RESEARCH ARTICLE

Asynchronous development of memory integration and differentiation influences temporal memory organization

Christine Coughlin[1] | **Athula Pudhiyidath**[1,2] | **Hannah E. Roome**[1] | **Nicole L. Varga**[1] | **Kim V. Nguyen**[1] | **Alison R. Preston**[1,2,3]

[1]Center for Learning and Memory, University of Texas at Austin, Austin, Texas, USA

[2]Department of Psychology, University of Texas at Austin, Austin, Texas, USA

[3]Department of Neuroscience, University of Texas at Austin, Austin, Texas, USA

Correspondence
Alison R. Preston, Department of Psychology, University of Texas at Austin, Austin, TX, USA.
Email: apreston@utexas.edu

Christine Coughlin, Department of Psychology, University of Illinois Chicago, Chicago, IL, USA.
Email: ccoughli@uic.edu

Abstract

Adults remember items with shared contexts as occurring closer in time to one another than those associated with different contexts, even when their objective temporal distance is fixed. Such temporal memory biases are thought to reflect within-event integration and between-event differentiation processes that organize events according to their contextual similarities and differences, respectively. Within-event integration and between-event differentiation are hypothesized to differentially rely on binding and control processes, which may develop at different ages. To test this hypothesis, 5- to 12-year-olds and adults ($N = 134$) studied quartets of image pairs that contained either the same scene (same-context) or different scenes (different-context). Participants remembered same-context items as occurring closer in time by older childhood (7–9 years), whereas different-context items were remembered as occurring farther apart by early adolescence (10–12 years). The differential emergence of these temporal memory biases suggests within-event integration and between-event differentiation emerge at different ages.

KEYWORDS
associative binding, context, control processes, episodic memory, event segmentation, temporal cognition

Research Highlights

- Children are less likely than adults to use contextual information (e.g., location) to organize their continuous experience in memory, as indicated by temporal memory biases.
- Biases reflecting *within-event integration* (i.e., remembering elements with a shared context as occurring closer together in time) emerged in late childhood.
- Biases reflecting *between-event differentiation* (i.e., remembering elements from different contexts as occurring farther apart in time) emerged in early adolescence.
- The differential emergence of biases reflecting within-event integration and between-event differentiation suggests they are distinct, yet complementary, processes that support developmental improvements in event memory organization.

Christine Coughlin and Athula Pudhiyidath contributed equally to this work.

1 | INTRODUCTION

Though life unfolds continuously, we remember our past as discrete events. Consider commuting home from work. During your bus ride home, you may encounter the bus driver and later a rude passenger. You may then exit at your bus stop and meet a friendly stranger while walking. Though these encounters unfolded continuously, you would likely organize them into two events in memory: integrating your encounters with the bus driver and rude passenger into a "bus ride event," which would be differentiated from the "walk home event" with the friendly stranger. Integrating experiences that share a context (e.g., the bus ride) helps link event elements into a meaningful memory representation (Clewett et al., 2019). Differentiating event elements that do not share a context enables later event discrimination based on unique memory details (e.g., the rude passenger vs. the friendly stranger; Clewett et al., 2019). Within-event integration and between-event differentiation based on contextual overlap, or lack thereof, are thus critical to how adults organize memories to support efficient recall (Zacks, 2020; Zacks et al., 2007). And yet, we know little about whether children similarly use context as a guiding factor for memory organization. Here, we test whether 5- to 12-year-old children and adults differ in their tendency to do so.

In adults, a shared context encourages the integration of elements across temporal gaps to form a single event, whereas a context change leads to the perception of an event boundary and the formation of distinct representations (Clewett et al., 2019). These contextual influences impact adults' subjective perception of time (Brunec et al., 2020; Lositsky et al., 2016). Event elements that occur the same objective temporal distance apart are subjectively remembered as occurring closer together in time (i.e., *temporally compressed*) when they share a context, and farther apart in time when they do not (i.e., *temporally expanded*; Ezzyat & Davachi, 2014). Neuroimaging data further indicate that items sharing a context are represented more similarly than items that do not, which tend to be neurally differentiated—resulting in subjective temporal compression or expansion, respectively (Ezzyat & Davachi, 2014). Context thus has a profound impact on adults' memory organization. Here, we quantify subjective biases in temporal memory behavior as a means to (1) address how context influences the organization of continuous experience in children relative to adults and (2) ask whether within-event integration and between-event differentiation emerge simultaneously in development or at different ages.

A rich history of cognitive development research indicates even infants organize events in memory and are impacted by multiple factors when doing so (Bauer et al., 2012; Bauer & Varga, 2017; Sharon & Wynn, 1998; Wynn, 1996; Yim et al., 2013). Infants are more likely to group elements into individual memories when a higher-order goal is present (Baldwin et al., 2001; Howard & Woodward, 2019), and toddlers use causal relations to chunk elements into memories (Bauer, 1992). And yet, studies using naturalistic viewing paradigms suggest there are continued developmental improvements in this ability. Such studies have typically examined behavioral and/or neural patterns associated with parsing a naturalistic movie into dis-

crete events online and in memory. Behavioral studies using this approach findings indicate 4/5- to 7-year-olds parse continuous experience into discrete events but agree less on when those parses occur compared to high-school students (Glebkin et al., 2019) and adults (Benear et al., 2022; Zheng et al., 2020). Corresponding neuroimaging work has found that neocortex activation becomes increasingly separated into stable and coherent events while watching a naturalistic movie between ages 5 and 19 years (Cohen et al., 2022). The intersubject correlation of neural activation during movie watching within sensory (Cohen et al., 2022), parietal, and prefrontal regions (Yates, Ellis, & Turk-Browne, 2021) also exhibits age-related increases across development. Together, this work shows continued refinements in how events are organized in memory across childhood and into adolescence.

Complementary, task-based research suggests within-event integration and between-event differentiation processes contribute to these refinements. While 4- to 6-year-olds exhibit some ability to integrate events in memory over time (Bauer & San Souci, 2010), and 6-year-olds do so particularly when event contexts are similar (Bauer et al., 2012), older children struggle to differentiate events in memory (Keresztes et al., 2017; Ngo et al., 2018, 2019). However, the majority of this research has examined within-event integration and between-event differentiation in isolation from one another, using discrete learning episodes. The question of how these processes support developmental change in the organization of continuous experience in memory—and whether they emerge at different ages—remains.

Importantly, there are protracted changes in binding and control processes deemed important for within-event integration and between-event differentiation (Clewett & Davachi, 2017; Radvansky, 2012), which may emerge at different ages (Ghetti & Bunge, 2012; Paz-Alonso et al., 2014). While the ability to bind an individual item to a context is present in infancy, developmental gains are particularly robust during middle- to late-childhood (e.g., 5–10 years) due to changes in hippocampal function (Ghetti & Bunge, 2012). Within-event memory integration also goes beyond binding an individual item to a context—instead linking temporally distributed items that share a context together in memory, which places additional demands on hippocampal processing. Such within-event integration may therefore emerge early but continue to develop across childhood with maturation of the hippocampus.

Between-event differentiation may emerge later than within-event integration given its reliance on processes supported by both the hippocampus and prefrontal cortex. One way the hippocampus keeps memories distinct is through pattern separation, which is the orthogonalization of highly similar input patterns into distinct neural codes (Yassa & Stark, 2011). This process happens automatically for all inputs due to the structure and firing rates of the dentate gyrus and CA_3 hippocampal subfields, which promote the formation of distinct event representations within memory. Prior work suggests that pattern separation supported by these subfields becomes more efficient between early and middle childhood (Ngo et al., 2019, 2018). However, differentiation mechanisms are proposed to go beyond

such automatic orthogonalization mechanisms to further pull apart the representations of similar events, resulting in partial to complete elimination of any overlap between events that share features (Hulbert & Norman, 2015). In contrast to pattern separation, differentiation is an active process that likely requires additional top-down control mechanisms supported by the prefrontal cortex, which further augment differentiation between hippocampal memory representations.

For instance, differentiation is proposed to rely on control processes involved in prediction, conflict, and error monitoring that are sensitive to context changes during continuous experience (Kurby & Zacks, 2008). Developmental improvements in these control processes extend into adulthood (Diamond, 2011; Luna, 2009) as prefrontal cortex function, structure, and connectivity with the hippocampus mature (Calaboro et al., 2020; Ghetti & Fandakova, 2020). Rodent studies suggest these changes may impact hippocampal differentiation in particular, with prefrontal cortex exerting a top-down influence on hippocampal remapping that can augment the differentiation of different-context elements (Colgin et al., 2008; Ito et al., 2015; Schlesiger et al., 2018). This augmentation is thus an active pulling apart within representational space as opposed to the automatic orthogonalization of pattern separation (Hulbert & Norman, 2015). The protracted development of these prefrontal-hippocampal processes and their underlying neural substrates may contribute to a later emergence of differentiation.

