate the impact of these dimensions on the development of binding relations between items.

Another possibility that might underlie the potential late development of item-item binding is that it might require that other, earlier developing binding operations come on-line first. This hierarchical dependency hypothesis can only be properly addressed with a longitudinal design. However, our exploratory path analysis model suggests that individual differences in the capacity to bind item-item relations may depend more on earlier developing operations supporting item-space binding than those supporting item-time binding, suggesting the hypothesis that item-space binding may be a developmental precursor of item-item binding.

One further possibility behind the relatively greater difficulty in remembering item-item relations might be that the stimuli used in the current study were visually complex, which might have magnified the difficulty in forming bound representations between these features, especially when those items were also novel and unique to each encoding phase. Relatedly, some have suggested that developmental improvements in episodic memory through middle-childhood and adolescence may in-part be due to a transition from static to flexible episodic representations (e.g., Edgin, Spano, Kawa, & Nadel, 2014); perhaps the use of novel items placed additional challenges on the capacity to encode and retrieve flexible episodic representations. However, a direct path from item recognition to item-item memory was not observed in our path analysis of children's behavior. Thus, to the extent that recognition of individual features contributes to performance, it seems to do so across all features, and in the case of memory for item-item relations, indirectly through item-space relation.

Relational Binding and the Development of Episodic Memory

The binding task designed for this study tested the capacity to encode the relation between features of an event and retain those relations in memory over a short delay. Due to this short delay, one could argue that this task measures capacities relevant to encoding some aspects of an experience, but have little bearing on how episodic memory is retained when information has to be retained over longer delays and contains features (e.g. cats, cars, calculators) that are semantically meaningful. Contrary to this possibility, we found that the capacity to remember relations in our binding task predicted performance on a traditional

episodic memory task, such as source memory, as well as performance on a standardized assessment of memory functioning, the WRAML-2; both the source memory task and the parts of the WRAML-2 require memory over delay and use materials that are familiar to participants (e.g., words and pictures of common objects). This relation with episodic memory stands even though our task employed novel and unfamiliar stimuli, the encoded relations among them were arbitrary and artificially imposed, and the associations with overall cognitive function, as indicated by IQ, were accounted for. These results strongly suggest that age-related differences in the TBT are central to episodic memory development; these basic operations encode relations about features of an event which might fundamentally shape children's episodic memories as they develop. Heterogeneous development of binding operations by type of relation might imply that children experience episodic memories that are different from those experienced by adults. For example, a young child might remember where she ran into her friend Dan and where she ran into her friend Mary, but not remember whom she had seen first, while her older sibling would be expected to remember this information. However, after these children later meet friends Johnny and Jack, both this young child and her older sibling would be expected to have difficulty remembering whether Johnny had been seen with Jack or if Johnny had been with Mary. This example not only suggests that the developmental state of binding mechanisms in middle and late childhood may impact our memories of personally meaningful events in childhood, they might also impact the capacity to navigate peer relationships in adolescence and beyond; for example remembering who said what, when, and with whom else might avoid social faux pas. However, episodic memory involves more than just objective retrieval of experiential details, but also involves monitoring the subjective re-experience of those details and then making attributions about the veracity of those memory states. If at the beginning of middle childhood the encoding of item-time relations produces more fragile memory representations than would the encoding of item-space relations, there may be greater requirements made upon procedural meta-memorial monitoring and control processes (e.g., Ghetti, Lyons, Lazzarin, & Cornoldi, 2008) for evaluating item-time relations than item-space relations, but this will need to be empirically evaluated.

Caveats and Future Directions

Before concluding, we note a few limitations of the present study. First, age-related differences in item-space, item-time and item-item memory were assessed with a task in which the encoding phase presented items varying in all of these dimensions. This procedure had the advantage to keep encoding constant across type of episodic feature thereby enabling us to compare trajectories; however, it may have increased the processing demands for younger children perhaps magnifying the apparent age-related differences. While, the condition differences in age-related trajectories minimize this concern, future research should examine the extent to which the present findings hold across different designs or task parameters. The present study has several strengths. First, a number of steps were taken to help ensure that age-related differences in binding of item-space, item-time, and item-item relations would reflect differences in core binding operations fundamental to the capacity to remember the past in rich detail. For example, the use of a recognition memory paradigm and the short delay between encoding and retrieval should have reduced the contribution of age-related differences in long-term storage capacity and retrieval search demands. The

experiment also employed novel stimuli that were nevertheless concrete and tangible; such stimuli were selected to ensure that age-related differences would not inordinately reflect development in semantic-based organizational strategies. Further, item-space, item-time, and item-item relations were arbitrary, which should have reduced the influence of unitization processes (Diana et al., 2008).

Future research should examine development of the neural underpinnings of binding operations involving space, time, and item association. One potential source of age-differences in childhood is the hippocampus, which is both thought to play a critical role in episodic binding operations, and to develop functionally (DeMaster & Ghetti, 2013; Ghetti, DeMaster, Yonelinas, & Bunge, 2010; Guillery-Girard et al., 2013), and structurally (DeMaster, Pathman, Lee, & Ghetti, 2014; Lee et al., 2014; Thompson et al., 2014), in childhood and adolescence. However, it is unknown how these age-differences in hippocampal structure and function may impact binding of item-space, item-time, and item-item relations.

