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Increasing representational capacity in the hippocampal-frontoparietal system underlies hierarchical development of temporal memory

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ABSTRACT

Time is a central dimension of episodic memory which allows us to remember not only what happened and where from past events, but also when those events occurred and how they relate to one another. Adults can form hierarchical knowledge derived from episodic experience that includes precise timing details about individual events and information about temporal patterns that encode regularities across experiences, alongside factual knowledge about time (e.g., the months of the year). Young children's temporal memory is more constrained, lacking both the level of local detail and limited global knowledge relative to adult temporal representation. Despite behavioral evidence for such developmental differences in temporal memory, we lack a unified model that explains how local and global temporal representation abilities emerge, interact, and are organized across development. Here, we propose a three-stage neurocognitive framework for the hierarchical development of temporal memory, resulting from increasing representational capacity across the hippocampal–frontoparietal memory system. Reviewing behavioral and neuroimaging evidence, we propose that: 1) young children's temporal memory is initially local and event-specific due to functional immaturity of hippocampus; 2) older children and adolescents form and reinstate global knowledge of temporal regularities resulting from enhanced interactions between hippocampus and lateral frontoparietal cortex; and 3) adults flexibly deploy hierarchical knowledge of local details and generalities in new environments mediated by hippocampus and medial frontoparietal cortex interactions. This framework thus provides a unified, empirically-grounded model of temporal memory development, supporting increasingly complex temporal representations that enable adaptive behaviors at a variety of temporal resolutions.

Time is a foundational dimension of episodic memory which enables us to segment continuous experiences into discrete events, remember those events in order, locate them in time, and derive knowledge of temporal patterns across related experiences. These abilities are critical not only for remembering the past but also for guiding future behavior in everyday contexts, from navigating routines to providing accurate eyewitness testimony (Tulving, 1993; Friedman, 2007; Wandrey et al., 2012). While adults form hierarchical temporal knowledge that includes information about individual event timing (***local temporal experience***) and how those events fit into broader temporal structures and routines (***global temporal patterns***; Fig. 1**A**), children often struggle with both recalling temporal details and forming knowledge of temporal regularities (Friedman, 2013; Bellmund et al., 2022; Tacikowski et al., 2024). However, memory for local temporal experience and global temporal patterns are often studied independently in development (c.f., Scales and Pathman, 2021; Pathman et al., 2022), despite evidence that these processes work in concert to support hierarchical memory which simultaneously represents *both* local and global information in adults (Bellmund et al., 2022). As a result, we lack an integrated understanding of how children come to represent both event-specific details and knowledge of temporal patterns with age.

Because methods for testing temporal memory vary widely across ages (Fig. 1**B**), events (Fig. 1**C**), and experimental approaches (Fig. 1**D**), differences in methods may often dictate which form of temporal memory is observed at different ages in a given individual study. Methodological differences between studies thus pose challenges in

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providing a unified account of how temporal memory develops. In this review, we integrate information across a wide range of literature on temporal memory to propose unifying principles of temporal memory development that cross methodological constraints. We define several key terms, drawing on broadly accepted definitions and common themes across the extensive but heterogeneous literature on temporal memory development (Fig. 1**A**) (see discussions in Friedman, 2013; Pathman and St. Jacques, 2013; McCormack and Hoerl, 2017; Scales and Pathman, 2021). Building on these definitions, we propose a unifying neurocognitive framework to explain how the maturation of the hippocampus, frontoparietal cortex, and their interactions through emerging adulthood progressively enable the representation of both local temporal experience and global temporal patterns. This framework integrates behavioral and neural evidence proposing that development of the hippocampal–frontoparietal memory system underlies increasing representational complexity across age. Specifically, we suggest that this system first enables acquisition of local temporal experience in early childhood and, beginning in middle to late childhood, progressively embeds those memories into global knowledge about the temporal structure of the world (i.e., global temporal patterns), ultimately allowing flexible access to the appropriate scale of representation (***hierarchical temporal memory***).