Here, we tested the prediction that between-event differentiation emerges later in development than within-event integration using a developmental version of a paradigm developed by Ezzyat and Davachi (2014) (Figure 1). This paradigm allowed us to assess age-related differences in the degree to which contextual information guides event memory organization by (1) quantifying the extent to which shared context biases participants to remember items as having occurred close in time relative to one another (indexing within-event integration) and (2) the extent to which changes in context bias participants toward remembering items as having occurred far apart in time relative to one another (indexing between-event differentiation). We recruited 5- to 12-year-old children and adults given that improvements in binding and control processes occur during this developmental age range (Ghetti & Bunge, 2012; Ghetti & Fandakova, 2020).

2 | METHODS

2.1 | Participants

One hundred and forty-eight volunteers participated in the experiment. Participants were divided into four age groups according to our age-related predictions: younger children (5–6 years), older children (7–9 years), young adolescents (10–12 years), and adults (18–35 years). Of the recruited sample, 14 participants were excluded from final analyses due to psychological symptoms outside the typical range ($n = 8$) (CBCL; Achenbach, 1999, SCL-90-R; Derogatis & Lazarus, 1994), computer problems ($n = 5$), or voluntary withdrawal ($n = 1$).

The remaining 134 participants included 38 younger children ($M = 6.00$ years, $SD = 6.97$ months, range = 5.08–6.92 years, 22 female), 32 older children ($M = 8.36$ years, $SD = 11.37$ months, range = 7.00–9.92 years, 22 female), 31 young adolescents ($M = 11.55$ years, $SD = 10.08$ months, range = 10.00–12.83 years, 14 female), and 32 adults ($M = 22.26$ years, $SD = 47.60$ months, range = 18.67–34.92 years, 19 female). The racial breakdown of the final sample was approximately 8% Asian, 3% Black, 10% mixed race, 73% White, and 6% unreported. Of these participants, 15% were of Hispanic or Latino ethnicity and 2% were unreported. Three participants included in the final sample were missing data for the source memory test (described in detail below) due to technical problems during the session. These participants were thus excluded from all analyses that included source memory performance (adjusted $N = 131$).

Because our experimental paradigm had not been previously used with a developmental sample, an a priori power analysis was not performed. Instead, to determine sample size, we relied on other temporal memory development work, which has typically targeted a minimum sample size of approximately 30 per age group (e.g., Pathman & Ghetti, 2014; Pathman et al., 2013). We also conducted a post hoc analysis derived from adult data using a similar paradigm (Ezzyat & Davachi, 2014). For this analysis, we used the effect size for a main effect of context condition on temporal distance memory ($d = 0.90$) and typical parameters (power = 0.90; alpha = 0.050). We found that a sample of 15 would be needed to detect an effect of context on memory (generated from R package pwr, Champely, 2013). Our sample included approximately twice that number per age group, which we deem appropriate given our interest in interactions with age and the large variability observed in developmental data (van Geert & van Dijk, 2002).

All participants were recruited from the Austin, TX area, with our sample reflecting the general economic and racial norms for that area. Participants were fluent in English and without a known developmental or psychological disorder. The study was conducted in a manner approved by the Institutional Review Board at the University of Texas at Austin, including the collection of informed consent (adult participants) or parental consent and minor assent (child and adolescent participants). All participants were compensated with $15 or, for some adult participants, participation credit for an introductory psychology course at the university.

2.2 | Stimuli

Experiment stimuli included pictures of 96 outdoor scenes, 112 everyday objects, and 112 cartoon faces. These stimuli were used to create 128 picture pairs comprised of a scene (always presented on the left) paired with a unique object or face (always presented on the right). Unbeknownst to participants, picture pairs were grouped into 16 *same-context quartets* and 16 *different-context quartets*, with each quartet consisting of four picture pairs (Figure 1a). In same-context quartets, the scene stimulus remained the same across all four picture pairs. In different-context quartets, the scene stimulus changed between the
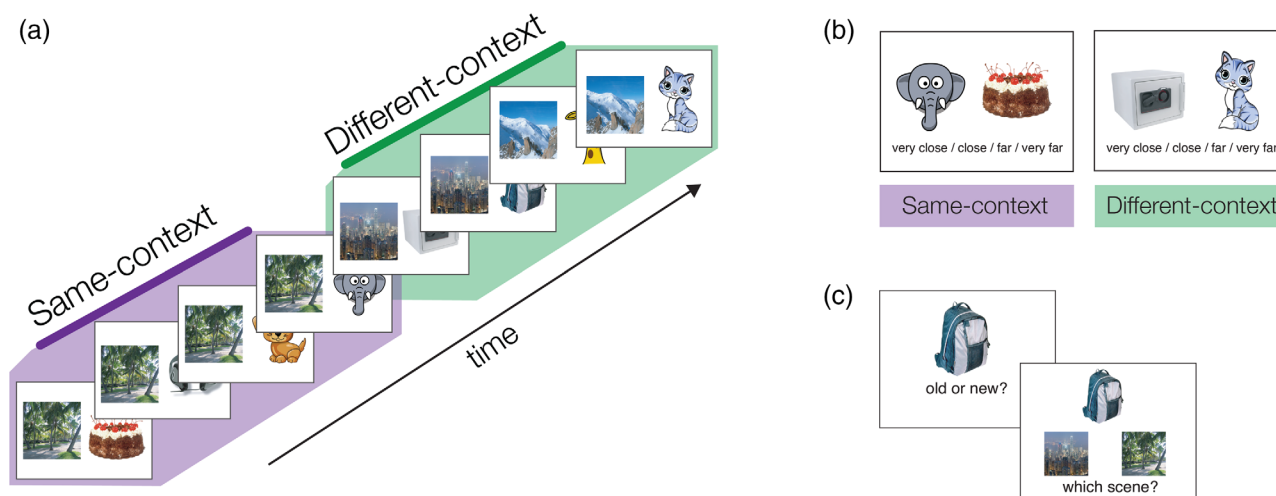
FIGURE 1 Participants completed three tasks over the course of the experiment. (a) *The imagination task*: Participants viewed a sequence of picture pairs consisting of a scene and a unique object or face appearing on the screen one at a time. For each picture pair, participants were given 4 s to imagine a story involving both of the pictures within the pair. Unbeknownst to participants, the picture pairs were organized into same-context (purple) and different-context quartets (green). Same-context quartets consisted of four picture pairs that shared the same scene. Different-context quartets consisted of four picture pairs that shared the same scene for the first two pairs, and then changed to a different shared scene for the last two pairs. (b) *The temporal memory test*: After viewing a block of picture pairs from the imagination task, participants were asked to judge how close in time they had viewed two items from different picture pairs, relative to one another; they were given 8 s to indicate their response. With this task, we aimed to test whether participants' judgments of temporal distance between the items was biased by whether they had been paired with the same scene or different scenes (i.e., context condition) during initial viewing. The two items displayed during each trial always came from a single quartet, half from same-context quartets and half from different-context quartets. Objective temporal distance was matched between same-context and different context items. (c) *The recognition plus source memory test*: Participants were given 5 s to identify which items were previously seen in the imagination task and which items were new. For each previously seen item, participants were given an additional 5 s to identify the scene with which it was paired.

second and third pairs of the quartet, such that the first two picture pairs shared the same scene and the last two picture pairs shared a different scene. The category of the picture (i.e., face or object) paired with each scene changed halfway through the quartet, such that quartets beginning with two face-scene pairs ended with two object-scene pairs and vice versa. This distribution of face and object stimuli was done in accordance with the original Ezzyat and Davachi (2014) paradigm, but was not of interest within the present study. Assignment of stimuli to same-context or different-context quartets and the order in which the stimuli were presented were randomized across participants.

2.3 | Procedure

The experiment consisted of three computer-based tasks: an imagination task, a temporal memory test, and a surprise recognition plus source memory test (Figure 1). Participants first completed four alternating rounds of the imagination task and temporal memory test (i.e., imagination block 1, temporal memory test 1, imagination block 2, temporal memory test 2, etc.). Next, their memory for the picture pairs presented during initial viewing was assessed in four rounds of a recognition plus source memory test. Each round of the recognition plus source memory test assessed memory for picture pairs presented in a corresponding imagination block (i.e., memory for the

pairs presented during imagination "block 1" was tested in recognition plus source memory "test 1," etc.). For all tasks, the experimenter entered participants' responses (either verbalized or gestured) via a button press to eliminate a potential confound resulting from age-related differences in motor responses. The experimenter also used child-friendly instructions and pictures to explain each task and administered short practice rounds of the imagination and temporal memory tasks prior to administering the first imagination block to ensure comprehension.