Konkel & Cohen (2009) hypothesized that episodic binding depends on the hippocampus equally across all types of features and relations. Others point to differences in memory for space, time, and association to different regions along the longitudinal axis of the hippocampus (e.g., Giovanello, Schnyer, & Verfaellie, 2009), or to different cytoarchitectural subfields in the hippocampus (e.g., for a review, Hunsaker & Kesner, 2013). The heterogeneous age-related trajectories reported here are potentially inconsistent with the Konkel & Cohen (2009) hypothesis. However despite these findings, our analysis of individual differences in binding underscores that these capacities are correlated, which is expected given prior data of shared dependence on the hippocampus (Konkel et al., 2008). We note that the hippocampus is both structurally (Insausti, Cebada-Sanchez, Marcos, 2010) and functionally (Yassa & Stark, 2011) heterogeneous. One possibility, then, is that while all binding operations depend on the hippocampus, each may place different demands on its cytoarchitectural network (Watrous, Tandon, Conner, Pieters, & Ekstrom, 2013; but see Azab, Stark, & Stark, 2014), a network of subfields which has been shown to develop heterogeneously in both human (Lee et al., 2014) and non-human (Lavenex & Lavenex, 2013) primates. Consistent with these ideas are prior data supporting age-related differences in the contribution of different longitudinal sub-regions of the hippocampus to episodic memory encoding and retrieval (e.g., DeMaster et al., 2014; Ghetti et al., 2010). Together, evidence suggests that a relation may be found between the heterogeneous trajectories of binding observed here and hippocampal development. These differences and those that may occur during adolescence for item-item binding need further clarification, most usefully within a longitudinal design addressing both changes in binding and brain.

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Figure 1.

Triplet Binding Task (TBT). (a) Item-Recognition, Item-Space, Item-Time, and Item-Item binding conditions share the identical encoding procedures. Depictions of target and lure test trials for (a) item-recognition, (b) item-space, (c) item-time, and (d) item-item binding conditions.

Figure 2.

Age-related differences in memory for item-space, item-time, and item-item relations are plotted for 8-year-olds ($n = 29$), 8½-year-olds ($n = 28$), 9½-year-olds ($n = 29$), 10-year-olds ($n = 27$), 11-year-olds ($n = 29$), and adults ($n = 32$). Error bars signify standard error.

Figure 3. Path analysis model diagrams using standardized maximum likelihood parameter estimates predicting memory for item-item relations in children, $n = 142$.

Table 1

Mean Hits and False Alarms by Age Group

Condition		Age Group					
		8-year-olds	8½-year-olds	9½-year-olds	10-year-olds	11-year-olds	Adults
		<i>M (SD)</i>	<i>M (SD)</i>	<i>M (SD)</i>	<i>M (SD)</i>	<i>M (SD)</i>	<i>M (SD)</i>
Item	Hits	.65 (.16)	.72 (.16)	.68 (.18)	.75 (.12)	.77 (.15)	.85 (.12)
	False Alarms	.34 (.15)	.38 (.18)	.31 (.15)	.33 (.17)	.27 (.19)	.18 (.15)
Item-Space	Hits	.76 (.16)	.77 (.15)	.75 (.14)	.83 (.11)	.83 (.13)	.88 (.11)
	False Alarms	.43 (.22)	.47 (.21)	.37 (.17)	.32 (.17)	.30 (.15)	.24 (.16)
Item-Time	Hits	.67 (.17)	.62 (.14)	.63 (.17)	.74 (.13)	.75 (.14)	.86 (.12)
	False Alarms	.49 (.19)	.47 (.16)	.41 (.16)	.40 (.17)	.33 (.17)	.21 (.17)
Item-Item	Hits	.61 (.16)	.64 (.15)	.60 (.15)	.64 (.14)	.70 (.12)	.80 (.09)
	False Alarms	.59 (.16)	.52 (.18)	.53 (.13)	.51 (.15)	.49 (.15)	.37 (.19)

Table 2

Zero-Order Correlations between Item-Space, Item-Time, and Item-Item Discrimination Scores

Condition	1	2	3
<i>(a) Children</i>			
1. Item-Space	—		
2. Item-Time	.38***	—	
3. Item-Item	.39***	.24**	—
<i>(b) Adults</i>			
1. Item-Space	—		
2. Item-Time	.67***	—	
3. Item-Item	.54**	.49**	—

**
p < .01***
p < .001

Table 3

Performance on WRAML-2 and Source Accuracy Assessments

Task	Age Group					
	<u>8-year-olds</u>	<u>8½-year-olds</u>	<u>9½-year-olds</u>	<u>10-year-olds</u>	<u>11-year-olds</u>	<u>Adults</u>
	<i>M (SD)</i>	<i>M (SD)</i>	<i>M (SD)</i>	<i>M (SD)</i>	<i>M (SD)</i>	<i>M (SD)</i>
WRAML-2 GMI	106 (14)	106 (11)	107 (12)	101 (14)	107 (12)	105 (12)
Source Accuracy	.44 (.17)	.43 (.15)	.50 (.18)	.56 (.15)	.62 (.13)	.68 (.13)

Note: WRAML-2 GMI = Wide Range Assessment of Memory and Learning, 2nd Edition, General Memory Index

Table 4

Summary of multiple regression analyses across children and adults predicting memory on the WRAML GMI (N = 173) and on the source accuracy task (N = 159)

Variable	WRAML GMI			Source Accuracy		
	<i>B</i>	<i>SE B</i>	β	<i>B</i>	<i>SE B</i>	β
Binding Composite	3.91	1.24	.26**	.05	.018	.25**
Age	-.41	.25	-.13	.01	.004	.31***
IQ	.44	.06	.48***	.002	.001	.14*
Adjusted R ²		.27			.25	
F for R ²		22.5***			18.8***	

Note:

* $p < .05$.

** $p < .01$.

*** $p < .001$. WRAML-2 GMI = Wide Range Assessment of Memory and Learning, 2nd Edition, General Memory Index