A comprehensive model of temporal memory development must explain not only when memory for local temporal experience and global temporal patterns emerge during development, but how they interact and influence each other. However, existing work has largely examined these aspects of temporal memory independently. Prior research focusing on memory for local temporal experience shows that children improve in sequencing and recalling individual events with greater accuracy and temporal resolution from early to late childhood (Friedman, 1991; Guillery-Girard et al., 2013; Pathman and Ghetti, 2014; Lee et al., 2016; McCormack and Hoerl, 2017; Canada et al., 2020; Pathman et al.,

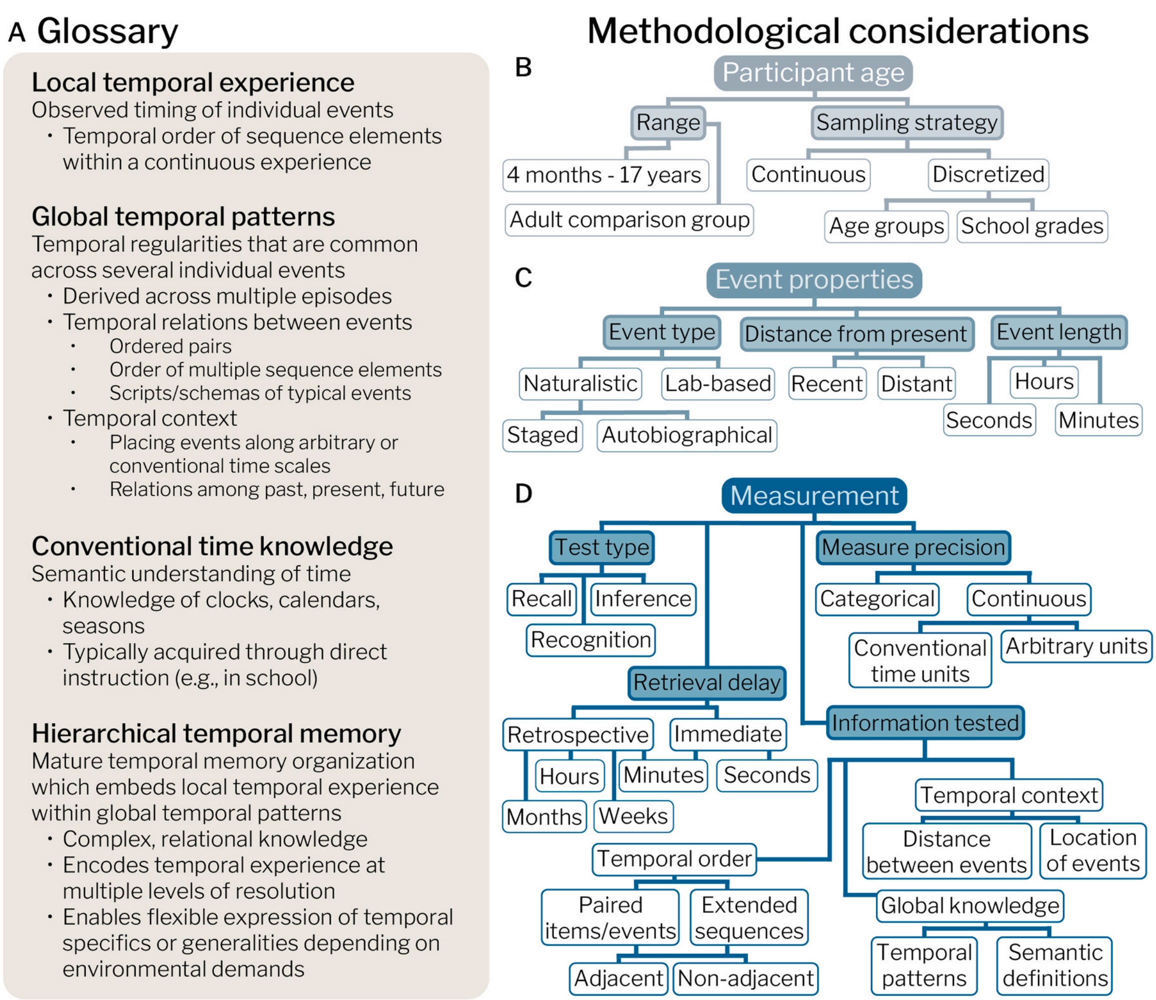

Fig. 1. Overview of key terminology and methodological considerations in the study of temporal memory development. **A)** Glossary of key terms defining different facets of temporal memory and knowledge. **B)** Several heterogeneous methods have been employed to study temporal memory development. Temporal memory is studied from infancy through adulthood, using both continuous-age samples and discretized groups, though the ages included and the grouping strategies vary widely across studies. Some of the most common methods for assessing temporal memory involve recall of temporal order and temporal context, asking children to recall sequences of events or judge when events occurred on arbitrary or conventional time scales, respectively. Tasks requiring inference or probing semantic knowledge of time are less common but are also represented in the literature. Overall, there is no single dominant paradigm for studying temporal memory, reflecting the multiple cognitive processes it encompasses and highlighting the need for a unifying neurocognitive framework to integrate this diverse literature. **C)** Episodic temporal memory tasks differ in the type of events being used as stimuli, ranging from naturalistic stories (e.g., narratives, movies), autobiographical events, staged classroom events, and laboratory-based tasks involving experimenter derived event sequences (e.g., word lists, object images). Such diverse tasks also mean the types of events being remembered differ in length, spanning seconds to several hours. **D)** The measures used to test individuals' temporal memory often differ in important ways, varying in the type of memory probe, the delay between the original experience and the test, the precision of the temporal measurement, and the type of content being remembered. While the current review focuses on human development, see Hoerl and McCormack (2017); (2019) for evolutionary and animal-focused perspectives on temporal memory development.