2.4 | Imagination task

The imagination task was comprised of four blocks. Each block consisted of 32 trials during which participants were shown a picture pair in the middle of the screen (Figure 1a). Each picture pair was made up of a scene and a trial-unique object or face. Unbeknownst to participants, these picture pairs were grouped into four same-context quartets and four different-context quartets, described in detail above. For each trial, participants were given 4 s to imagine a story about how the two pictures within the pair might go together. They were then shown a new screen for 1.5 s with the prompt "Were you able to imagine that?" along with "yes" and "no" responses displayed below it. At that time, they were instructed to say or point to "yes" if they were able to imagine a story involving the previously viewed picture pair or "no" if they

were unable to do so. Trials proceeded in immediate succession, one after another. The goal of this task was to support attention to, and encoding of, the picture pairs. We sought to direct attention toward the individual pairings rather than a conscious consideration of the time that elapsed between pairs.

2.5 | Temporal memory test

Immediately following each imagination block, participants' temporal memory for the picture pairs was assessed (Figure 1b). During each test trial, participants were shown two pictures from the previous imagination block (an object and face picture taken from the same quartet) and asked to judge how close in time they had viewed the two pictures relative to one another. Responses were reported on a 4-point Likert scale ranging from "very close," "close," "far," and "very far." Response options were displayed on every trial, and participants advanced to the next trial after they either provided a response or failed to do so within 8 s.

Each of the four temporal memory test blocks consisted of 16 trials, half derived from same-context quartets and half derived from different-context quartets. Furthermore, half of the trials displayed face/object pictures that had been presented back-to-back during the imagination task (i.e., from the 2nd and 3rd ordinal positions of a single quartet; *adjacent pairs*), and half of the trials displayed face/object pictures that had been separated by two other pairs during imagination (i.e., from the 1st and 4th ordinal positions of a single quartet; *nonadjacent pairs*). Importantly, adjacent and nonadjacent pairs were equally distributed across the same- and different-context conditions. This design feature matched the objective temporal distance of pairs from each context condition, allowing us to examine the degree to which participants' temporal distance judgments were biased by context shifts. Specifically, we could examine the extent to which participants reported more close responses for pairs from same-context quartets (indexing within-event integration) and more far responses for pairs from different-context quartets (indexing between-event differentiation). While including both adjacent and nonadjacent pairs ensured variability in objective temporal distance, it also allowed us to examine the extent to which participants' temporal distance ratings were sensitive to objective temporal distance irrespective of our context manipulation.

2.6 | Recognition plus source memory test

After completing four alternating rounds of the imagination task and temporal memory test, participants completed a surprise recognition plus source memory test (Figure 1c). This test consisted of four blocks, with each block testing participants' memory for the item-scene pairings from its corresponding imagination task block (i.e., memory for item-scene pairings from the first imagination block was tested during the recognition plus source memory test "block 1," etc.). Each block consisted of 56 trials. During each trial, participants were shown a picture of a face or an object with "old or new?" displayed below it.

Upon seeing each picture, participants were instructed to say or point to "old" if they remembered seeing the picture during the imagination task, and to say or point to "new" if they did not. They had up to 5 s to provide a response after which response feedback was provided in the form of "correct!" or "incorrect" displayed on the screen for 0.5 s. Thirty-two trials displayed a face or object picture from the associated imagination block (old pictures), and 24 trials displayed a novel face or object picture (new pictures). If the picture was new (regardless of response accuracy), the participant advanced to the next trial. If the picture was old (regardless of response accuracy), they were then asked to choose which of two scenes it had been paired with during imagination. The two scenes included the correct picture as well as a foil scene taken from the same imagination block. The two scenes and the text "which one?" were displayed beneath the original face or object picture. No feedback was provided during this phase of the trial, with participants advancing to the next trial after they either provided a response or failed to do so within 8 s.

2.7 | Analytic approach

We first ensured that imagination and source memory performance was high across age group, context condition, and block. Imagination performance was calculated as the percentage of trials for which participants reported successful imagination. Source memory was calculated as the proportion of old items whose associated scene from the imagination task was correctly identified by participants. These scores were then entered into separate 4 (age: younger children, older children, young adolescents, adults) × 2 (context condition: same vs. different) × 4 (block: 1, 2, 3, 4) mixed ANOVAs.

After ensuring high imagination and source memory performance, we addressed our primary aim by examining age-related differences in the influence of contextual information on event memory organization. Specifically, we compared the extent to which each age group remembered items as occurring close together in time when they shared the same context (indexing within-event integration), and far apart in time when they did not (indexing between-event differentiation). We transformed temporal distance ratings into *bias scores* to facilitate this analysis. First, consistent with the approach taken by Ezzyat and Davachi (2014), the proportion of close (collapsed across "close" and "very close") and far (collapsed across "far" and "very far") responses was computed within each context condition. Next, the proportion of far responses was subtracted from the proportion of close responses within each condition. This process resulted in positive or *"close-response bias"* scores and negative or *"far-response bias"* scores. We then used these scores to assess within-event integration (i.e., a greater close-response bias in the same-context condition) and between-event differentiation (i.e., a greater far-response bias in the different-context condition) within each age group. Specifically, bias scores were entered into a 4 (age: younger children, older children, young adolescents, adults) × 2 (context condition: same vs. different) × 2 (pair distance: adjacent vs. nonadjacent) × 4 (block: 1, 2, 3, 4) mixed ANOVA. Although pair distance was not central to our

primary aim, we included this variable in the ANOVA to examine whether participants demonstrated sensitivity to objective temporal distance.

Given that memory for contextual information improves with age (Ghetti & Bunge, 2012), we also analyzed bias scores controlling for source memory performance. This control analysis ensured that age-related differences in the influence of context on bias scores could not be explained by developmental improvements in memory for the contextual information (i.e., knowledge of the item–scene pairings). For this analysis, we first identified temporal distance trials for which participants demonstrated intact source memory (i.e., correctly identified which scene both items had been paired with during the imagination phase). Bias scores were recalculated for these trials only and then entered into a 4 (age: younger children, older children, young adolescents, adults) $\times$ 2 (context condition: same vs. different) mixed ANOVA. Pair distance and block were not included in this analysis because they were not of primary interest, and also because subsampling resulted in a reduced number of trials.

Previewing results, we found an age-related increase in both source memory and imagination success. We, therefore, conducted ancillary analyses examining whether main bias score findings held (1) controlling for successful imagination (i.e., only including temporal distance trials whose items had been successfully imagined with their respective scene during imagination) and (2) controlling for both successful imagination and source memory. One participant was excluded from the first analysis (adjusted $N = 130$) and three participants were excluded from the second analysis (adjusted $N = 128$) because they did not have trials that were successfully imagined and/or later recalled in the source memory test in either the same-context condition ($n = 1$), the different-context condition ($n = 1$), or both conditions ($n = 1$). For both analyses, bias scores from the subsampled trials were entered into a 4 (age: younger children, older children, young adolescents, adults) $\times$ 2 (context condition: same vs. different) mixed ANOVA. As with the analysis controlling for successful source memory only, pair distance and block were not factored into this analysis because they were not of primary interest, and also because subsampling resulted in a reduced number of trials.

3 | RESULTS

3.1 | Participants actively engaged in imagination

The mixed effects ANOVA assessing imagination performance showed a main effect of age ($F(3, 130) = 5.28$, $p = 0.002$, $\eta_p^2 = 0.109$). Subsequent comparisons showed that adults ($M = 0.83$, 95% CI = [0.77, 0.90]) reported greater imagination success than younger children ($M = 0.66$, 95% CI = [0.61, 0.72]; $p < 0.001$), older children ($M = 0.74$, 95% CI = [0.67, 0.80]; $p = 0.031$), and young adolescents ($M = 0.72$, 95% CI = [0.65, 0.78]; $p = 0.011$). The three younger age groups did not differ from one another, $ps < 0.094$. Despite greater imagination success in adults, a series of single sample t-tests confirmed all age groups reported successful imagination at rates significantly above

50% ($ps < 0.001$), suggesting active engagement with the imagination task across participants.

Results also showed a significant interaction between context and block, ($F(3, 130) = 2.65$, $p = 0.049$, $\eta_p^2 = 0.020$). Follow-up comparisons found that participants reported greater imagination success in the different context condition ($M = 0.75$, 95% CI = [0.71, 0.78]) compared to the same context condition ($M = 0.72$, 95% CI = [0.68, 0.75]) in the first block, $p = 0.013$ (all other blocks: $ps \geq 0.099$).