2023). In parallel, separate studies have demonstrated that children gradually acquire knowledge of recurring global temporal patterns derived from consistent temporal regularities shared across individual episodes through adolescence (also called scripts or schemas, e.g., schedules, routines, ordering across episodes; Fig. 1**A**) (Friedman, 1986; McCormack and Hoerl, 2017; Pathman et al., 2013b; 2022; Bettencourt et al., 2021; Deker and Pathman, 2021). It is important to note that we further differentiate memory for local temporal experience and global temporal patterns from factual knowledge about how time works (e.g., clock time, calendar dates), often referred to as ***conventional time knowledge*** (Fig. 1**A**), which is more semantic than episodic in nature (Friedman, 1978; 1986,; McCormack and Hoerl, 1999; Pathman et al., 2022). Here, our theoretical focus is on how temporal memory is derived from episodic experience at different levels of resolution – local temporal experience and global temporal patterns and relations. While we know that both temporal memory abilities improve with age, key questions remain about how these cognitive abilities interact to shape one another during development. For example, how does the ability to reinstate memory for individual events influence the formation of memories that capture temporal regularities shared across multiple episodes? Conversely, how might knowledge of regularities scaffold or bias encoding of new event sequences to relate them to previously experienced events? And how and when do children learn to flexibly access different levels of temporal representation to guide their behavior in new settings? Understanding the development and interaction of temporal memory mechanisms is critical for explaining children's behavior across everyday and high-stakes situations.

To address these questions, we propose that development progressively enables the emergence of hierarchical temporal memory representations, in which specific event memories are embedded within broader knowledge structures. In the mature brain, this hierarchy would allow one to access both when a unique event occurred and, if necessary, how that event relates to other events, allowing one to differentiate temporal details that are unique from other similar episodes or to learn commonalities that are true across individual events. Critically, this hierarchical organization develops through late adolescence and emerging adulthood, as it requires the ability to both abstract global temporal patterns and flexibly relate new experiences to those patterns (Pudhiyidath et al., 2020).

For example, a younger child attending summer camp may remember individual activities (e.g., canoeing) or short event sequences (e.g., hiking after lunch). By contrast, an older child or adolescent may not only recall these local experiences but also remember their broader temporal context independent of sequence, such as remembering that canoeing occurred at the beginning of the week (i.e., placing canoeing on an arbitrary temporal scale representing the camp week) or even relating canoeing to conventional time scales (i.e., recalling that canoeing happened in the morning or on Monday; Pathman and Ghetti, 2014). Older adolescents may further relate these experiences to global temporal patterns, such as learning that while canoeing always occurs on Monday mornings, hiking alternates between morning and afternoon. Access to both local and global temporal information, in turn, supports both retrospection and prospection. For example, hierarchical temporal memory preserves local details about one's favorite hike while also enabling predictions about future activities, such as anticipating that tomorrow's hike will occur in the morning because today's occurred in the afternoon, or using calendar knowledge to infer that canoeing will occur four times this month because it occurs on Mondays. Critically, such predictions cannot be derived from memory for event sequences or temporal context alone; rather, they require integration of both within a higher-order temporal structure. As such, only hierarchical representations that embed event-specific information within a global temporal framework afford this flexibility, enabling access to either local or global information as task demands change. Evidence from adult neuroimaging supports the utility of such hierarchical representations, demonstrating that the mature hippocampus concurrently represents discrete experiences and broader temporal context to support temporal memory and inference (Bellmund et al., 2022). Accordingly, we propose that the developmental progression from isolated local temporal memories to structured, flexible temporal hierarchies depends on hippocampal maturation (Fig. 2**A**), its evolving interactions with lateral frontoparietal regions during late childhood and early adolescence (Fig. 2**B-C**), and its integration with medial frontoparietal regions during later adolescence and emerging adulthood (Fig. 2**D**).

Brain regions that support temporal memory in adults including hippocampus, medial prefrontal cortex (mPFC), and frontoparietal cortex (Howard and Eichenbaum, 2013; Ranganath and Hsieh, 2016), undergo protracted maturation extending into the third decade of life which may give rise to qualitatively distinct memory behaviors at different ages (Chang et al., 2016; Gómez and Edgin, 2016; Calabro et al., 2020). Moreover, converging evidence suggests that this development is non-uniform and that different functions emerge from the same structures at different stages of development. Within hippocampus, several studies show that posterior regions have been demonstrated to mature earlier than anterior hippocampus (Strange et al., 2014; Langnes et al., 2020; c.f., Callaghan et al., 2021), showing adult-like engagement during memory tasks by early adolescence and are thought to support detailed, instance-based memory for individual events (Ghetti and Bunge, 2012; DeMaster and Ghetti, 2013). By contrast, anterior hippocampus has been shown to mature more gradually throughout adolescence, progressively enabling the representation of regularities across separate but related experiences (DeMaster et al., 2014; Schlichting et al., 2017; Varga et al., 2025a).

Finally, prefrontal and frontoparietal regions, which are among the last to mature in adulthood, enable the flexible expression of memory based on contextual or environmental demands by both representing hierarchical structure and shaping hippocampal representations to align with behavioral goals (Hasson et al., 2008; Calabro et al., 2020; Pudhiyidath et al., 2020; Morton and Preston, 2021). Thus, the extended and heterogeneous development of brain systems supporting different types of memory representation may constrain the memory behaviors available at different ages. Here, we propose that the development of the hippocampal–frontoparietal memory system confers increasingly complex and flexible temporal memory behaviors with age. Below, we review both behavioral and neural evidence from children and adults to argue that increases in representational complexity during development support the emergence of hierarchical temporal memory. Further, we highlight several future directions for direct investigation and detail how the proposed framework relates to critical real-world behaviors from education to child testimony. By viewing temporal memory through the lens of representational change, this framework offers a unified account of how a single cognitive system gives rise to increasingly flexible and abstract temporal knowledge across development.

1. Children's temporal memory is primarily local and event-based

1.1. Early developmental improvements in sequence memory and event binding

During early and middle childhood, the primary developmental transition in temporal memory involves improvements in remembering specific instances and linking continuous experiences in sequence (Fig. 2**A**). In line with this transition, theoretical accounts describe early childhood temporal memory as "event-dependent," emphasizing that while children increasingly recall individual experiences with greater specificity, their memories remain largely tied to discrete episodes rather than integrated temporal structures (McCormack and Hoerl, 1999). Accordingly, developmental research has largely focused on children's ability to learn and remember the order of directly observed events. This ability depends on ***within-event binding,*** the linking of related memory elements within an episode, which allows for memory