3.2 | Participants remember item-scene associations

Having established successful imagination performance at all ages, we next examined memory for the item-scene associations via source memory performance. The mixed ANOVA on source memory scores found a main effect of age ($F(3, 127) = 47.06$, $p < 0.001$, $\eta_p^2 = 0.526$). Follow-up comparisons showed that adults had significantly higher source memory accuracy ($M = 0.88$, 95% CI = [0.85, 0.92]) than both younger ($M = 0.64$, 95% CI = [0.61, 0.67]; $p < 0.001$) and older children ($M = 0.79$, 95% CI = [0.76, 0.82]; $p < 0.001$), but did not differ from young adolescents ($M = 0.88$, 95% CI = [0.84, 0.91]; $p = 0.801$). Younger children, older children, and young adolescents all differed significantly from one another ($ps < 0.0001$), such that accuracy increased with age. Despite these age-related differences, a series of single sample t-tests showed that all age groups demonstrated source memory accuracy that was high and significantly above chance ($ps \leq 0.0001$; also see Figure S1 for source memory performance plotted by age in years).

Results also showed main effects of context condition ($F(1, 127) = 4.05$, $p = 0.046$, $\eta_p^2 = 0.031$) and block ($F(3, 381) = 4.20$, $p = 0.006$, $\eta_p^2 = 0.032$) that were further qualified by an age $\times$ context condition $\times$ block interaction, $F(9, 381) = 1.92$, $p = 0.049$, $\eta_p^2 = 0.043$ (Figure 2). Follow-up comparisons showed that, while overall performance was slightly better in the different-context condition ($M = 0.80$, 95% CI = [0.79, 0.82]) compared to the same-context condition ($M = 0.79$, 95% CI = [0.77, 0.81]), this effect was especially evident in younger children ($p = 0.004$) and adults ($p = 0.028$) during the first block (older children and adolescents: $ps \leq 0.196$). Effects in subsequent blocks for each age group were less strong ($ps < 0.077$). That item–scene pairings were better remembered in the condition that involved a context shift aligns with prior work showing context shifts can lead to the perception of an event boundary (Clewett et al., 2019), and that event boundaries strengthen item-context binding (Heusser et al., 2018).

3.3 | Asynchronous development of within-event integration and between-event differentiation

Next, we examined whether the impact of our context manipulation extended to how participants subjectively remembered the temporal distance among sequence elements. The mixed ANOVA on bias
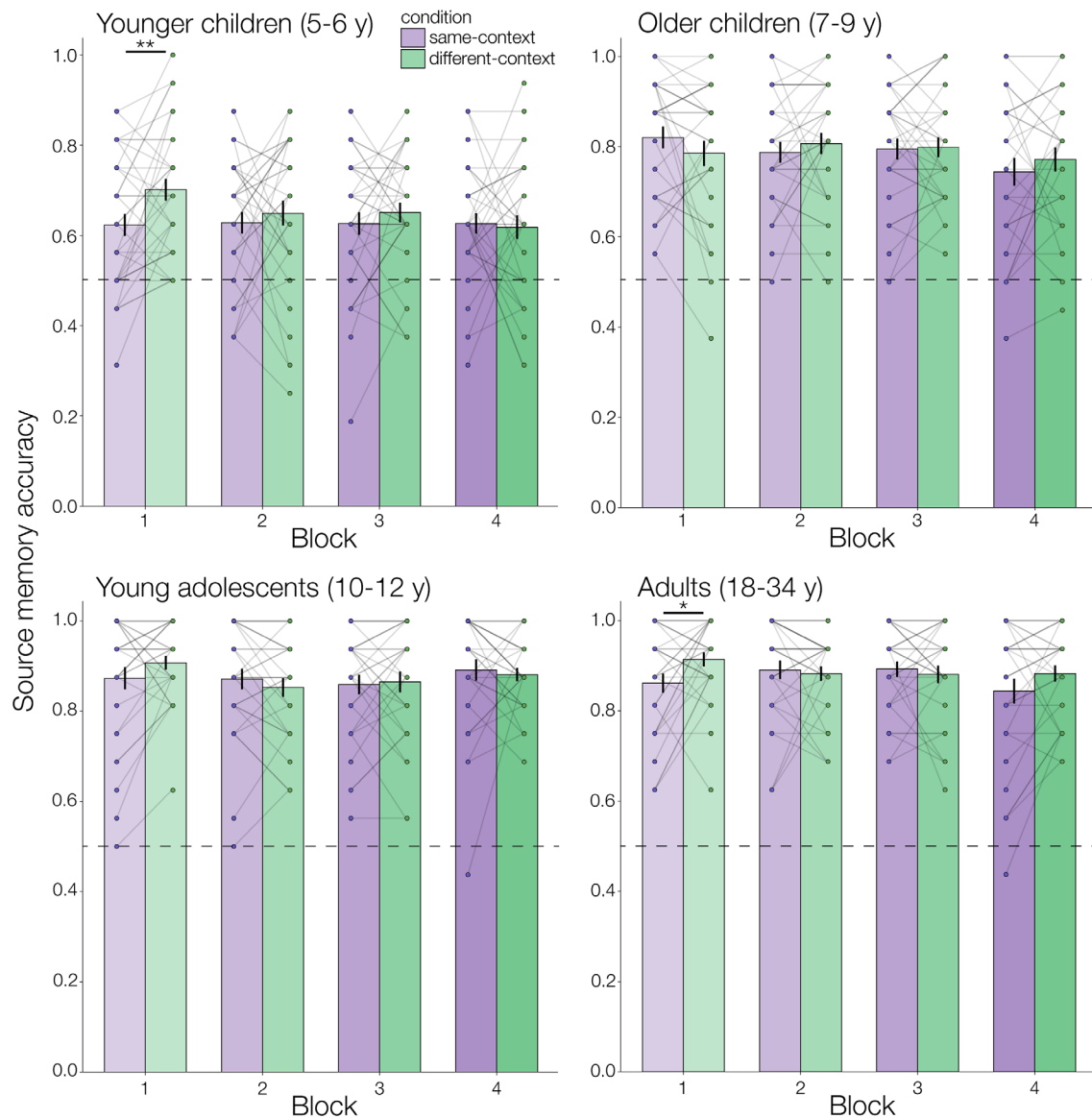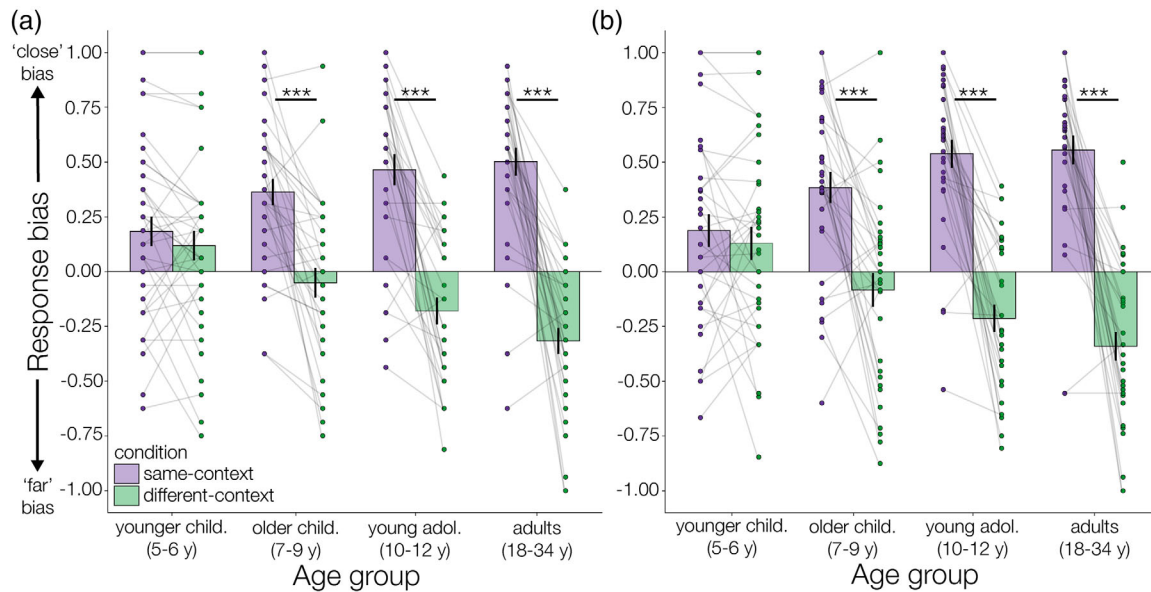
FIGURE 2 *Source memory accuracy* (±SE) for same- versus different-context conditions by block and age group. Solid lines connect observations for the same participant across the two context conditions. Dashed lines indicate chance performance. Performance was slightly better in the different-context condition compared to the same-context condition, especially during the first block for younger children and adults.

scores showed a main effect of context condition ($F(1, 130) = 170.94$, $p < 0.001$, $\eta_p^2 = 0.568$) that was qualified by an interaction with age ($F(3, 130) = 19.10$, $p < 0.001$, $\eta_p^2 = 0.306$; Figure 3a; also see Figure S2a for age plotted in years instead of binned). Follow-up comparisons showed an effect of context condition on the bias scores of older children, young adolescents, and adults ($ps < 0.001$), but not younger children, $p = 0.264$. Context thus influenced how these groups organized events within temporal memory, albeit in ways that differed by age. We further interrogated these differences by examining age effects separately within the same- and different-context conditions.