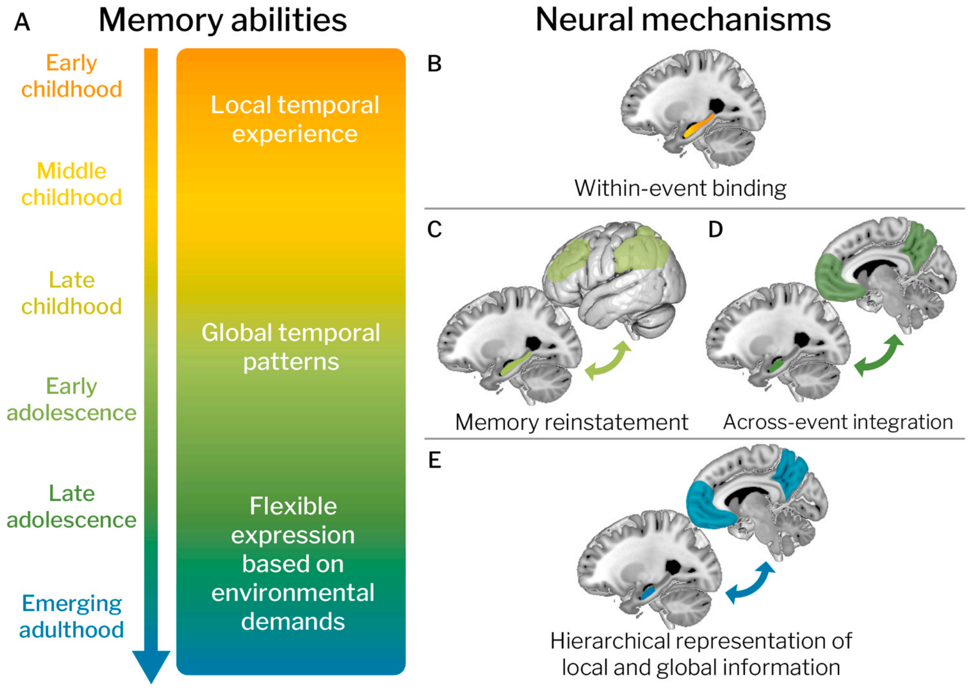

Fig. 2. Schematic of proposed neurocognitive framework for temporal memory development. **A)** We propose a progression of temporal memory development in which neural maturation confers specific memory behaviors at different ages. Color gradients reflect the maturation of different abilities that result from the increasing complexity of temporal memory. We first propose that early in childhood, temporal memory will be local and based on direct observation, with memory for simpler aspects of temporal relations, such as the order of event elements improving through middle childhood. In late childhood and early adolescence, the ability to relate episodes to one another will confer increased knowledge of global temporal patterns. In emerging adulthood, temporal knowledge will be at its most flexible, drawing upon both local and global temporal memory depending on an individual's goals. **B)** Our framework aligns specific temporal memory abilities to maturation of specific parts of the hippocampal–frontoparietal network. During early and middle childhood, children gain the ability to bind information within episodes across broader windows of time due to the early emergence of posterior hippocampus (orange) and relatively later development of anterior hippocampus (yellow). During late childhood and adolescence, children increasingly form knowledge of global temporal patterns common across events by **C)** reinstating past experiences and **D)** integrating current observations into reactivated memory representations. Reinstatement abilities emerge with emergent connectivity of hippocampus with lateral frontoparietal cortex, and emerge earlier in adolescence than across-event integration is primarily supported by anterior hippocampus connectivity with medial frontoparietal cortex, which develops later. **E)** By emerging adulthood, individuals hierarchically represent both local episodic details and global temporal patterns simultaneously, within anterior hippocampus and medial frontoparietal cortex, allowing for dynamic memory expression based on environmental demands or an individual's goals. Such hierarchical representation allows for more precise memory for local experiences and greater ability to use knowledge of global time patterns to infer when past experiences occurred in the absence of a direct memory about time (temporal reconstruction; Friedman, 1993; Pathman et al., 2013b).

of longer sequences with age as these binding processes mature (Ghetti, 2017). Notably, we define local within-event sequencing as the ordering of event elements within the same continuous experience (spanning seconds to hours), while ordering distant events by reactivating prior experiences is defined as global, across-event integration (see Fig. 1**A**, **Sections 2.1–2.4**).

Although children show sensitivity to the order of actions within an event in late infancy (Bauer, 2007; Bauer et al., 2010; Bauer and Leventon, 2013), the ability to accurately recall sequences and bind elements within them develops primarily across early and middle childhood (ages 4–9 years; Fig. 2**A**) (Canada et al., 2020). Specifically, a significant developmental shift in temporal memory occurs during early childhood (4–5 years) as children begin to learn about linear timelines and relative sequencing terms (e.g., "before," "after," "today," "yesterday") as they begin formal education (McCormack and Hoerl, 2017; Tillman et al., 2018; Canada et al., 2020). This emerging understanding of linear and relational temporal concepts scaffolds children's ability to recall sequences more accurately from ages 4–6 years (Friedman, 1991; Pathman et al., 2013). However, even within-event binding remains limited in early childhood, with younger children typically remembering short sequences (i.e., 2–3 events in order) or sequences that are repeated frequently, thus providing several opportunities for encoding (Fivush, 1984; Forest et al., 2023b).

From early to middle childhood (7–9 years), local temporal memory expands in scale, as children remember more events in order and begin to link events that are farther apart in time (Pathman et al., 2013a; Forest et al., 2023a). Though the scale of this effect varies with task demands – young children more readily link temporally distant events in autobiographical tasks than in lab-based experiments – in both contexts, within-event binding extends across broader temporal windows with age (Pathman et al., 2011, 2013a; 2013b; Deker and Pathman, 2021). For example, in one study wherein children repeatedly viewed sequences of three items that always occurred in the same order (i.e., A–B–C), 5- to 7-year-olds recalled only adjacent pairs (A–B or B–C), while 8- to 9-year-olds and adults showed above-chance memory for the entire triplet (A–B–C) (Forest et al., 2023a). With age, children also increasingly link event elements (for instance, words in a list) that appear close together in time, regardless of any semantic similarities the elements may share (Lehmann and Hasselhorn, 2010; Pathman et al., 2023). Moreover, from middle childhood to late adolescence (e.g., from age 7–10 years; orange-yellow/green gradient in Fig. 2**A**), children also demonstrate improved memory for temporal context - that is, memory for the broader timing of when events occurred and the ability to place events in time on arbitrary or conventional time scales (Friedman and Lyon, 2005; Pathman and Ghetti, 2014). Memory for temporal context allows for the binding of event elements across longer timescales and with greater flexibility because elements do not need to be directly adjacent in time, differentiating temporal context from temporal order.

These findings highlight improvements in within-event binding expand to broader temporal scales across childhood to early adolescence.

Developmental differences in the "temporal distance effect" similarly illustrate an expanding scale of within-event binding across childhood. Children aged 8–10 years, like young adults, are more accurate at ordering events that are farther apart in time, a pattern thought to reflect "distance-based processes" that allow judgments of order based on the temporal distance between events (Pathman et al., 2013a; Deker and Pathman, 2021). In particular, events that are farther apart in time are recalled more accurately because they are more easily distinguished from each other, as greater temporal distance reduces overlap in memory (Madsen and Kesner, 1995; St. Jacques et al., 2008; Pathman et al., 2013a). Younger children (age 4–7 years) notably do not show this effect, suggesting that their memory is more constrained to localized, individual episodes, making the distance between events uninformative and resulting in sequence memory that is unaffected by temporal distance (Pathman et al., 2013a; Deker and Pathman, 2021). By contrast, 8–10-year-olds and young adults both demonstrate enhanced sequence accuracy for events spanning broader distances, suggesting that only by middle childhood do children begin to bind events across broader temporal windows.

Together, behavioral evidence suggests that local temporal memory becomes more accurate and spans broader timescales from early to middle childhood, enabling children to remember both adjacent and non-adjacent sequences of events. Critically, these behavioral gains align with developmental changes in hippocampus (Riggins et al., 2015; 2016). In particular, the structural and functional maturation of hippocampus during early and middle childhood may underlie these behavioral changes by increasingly supporting within-event and across-event binding and representation with age.

1.2. Hippocampal maturation increases the scale and specificity of local temporal memories

Developmental neuroimaging evidence supports our proposal that the increasing representational capacity of hippocampus underlies age-related gains in local temporal memory. In particular, a body of converging evidence suggests that development along the hippocampal long axis is non-uniform with relatively extended maturation of anterior hippocampus relative to posterior giving rise to different memory behaviors at different developmental stages (Figs. 2**B**, 3**A;** Ghetti et al., 2010; DeMaster and Ghetti, 2013; DeMaster et al., 2014; 2016; Schlichting et al., 2017; Langnes et al., 2020; Nichols et al., 2023; Varga et al., 2025a; 2025b; though see Callaghan et al., 2021 for evidence of an alternative developmental trajectory). As early as infancy and throughout early childhood, children engage posterior hippocampus to bind related elements into episodic memories, enabling them to encode and integrate directly observed event features such as sequence order (Olson and Newcombe, 2013; Yates et al., 2025). Further, more adult-like hippocampal activity during continuous experiences corresponds to better memory for both event content and event order during early childhood (4–8 years; Benear et al., 2023).

Based on evidence of developmental increases in posterior hippocampal volume and engagement during infancy and early childhood, it is theorized that even very young children recruit this region to bind related elements into episodic memories, such as linking two events in order (Olson and Newcombe, 2013; Mooney et al., 2021; Yates et al., 2025). Indeed, children have been shown to primarily rely on posterior hippocampus during memory tasks and engage anterior hippocampus to a lesser extent, displaying adult-like posterior hippocampal function by ages 9–10 years but not anterior recruitment until adolescence or early adulthood (Ghetti and Bunge, 2012). This preferential engagement and non-uniform hippocampal development may constrain children's temporal memory behaviors given posterior hippocampus's specialization for precise, local representations due to its small, high-resolution place fields (Nadel et al., 2013; Strange et al., 2014). Therefore, an early reliance on posterior hippocampus may directly constrain children's temporal memory to direct observations and narrow windows of time (i.e., narrow "time fields", Fig. 2**B**; Eichenbaum, 2017). As such, we propose that posterior hippocampus's specialization in discrete representation and its early maturation constrain temporal memory to local temporal experience during childhood.