Within the same-context condition, close–response bias (indexing within-event integration) was high and comparable across the three oldest age groups ($ps \geq 0.148$), all of whom exhibited a greater bias than younger children ($ps \leq 0.050$). Despite these age-related differences, a series of single sample *t*-tests confirmed that all age groups

had a close-response bias that was significantly greater than zero ($ps \leq 0.009$), indicating that participants of all ages were more likely to rate items from same-context quartets "close" than "far." However, our findings further indicate that within-event integration increases between the ages of 5–9 years, becoming comparable to adult levels in late childhood.

A different developmental pattern was observed in the different-context condition. In this condition, only young adolescents and adults showed a high and comparable far-response bias (indexing between-event differentiation), $p = 0.154$. Younger children were less biased than both of these age groups ($ps \leq 0.002$), and older children were less biased than adults, $p = 0.005$. Single sample *t*-tests confirmed that young adolescents and adults were the only groups with a far-response bias significantly less than zero ($ps \leq 0.007$), indicating that they were more likely to rate items from different-context quartets "far" than
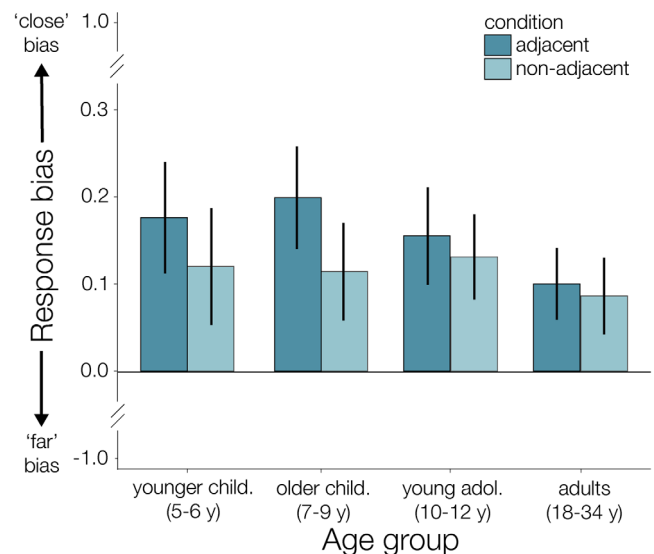
FIGURE 3 (a) Mean *response bias scores* (±SE) and (b) *source memory corrected response bias scores* (± SE) for same- versus different-context conditions by age group. The latter reflect temporal memory test trials for which participants later demonstrated intact memory for item-scene pairings during the source memory test. Lines connect observations for the same participant across the two context conditions. Both score types differed by context condition for all age groups except younger children. A close-response bias for same-context items emerged in older childhood, whereas a far-response bias for different-context items did not emerge until early adolescence. Thus, biases consistent with within-event integration emerged earlier than those consistent with between-event differentiation. ***$p \leq 0.001$.

"close." In contrast, younger ($ps = 0.088$) and older children's ($p = 0.457$) bias scores did not differ from zero. Although not significant, younger children actually showed a pattern opposite to that observed in the oldest two age groups, tending to rate items from different-context quartets "close" more often than "far." That younger children adopted a slight close-response bias in both context conditions shows a tendency to rate items as close regardless of their context, indicating they were insensitive to our context manipulation. Together, these data suggest that early adolescence is a critical period of improvement for between-event differentiation, and that this process emerges later than within-event integration.

Though not central to our hypotheses, we also found a main effect of pair adjacency ($F(1, 130) = 5.03$, $p = 0.027$, $\eta_p^2 = 0.037$; Figure 4). This effect was driven by a greater close-response bias for adjacent ($M = 0.16$, 95% CI = [0.10, 0.21]) versus nonadjacent ($M = 0.11$, 95% CI = [0.06, 0.17]) items. Participants, therefore, showed some sensitivity to objective temporal distance, rating adjacent pairs "close" more frequently than nonadjacent pairs. This sensitivity was observed across age groups and did not interact with context or age either alone ($p = 0.587$) or in combination with other variables ($ps > 0.102$).

FIGURE 4 Main effect of pair adjacency on *bias scores* (±SE; $p = 0.027$). Participants exhibited a greater close-response bias for adjacent versus nonadjacent items that did not interact with age. The difference between adjacent and nonadjacent items did not reach statistical significance within individual age group ($ps \geq 0.103$).

3.4 | Temporal memory biases persist when controlling for context memory

Though source memory analyses showed that each age group remembered the contextual information at a high level, we wanted to ensure that our observed effects of context on subjective temporal memory

were not due to age-related differences in source memory. We, therefore, examined whether the same pattern of temporal memory biases persisted controlling for source memory performance. Results from the mixed ANOVA that controlled for source memory again showed a main effect of context ($F(1, 127) = 164.25$, $p < 0.001$, $\eta_p^2 = 0.564$)

that was qualified by an interaction with age (F(3, 127) = 19.83, $p < 0.001$, $\eta_p^2 = 0.319$; Figure 3b; also see Figure S2b for age plotted in years instead of binned). Follow-up comparisons revealed a pattern of results that was nearly identical to that observed in the initial analysis. Again, there was an effect of context condition on the bias scores of older children, young adolescents, and adults ($ps \leq 0.001$), but not younger children, $p = 0.474$. Once more, we interrogated these differences by examining age effects separately within the same- and different-context conditions.

The same pattern of results was observed in the same-context condition when controlling for source memory performance. Close-response bias was high and comparable across the three oldest age groups ($ps \geq 0.086$), all of whom exhibited a greater close-response bias than younger children ($ps \leq 0.043$). Single sample t-tests also confirmed that all groups had a close-response bias significantly greater than zero ($ps < 0.016$), indicating that they were more likely to rate items from same-context quartets "close" than "far." This pattern again suggests that late childhood is a critical period of improvement for within-event integration.

When controlling for source memory, our findings in the different-context condition were preserved from the initial analysis. Young adolescents and adults exhibited a comparable far-response bias ($p = 0.212$). Younger children were less biased than all older age groups ($ps \leq 0.033$), and older children were less biased than adults, $p < 0.012$. Single sample t-tests confirmed that young adolescents and adults were also the only groups with a far-response bias significantly less than zero ($ps \leq 0.002$), indicating they were more likely to rate items from different-context quartets "far" than "close." The bias scores of younger ($p = 0.092$) and older ($p = 0.291$) children did not differ from zero. Results, therefore, paralleled those from the initial analysis: Biases consistent with within-event integration were present in older children, whereas those consistent with between-event differentiation did not emerge until adolescence. Importantly, these age-related differences cannot be attributed to limitations in children's ability to remember contextual information. See Supplemental Materials for additional analyses showing an identical pattern of results when controlling for source memory across entire quartets, as well as preservation of the context by age interaction when including source memory within a linear mixed-effects model.

3.5 | Ancillary analyses

Given that imagination success also showed age-related improvements, we performed ancillary analyses to examine whether main bias score findings held controlling for (1) successful imagination and (2) both successful imagination and source memory. As with all other analyses, mixed ANOVAs found an effect of context that was further qualified by age controlling for imagination success either alone (F(3,126) = 16.85, $p < 0.001$, $\eta_p^2 = 0.286$) or in conjunction with source memory performance (F(3,124) = 17.21, $p < 0.001$, $\eta_p^2 = 0.294$). Age-related differences in bias scores were therefore not driven by limitations in children's ability to successfully imagine or remember

contextual information. See Supplemental Materials for additional analyses showing an identical pattern of results when controlling for successful imagination alone and in conjunction with source memory across entire quartets.

4 | DISCUSSION

We examined how context guides within-event integration and between-event differentiation during development. Prior work indicates adults use these processes to parse continuous experience into meaningful event memories (Zacks et al., 2007). As a result, subjective perceptions of time are altered; adults perceive event elements that share a context as having occurred closer together in time, whereas elements that are objectively the same temporal distance apart, but do not share a context, are perceived as having occurred farther apart in time (Ezzyat & Davachi, 2014). Anecdotally, the impact of spatial context on temporal memory might have been particularly evident during the global pandemic. While a prepandemic day might have involved spending time in numerous locations (e.g., home, office, restaurant), social distancing restrictions led many individuals to spend entire days in a single location. As a result, one may have experienced a decreased ability to remember when specific events occurred, which perhaps contributed to a feeling of "days blurring together." Here, we show that children do not use context to organize continuous experience into discrete memories in the same way as adults. That younger children failed to exhibit temporal memory biases reflecting within-event integration and between-event differentiation suggests their memories may reflect a similar "blurring" even when context shifts are frequent. Only in early adolescence did spatial context impact temporal memory biases similarly to adults, suggesting a continued refinement in event memory organization past childhood.

We predicted that within-event integration would emerge during late childhood given robust improvements in binding processes during this period. While some binding abilities are in place early in life (Bauer, 1997), improvements continue to occur across childhood due to hippocampal maturation (Ghetti & Bunge, 2012). Many studies have examined developmental improvements in binding elements that either co-occur simultaneously (e.g., Lorsbach & Reimer, 2005; Shing et al., 2008) or that occur across discrete learning episodes (e.g., Bauer & San Souci, 2010; Schlichting et al., 2021), with less work dedicated to linking elements that unfold continuously across time. Studies examining the latter have focused on the binding of sequential items separated by short temporal windows, with a focus on understanding memory for temporal order (e.g., Canada et al., 2020; Picard et al., 2012; Schlichting et al., 2017). These studies demonstrate that children's ability to remember event order improves with age but provide less insight into the representational mechanisms guiding when sequentially presented experiences are integrated into the same event or differentiated into separate events. Here, we show that within-event integration and across-event differentiation emerge at different ages, leading to behavioral differences in how children, adolescents, and adults subjectively remember the temporal distance between events.

That the three eldest age groups remembered same-context items as occurring closer together in time aligns with a temporal compression of items when the context is stable. We speculate this compression may reflect greater similarity in the neural codes for items presented in the same context. One adult study found that similarity coding in neocortex and hippocampus related to temporal biases; more similar patterns of activation across items led to greater compression of temporal distance judgments (Ezzyat & Davachi, 2014). While prior work has shown that 4–6-year-olds can integrate discrete events, this integration is only likely upon an explicit demand to do so (Bauer et al., 2015). Five- to 6-year-olds' failure to show within-event integration in the present study may thus reflect a limitation in the neural coding that mediates the spontaneous integration of experienced elements, leading to less structured event representations and a lack of temporal memory biases.

Critically, our developmental approach allowed us to dissociate mechanisms supporting between-event differentiation from those supporting within-event integration, revealing the two mechanisms emerge at different ages. While participants tended to show some sensitivity to context shifts (i.e., better source memory for different-context pairs), only adolescents and adults remembered different-context items as occurring farther apart in time relative to one another than same-context items, despite the objective temporal distance being fixed. This expansion of subjective temporal distance between different-context items suggests context shifts triggered boundaries within their event memory (Clewett et al., 2019; Ezzyat & Davachi, 2014).

Theories suggest event boundaries are formed when contexts shift or predictions based on prior experience are violated (Zacks et al., 2007). Cognitive control processes may signal these context shifts or prediction errors (Zacks, 2020; Zacks et al., 2007). Consistent with this idea, prefrontal cortex is engaged at contextual boundaries (Sridharan et al., 2007; Zacks et al., 2001), with rodent work suggesting this region may promote a remapping of hippocampal ensembles that leads to differentiated representations (Ito et al., 2015; Leutgeb et al., 2005; Schlesiger et al., 2018). We speculate children's lack of differentiation reflects limitations in these prefrontal and hippocampal mechanisms. Prior work indicates strategic memory processes increase into adulthood (Bjorklund et al., 2009) and are associated with changes in prefrontal structure (Yu et al., 2018) and function (Nussenbaum & Hartley, 2021). There are also age-related increases in the degree to which prefrontal function during encoding—perhaps reflecting engagement in strategies—predicts subsequent memory between late childhood and adulthood (Ofen et al., 2007; Shing et al., 2016; see Ghetti & Fandakova, 2020 for review). These changes in prefrontal cortex occur alongside protracted age-related shifts in hippocampal structure and function (Daugherty et al., 2017; Demaster & Ghetti, 2013; Keresztes et al., 2017; Riggins et al., 2018), as well as continued development of white matter connectivity between the two regions (Simmonds et al., 2014). Together, these changes in the prefrontal-hippocampal circuit likely contribute to later developmental refinements in between-event differentiation versus within-event integration.

Our findings also contribute to a broader literature on the development of contextual processing within memory. This literature indicates an early propensity to represent contextual information within memory, with even infants demonstrating some ability to learn item-context associations (Bertels et al., 2017). However, developmental improvements in this capacity continue to occur. Prior work shows accelerated age-related increases in the ability to bind an item with its context between ages 5 and 7 years (Riggins, 2014), as well as improvements in the ability to report autobiographical events that are rich in contextual details between middle- to late-childhood (Coughlin et al., 2019; for relevant reviews see: Ghetti & Fandakova, 2020; Newcombe et al., 2012). At the same time, the ability to discriminate between similar spatial contexts within memory is also improving (Ngo et al., 2019). The present study extends this work by showing protracted age-related changes in how contextual information influences the organization of events within memory. However, these changes were observed taking a cross-sectional approach within an educated, industrialized, rich, and democratic society (Henrich et al., 2010). Longitudinal work across diverse samples will therefore be an important future extension. Future work that examines the relation between different aspects of contextual processing in memory would also be informative. While our age-by-context interaction on temporal memory biases held controlling for source memory—both by limiting our analysis to correct trials and by incorporating source memory into a mixed effects model (see Supplemental Materials)—theoretical and empirical work show an influence of context shifts on nontemporal aspects of memory including source memory (see Clewett et al., 2019 for a review). Studies designed to further interrogate this influence could be particularly informative. For example, knowing whether our observed temporal memory biases look different for correct versus incorrect source trials (for which we had too few trials) could provide additional insight into underlying temporal processes (e.g., associative chaining vs. novelty).

In summary, we found that context increasingly influenced event memory organization with age. While contextual stability was associated with within-event integration by older childhood, contextual shifts were not associated with between-event differentiation until early adolescence. Our developmental approach therefore provides evidence of a dissociation between these processes, suggesting they are distinct but complementary. Outlining the differential emergence of these two processes also contributes to a better understanding of how memory organization changes with age. Our findings suggest that young children do not exploit context as an organizational principle. Only with increasing age do they begin to use contextual similarity to meaningfully integrate experienced elements into bound events. Even later, they become capable of using contextual shifts to meaningful differentiate between events. Through this developmental process, they acquire event memories that are more efficiently organized and meaningfully remembered (Zacks, 2020).

ACKNOWLEDGMENTS

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data for this research are available at https://osf.io/2v76w/?view_only=6303cbe1be154f6faaa3a6ccf8041ae0.

ETHICS APPROVAL

The research reported in this manuscript conforms to recognized standards for research with human subjects and was approved by The University of Texas at Austin Institutional Review Board.

PERMISSION TO REPRODUCE MATERIAL FROM OTHER SOURCES

This manuscript does not contain material reproduced from other sources.

ORCID

Christine Coughlin https://orcid.org/0000-0002-0302-2075

REFERENCES

Achenbach, T. M. (1999). The child behavior checklist and related instruments. In M. E. Maruish (Ed.), *The use of psychological testing for treatment planning and outcomes assessment* (pp. 429–466). Lawrence Erlbaum Associates Publishers.

Baldwin, D. A., Baird, J. A., Saylor, M. M., & Clark, M. A. (2001). Infants parse dynamic action. *Child Development*, 72(3), 708–717. https://doi.org/10.1111/1467-8624.00310

Bauer, P. J. (1997). Development of memory in early childhood. In N. Cowan (Ed.), *The development of memory in childhood* (pp. 83–111). Psychology Press/Erlbaum (UK) Taylor & Francis.