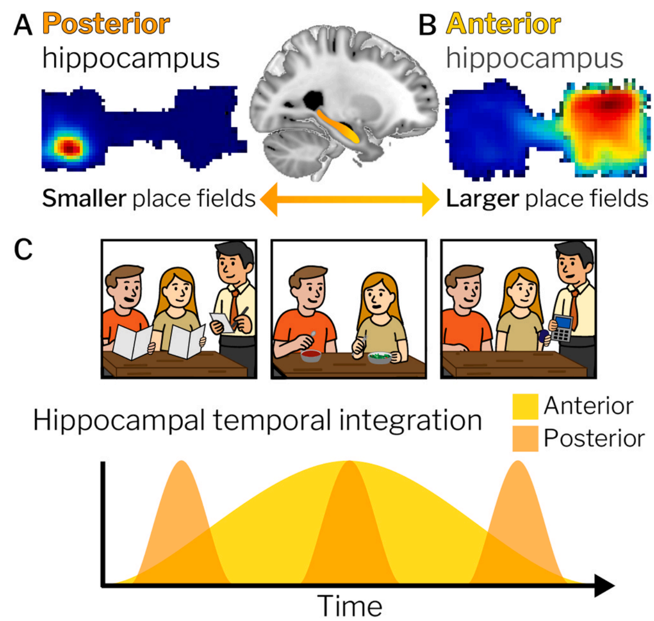

Fig. 3. Representational differences along the hippocampal long axis may facilitate within-event binding at different timescales thus conferring different temporal memory abilities at different ages. **A)** Posterior hippocampus's smaller place fields are specialized for discrete, precise representation (e.g., a specific location in a maze) and thus may similarly constrain the scale of time across which details are linked (i.e., smaller "time fields"; Eichenbaum et al., 2017). **B)** Anterior hippocampus has larger place fields which are specialized for broader representation (e.g., an entire side of a maze), which may allow for within-event binding across broader windows of time. Place field images adapted from Komorowski et al., (2013). **C)** Differences in representational resolution may result in the integration of event elements across different time scales, with posterior hippocampus representing precise but limited intervals of time (e.g., ordering at a restaurant) and anterior hippocampus representing more extended experiences (e.g., one's full experience at a restaurant).

Anterior hippocampus, by contrast, is functionally specialized to integrate information across broader spatiotemporal scales than posterior hippocampus (Fig. 3**B**), but develops more gradually, maturing into early adulthood (Lenroot and Giedd, 2006; DeMaster et al., 2014). Importantly, this extended developmental trajectory has direct behavioral consequences, as posterior hippocampal volume is predictive of episodic memory performance in childhood while anterior hippocampal volume is predictive of memory in adulthood (DeMaster et al., 2014). Anterior hippocampus's extended maturation across childhood and adolescence is closely tied to increased flexibility in retrieving and organizing memories relative to each other (DeMaster and Ghetti, 2013; Ghetti and Bunge, 2012). For example, volumetric differences in anterior hippocampus predict temporal context judgments in older but not younger children, highlighting its role in integrating temporally related events (Lee et al., 2020). Structural differences in anterior hippocampus are also predictive of statistical learning abilities during childhood and adolescence, specifically linking the maturation of anterior hippocampus to the ability to integrate information over extended windows of time (Schlichting et al., 2017). Developmental studies of the medial temporal lobe more broadly also demonstrate shifts in functional specialization from childhood to adolescence as anterior hippocampus matures, highlighting a qualitative shift from basic memory binding to flexibly representing relational knowledge (Ghetti et al., 2010;

Townsend et al., 2010).

Notably, associations between anterior hippocampal structure and memory vary across development, with greater volume supporting memory in younger children (4–8 years; Riggins et al., 2018) while reduced volume supports memory in adults (DeMaster et al., 2014). These patterns are consistent with work across a broader age range (6–30 years) demonstrating a non-linear trajectory of anterior hippocampal volume (Schlichting et al., 2017), with mature volumetric profiles rather than volume itself relating to memory. Together with recent evidence that anterior hippocampal function continues to emerge across development (5–34 years) while posterior function remains relatively stable (Varga et al.,. 2025a), these findings suggest that structural maturation supports increasingly differentiated hippocampal function along the long axis. Accordingly, the developmental changes proposed here should be interpreted as functional and representational shifts supported by neural maturation rather than as direct hypotheses about structural change per se.

Studies of the mature brain provide important context for understanding the functional capacities of hippocampus, including how these functions may differ along the hippocampal axis and mature with age. Neuroimaging research in adults indicates that anterior hippocampus is specialized for integrating information over broader windows of time than posterior hippocampus due to its larger place fields (Nadel et al., 2013; Strange et al., 2014; Fig. 3**A,B**) and more consistent activity patterns (Brunec et al., 2018). In the domain of space, these differences in representational scale can be demonstrated by assessing the place fields of hippocampal neurons and their differences in resolution along the long axis. Posterior hippocampal place fields represent very precise locations within individual contexts (e.g., the bottom left portion of a maze; Fig. 3**A**), whereas anterior hippocampal place fields are much broader and may represent anything within an entire spatial context (i.e., the entire right chamber of a maze; Fig. 3**B;** Komorowski et al., 2013).