Bauer, P. J., & San Souci, P. (2010). Going beyond the facts: Young children extend knowledge by integrating episodes. *Journal of Experimental Child Psychology*, 107(4), 452–465. https://doi.org/10.1016/j.jecp.2010.05.012

Bauer, P. J. (1992). Holding it all together: How enabling relations facilitate young children's event recall. *Cognitive Development*, 7(1), 1–28. https://doi.org/10.1016/0885-2014(92)90002-9

Bauer, P. J., King, J. E., Larkina, M., Varga, N. L., & White, E. A. (2012). Characters and clues: Factors affecting children's extension of knowledge through integration of separate episodes. *Journal of Experimental Child Psychology*, 111(4), 681–694. https://doi.org/10.1016/J.JECP.2011.10.005

Bauer, P. J., & Varga, N. L. (2017). Similarity and deviation in event segmentation and memory integration: Commentary on Richmond, Gold, & Zacks. *Journal of Applied Research in Memory and Cognition*, 6(2), 124–128. https://doi.org/10.1016/J.JARMAC.2017.01.006

Bauer, Patricia J., Varga, N. L., King, J. E., Nolen, A. M., & White, E. A. (2015). Semantic elaboration through integration: Hints both facilitate and inform the process. *Journal of Cognition and Development*, 16(2), 351–369. https://doi.org/10.1080/15248372.2013.849707

Benear, S. L., Popal, H. S., Zheng, Y., Tanriverdi, B., Murty, V. P., Perlman, S. B., Olson, I. R., & Newcombe, N. (2023). Setting boundaries: Development of neural and behavioral event cognition in early childhood. *Developmental Science*, 26(6), e13409.

Bertels, J., San Anton, E., Gebuis, T., & Destrebecqz, A. (2017). Learning the association between a context and a target location in infancy. *Developmental Science*, 20(4), e12397. https://doi.org/10.1111/DESC.12397

Bjorklund, D., Dukes, C., & Brown, R. (2009). The development of memory strategies. In M. Courage, & N. Cowan (Eds.), *The development of memory in infancy and childhood* (pp. 145–175). Psychology Press.

Brunec, I. K., Robin, J., Olsen, R. K., Moscovitch, M., & Barense, M. D. (2020). Integration and differentiation of hippocampal memory traces. *Neuroscience and Biobehavioral Reviews*, 118, 196–208. https://doi.org/10.1016/J.NEUBIOREV.2020.07.024

Calabro, F. J., Murty, V. P., Jalbrzikowski, M., Tervo-Clemmens, B., & Luna, B. (2020). Development of hippocampal-prefrontal cortex interactions through adolescence. *Cerebral Cortex*, 30(3), 1548–1558. https://doi.org/10.1093/cercor/bhz186

Canada, K. L., Pathman, T., & Riggins, T. (2020). Longitudinal development of memory for temporal order in early to middle childhood. *The Journal of Genetic Psychology*, 181(4), 237–254. https://doi.org/10.1080/00221325.2020.1741504

Champely, S. (2013). *pwr: Basic functions for power analysis*. https://cran.r-project.org/package=pwr

Clewett, D., & Davachi, L. (2017). The ebb and flow of experience determines the temporal structure of memory. *Current Opinion in Behavioral Sciences*, 17, 186–193. https://doi.org/10.1016/J.COBEHA.2017.08.013

Clewett, D., DuBrow, S., & Davachi, L. (2019). Transcending time in the brain: How event memories are constructed from experience. *Hippocampus*, 29(3), 162–183. https://doi.org/10.1002/HIPO.23074

Cohen, S. S., Tottenham, N., & Baldassano, C. (2022). Developmental changes in story-evoked responses in the neocortex and hippocampus. *ELife*, 11, e69430.

Colgin, L. L., Moser, E. I., & Moser, M. B. (2008). Understanding memory through hippocampal remapping. *Trends in Neurosciences*, 31(9), 469–477. https://doi.org/10.1016/J.TINS.2008.06.008

Coughlin, C., Robins, R. W., & Ghetti, S. (2019). Development of episodic prospection: Factors underlying improvements in middle and late childhood. *Child Development*, 90(4), 1109–1122. https://doi.org/10.1111/cdev.13001

Coughlin, C., Pudhiyidath, A., Roome, H. E., Varga, N. L., Nguyen, K. V., & Preston, A. R. (2023, July 31). Asynchronous development of memory integration and differentiation influences temporal memory organization. Retrieved from osf.io/2v76w.

Daugherty, A. M., Flinn, R., & Ofen, N. (2017). Hippocampal CA3-dentate gyrus volume uniquely linked to improvement in associative memory from childhood to adulthood. *NeuroImage*, 153, 75–85. https://doi.org/10.1016/J.NEUROIMAGE.2017.03.047

Demaster, D. M., & Ghetti, S. (2013). Developmental differences in hippocampal and cortical contributions to episodic retrieval. *Cortex*, 49(6), 1482–1493. https://doi.org/10.1016/j.cortex.2012.08.004

Derogatis, L. R., & Lazarus, L. (1994). SCL-90-R, Brief Symptom Inventory, and matching clinical rating scales. In M. E. Maruish (Ed.), *The use of psychological testing for treatment planning and outcome assessment* (pp. 217–248). Lawrence Erlbaum Associates, Inc.

Diamond, A. (2011). Biological and social influences on cognitive control processes dependent on prefrontal cortex. *Progress in Brain Research*, *189*, 319. https://doi.org/10.1016/B978-0-444-53884-0.00032-4

Ezzyat, Y., & Davachi, L. (2014). Similarity breeds proximity: pattern similarity within and across contexts is related to later mnemonic judgments of temporal proximity. *Neuron*, *81*(5), 1179–1189. https://doi.org/10.1016/J.NEURON.2014.01.042

Ghetti, S., & Bunge, S. A. (2012). Neural changes underlying the development of episodic memory during middle childhood. *Developmental Cognitive Neuroscience*, *2*(4), 381–395. https://doi.org/10.1016/J.DCN.2012.05.002

Ghetti, S., & Fandakova, Y. (2020). Neural development of memory and metamemory in childhood and adolescence: Toward an integrative model of the development of episodic recollection. *Annual Review of Developmental Psychology*, *2*, 365–388. https://doi.org/10.1146/ANNUREV-DEVPSYCH-060320-085634

Glebkin, V., Olenina, E., & Safronov, N. (2019). Event cognition from the perspective of cognitive development. In A. K. Goel, C. M. Seifert, & C. Freksa (Eds.), *Proceedings of the 41st Annual Conference of the Cognitive Science Society*, Montreal, QB (pp. 1844–1850). Cognitive Science Society.

Henrich, J., Heine, S. J., & Norenzayan, A. (2010). Most people are not WEIRD. *Nature*, *466*(7302), 29–29. https://doi.org/10.1038/466029a

Heusser, A. C., Ezzyat, Y., Shiff, I., & Davachi, L. (2018). Perceptual boundaries cause mnemonic trade-offs between local boundary processing and across-trial associative binding. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *44*(7), 1075–1090. https://doi.org/10.1037/XLM0000503

Howard, L. H., & Woodward, A. L. (2019). Human actions support infant memory. *Journal of Cognition and Development*, *20*(5), 772–789. https://doi.org/10.1080/15248372.2019.1664549

Hulbert, J. C., & Norman, K. A. (2015). Neural differentiation tracks improved recall of competing memories following interleaved study and retrieval practice. *Cerebral Cortex*, *25*(10), 3994–4008. https://doi.org/10.1093/cercor/bhu284

Ito, H. T., Zhang, S. J., Witter, M. P., Moser, E. I., & Moser, M. B. (2015). A prefrontal-thalamo-hippocampal circuit for goal-directed spatial navigation. *Nature*, *522*(7554), 50–55. https://doi.org/10.1038/NATURE14396

Keresztes, A., Bender, A. R., Bodammer, N. C., Lindenberger, U., Shing, Y. L., & Werkle-Bergner, M. (2017). Hippocampal maturity promotes memory distinctiveness in childhood and adolescence. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(34), 9212–9217. https://doi.org/10.1073/PNAS.1710654114/SUPPL_FILE/PNAS.201710654SI.PDF

Kurby, C. A., & Zacks, J. M. (2008). Segmentation in the perception and memory of events. *Trends in Cognitive Sciences*, *12*(2), 72–29. https://doi.org/10.1016/j.tics.2007.11.004

Leutgeb, S., Leutgeb, J. K., Barnes, C. A., Moser, E. I., McNaughton, B. L., & Moser, M. B. (2005). Independent codes for spatial and episodic memory in hippocampal neuronal ensembles. *Science*, *309*(5734), 619–623. https://doi.org/10.1126/SCIENCE.1114037

Lorsbach, T. C., & Reimer, J. F. (2005). Feature binding in children and young adults. *The Journal of Genetic Psychology*, *166*(3), 313–328. https://doi.org/10.3200/GNTP.166.3.313-328

Lositsky, O., Chen, J., Toker, D., Honey, C. J., Shvartsman, M., Poppenk, J. L., Hasson, U., & Norman, K. A. (2016). Neural pattern change during encoding of a narrative predicts retrospective duration estimates. *ELife*, *5*, e16070. https://doi.org/10.7554/ELIFE.16070

Luna, B. (2009). Developmental changes in cognitive control through adolescence. *Advances in Child Development and Behavior*, *37*, 233–278. https://doi.org/10.1016/S0065-2407(09)03706-9

Newcombe, N. S., Lloyd, M. E., & Balcomb, F. (2012). Contextualizing the development of recollection: Episodic memory and binding in young children. In S. Ghetti, & P. J. Bauer (Eds.), *Origins and development of recollection perspectives from psychology and neuroscience*. (pp. 73–100). Oxford University Press. https://doi.org/10.1093/acprof:oso/9780195340792.003.0004

Ngo, C. T., Lin, Y., Newcombe, N. S., & Olson, I. R. (2019). Building up and wearing down episodic memory: Mnemonic discrimination and relational binding. *Journal of Experimental Psychology: General*, *148*(9), 1463–1479. https://doi.org/10.1037/XGE0000583

Ngo, C. T., Newcombe, N. S., & Olson, I. R. (2018). The ontogeny of relational memory and pattern separation. *Developmental Science*, *21*(2). https://doi.org/10.1111/DESC.12556

Nussenbaum, K., & Hartley, C. A. (2021). Prefrontal-striatal circuitry supports adaptive memory prioritization across development. *Elife*, *10*(e69796). https://doi.org/10.7554/eLife.69796

Ofen, N., Kao, Y. C., Sokol-Hessner, P., Kim, H., Whitfield-Gabrieli, S., & Gabrieli, J. D. E. (2007). Development of the declarative memory system in the human brain. *Nature Neuroscience*, *10*(9), 1198–1205. https://doi.org/10.1038/NN1950

Pathman, T., & Ghetti, S. (2014). The eyes know time: A novel paradigm to reveal the development of temporal memory. *Child Development*, *85*(2), 792–807. https://doi.org/10.1111/CDEV.12152

Pathman, T., Larkina, M., Burch, M. M., & Bauer, P. J. (2013). Young children's memory for the times of personal past events. *Journal of Cognition and Development*, *14*(1), 120–140. https://doi.org/10.1080/15248372.2011.641185

Paz-Alonso, P. M., Bunge, S. A., & Ghetti, S. (2014). Emergence of higher cognitive functions: Reorganization of large-scale brain networks during childhood and adolescence. Oxford handbook topics in psychology, https://doi.org/10.1093/oxfordhb/9780199935291.013.003

Picard, L., Cousin, S., Guillery-Girard, B., Eustache, F., & Piolino, P. (2012). How do the different components of episodic memory develop? Role of executive functions and short-term feature-binding abilities. *Child Development*, *83*(3), 1037–1050. https://doi.org/10.1111/J.1467-8624.2012.01736.X

Radvansky, G. A. (2012). Across the event horizon. *Current Directions in Psychological Science*, *21*(4), 269–272. https://doi.org/10.1177/0963721412451274

Riggins, T. (2014). Longitudinal investigation of source memory reveals different developmental trajectories for item memory and binding. *Developmental Psychology*, *50*(2), 449–459. https://doi.org/10.1037/A0033622

Riggins, T., Geng, F., Botdorf, M., Canada, K., Cox, L., & Hancock, G. R. (2018). Protracted hippocampal development is associated with age-related improvements in memory during early childhood. *NeuroImage*, *174*, 127. https://doi.org/10.1016/J.NEUROIMAGE.2018.03.009

Schlesiger, M. I., Boublil, B. L., Hales, J. B., Leutgeb, J. K., & Leutgeb, S. (2018). Hippocampal global remapping can occur without input from the medial entorhinal cortex. *Cell Reports*, *22*(12), 3152–3159. https://doi.org/10.1016/J.CELREP.2018.02.082

Schlichting, M. L., Guarino, K. F., Schapiro, A. C., Turk-Browne, N. B., & Preston, A. R. (2017). Hippocampal structure predicts statistical learning and associative inference abilities during development. *Journal of Cognitive Neuroscience*, *29*(1), 37–51. https://doi.org/10.1162/jocn_a_01028

Schlichting, M. L., Guarino, K. F., Roome, H. E., & Preston, A. R. (2021). Developmental differences in memory reactivation relate to encoding and inference in the human brain. *Nature Human Behaviour*, *6*(3), 415–428. https://doi.org/10.1038/s41562-021-01206-5

Sharon, T., & Wynn, K. (1998). Individuation of actions from continuous motion. *Psychological Science*, *9*(5), 357–362. https://doi.org/10.1111/1467-9280.00068

Shing, Y. L., Brehmer, Y., Heekeren, H. R., Bäckman, L., & Lindenberger, U. (2016). Neural activation patterns of successful episodic encoding: Reorganization during childhood, maintenance in old age. *Developmental Cognitive Neuroscience*, *20*, 59. https://doi.org/10.1016/J.DCN.2016.06.003

Shing, Y. L., Werkle-Bergner, M., Li, S. C., & Lindenberger, U. (2008). Associative and strategic components of episodic memory: A life-span

dissociation. *Journal of Experimental Psychology. General*, 137(3), 495–513. https://doi.org/10.1037/0096-3445.137.3.495

Simmonds, D. J., Hallquist, M. N., Asato, M., & Luna, B. (2014). Developmental stages and sex differences of white matter and behavioral development through adolescence: a longitudinal diffusion tensor imaging (DTI) study. *NeuroImage*, 92, 356–368. https://doi.org/10.1016/J.NEUROIMAGE.2013.12.044

Sridharan, D., Levitin, D. J., Chafe, C. H., Berger, J., & Menon, V. (2007). Neural dynamics of event segmentation in music: Converging evidence for dissociable ventral and dorsal networks. *Neuron*, 55(3), 521–532. https://doi.org/10.1016/J.NEURON.2007.07.003

van Geert, P., & van Dijk, M. (2002). Focus on variability: New tools to study intra-individual variability in developmental data. *Infant Behavior and Development*, 25(4), 340–374. https://doi.org/10.1016/S0163-6383(02)00140-6

Wynn, K. (1996). Infants' individuation and enumeration of actions. *Psychological Science*, 7(3), 164–169. https://doi.org/10.1111/J.1467-9280.1996.TB00350.X

Yassa, M. A., & Stark, C. E. L. (2011). Pattern separation in the hippocampus. *Trends in Neurosciences*, 34(10), 515–525. https://doi.org/10.1016/J.TINS.2011.06.006

Yates, T. S., Ellis, C. T., & Turk-Browne, N. B. (2021). Emergence and organization of adult brain function throughout child development. *NeuroImage*, 226(117606), 117606. https://doi.org/10.1016/j.neuroimage.2020.117606

Yim, H., Dennis, S. J., & Sloutsky, V. M. (2013). The development of episodic memory: Items, contexts, and relations. *Psychological Science*, 24(11), 2163–2172. https://doi.org/10.1177/0956797613487385

Yu, Q., McCall, D., Homayouni, R., Tang, L., Chen, Z., Schoff, D., Nishimura, M., Raz, S., & Ofen, N. (2018). Age-associated increase in mnemonic strategy use is linked to prefrontal cortex development. *Neuroimage*, 181, 162–169. https://doi.org/10.1016/j.neuroimage.2018.07.008

Zacks, J. M. (2020). Event perception and memory. *Annual Review of Psychology*, 71, 165–191. https://doi.org/10.1146/ANNUREV-PSYCH-010419-051101

Zacks, J. M., Braver, T. S., Sheridan, M. A., Donaldson, D. I., Snyder, A. Z., Ollinger, J. M., Buckner, R. L., & Raichle, M. E. (2001). Human brain activity time-locked to perceptual event boundaries. *Nature Neuroscience*, 4(6), 651–655. https://doi.org/10.1038/88486

Zacks, J. M., Speer, N. K., Swallow, K. M., Braver, T. S., & Reynolds, J. R. (2007). Event perception: A mind/brain perspective. *Psychological Bulletin*, 133(2), 273–293. https://doi.org/10.1037/0033-2909.133.2.273

Zheng, Y., Zacks, J. M., & Markson, L. (2020). The development of event perception and memory. *Cognitive Development*, 54, 100848. https://doi.org/10.1016/J.COGDEV.2020.100848

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Coughlin, C., Pudhiyidath, A., Roome, H. E., Varga, N. L., Nguyen, K. V., & Preston, A. R. (2024). Asynchronous development of memory integration and differentiation influences temporal memory organization. *Developmental Science*, 27, e13437. https://doi.org/10.1111/desc.13437