If we extend what has been observed in spatial studies to the representation of time, the unique representational properties of posterior and anterior hippocampus may similarly relate to event binding at different temporal scales. For example, a more precise posterior "time field" (Eichenbaum, 2017) may respond to a single event element on the order of seconds (e.g., ordering one's meal), whereas a more generalized anterior "time field" may track an entire episode on the order of minutes (e.g., eating at a restaurant; Fig. 3**C**). Thus, the temporal scale at which event elements are bound and represented may depend on the progressive development of hippocampus. Such a mechanism would explain why children's within-event binding behaviors increase in scale with age, as posterior hippocampus matures earlier and anterior hippocampus matures more progressively. In other words, the extended development of anterior relative to posterior hippocampus may underlie behavioral gains in the scale of within-event binding across childhood.

It is also important to note that the emergence of broader anterior hippocampal representations do not necessitate a loss of temporal specificity. Rather, evidence from the mature brain suggests that population activity in anterior hippocampus can simultaneously differentiate event-specific details while also aligning shared structure across experiences (i.e., hierarchical representations, see **Section 4**; Mack et al., 2016; Morton et al., 2020). By contrast, posterior hippocampus is more likely to remap than integrate experiences, representing event specifics but not broader commonalities (Brunec et al., 2018; Julian and Doeller, 2021). Accordingly, integration at broader timescales in anterior hippocampus builds on, rather than replaces, discrete encoding. Specialization along the hippocampal long axis therefore supports both discrete encoding and integration across longer timescales, suggesting that the developmental emergence of this specialization may enable within-event binding across broader temporal contexts without sacrificing event-specific detail.

To further support our proposed function and representational scale of the anterior hippocampus, recent adult work demonstrates that the anterior hippocampus simultaneously represents local event sequences and broader temporal structure. Across fMRI (Bellmund et al., 2022) and population-level neuronal measures (Tacikowski et al., 2024), this work reveals hierarchical memory representations that capture both local and global temporal relations. Specifically, adults integrate adjacent event elements within anterior hippocampus while simultaneously aligning sequences across time, thereby encoding the higher-order temporal context in which individual sequences are embedded, independent of the order of events within each sequence (Bellmund et al., 2022). For example, this structure yields more similar representations among event elements that occur first in a sequence regardless of sequence membership, while preserving distinct links between each first element and its corresponding second element, with both forms of representation relating to memory behavior. Accordingly, the mature hippocampus represents information hierarchically by concurrently maintaining local and global information, each of which can be recruited depending on current memory demands. We therefore argue that the emergence of such hierarchical organization supports gains in flexible memory by enabling recall of general temporal structure across experiences, alongside memory for individual event details.

In addition to simultaneous representation of local and global temporal structure, anterior hippocampal representations scale with temporal distance, with events occurring closer in time (e.g., one day) represented closer in neural distance than highly extended intervals of time such as a week or month (Nielson et al., 2015). Adult work also reveals bidirectional representation of temporal sequences in anterior hippocampus that reflect both past experiences and future predictions, highlighting its representational flexibility (Tarder-Stoll et al., 2024). Furthermore, while posterior hippocampal activity increases only when retrieving recent events, anterior hippocampus exhibits increased activity when retrieving events regardless of their temporal distance (Audrain et al., 2022), further suggesting a transition from local to global representation along the posterior-to-anterior axis. Together, integrating evidence across child and adult behavioral and neural literatures reveal that hippocampal development leads to more mature memory for both individual event timing and linking events across broader windows of time. We propose, therefore, that the functional development of anterior hippocampus across adolescence enables local temporal memory behaviors at a greater scale and across broader windows of time, with these critical gains in representational capacity setting the stage for the emergence of global temporal knowledge during late childhood and adolescence.

2. Older children and adolescents form knowledge of global temporal patterns from multiple individual experiences

2.1. Behavioral emergence of knowledge of global temporal patterns

Despite gains in within-event binding at increasingly broader temporal scales brought about by hippocampal maturation into middle childhood, ***across-event integration,*** the ability to integrate multiple episodes into coherent, relational knowledge structures, continues to develop throughout adolescence (Murty et al., 2016; Schlichting et al., 2017). Whereas within-event binding links elements that occur close together in time within a single context (e.g., events unfolding over seconds or minutes within one episode), across-event integration is the ability to relate elements that occur in different episodes, often separated by longer time intervals and occurring in distinct contexts. As a result, across-event integration supports the formation of global knowledge which includes information about commonalities and differences derived across several past experiences which can be applied in future scenarios (Schlichting and Preston, 2015). For example, although the specific elements of a restaurant visit may vary (e.g., ordering different meals), repeated experiences with restaurants allows individuals to form global knowledge about what events usually happen at a restaurant. Notably, this example also highlights a critical factor differentiating knowledge of global temporal patterns from conventional time knowledge - while conventional time knowledge is explicitly taught through direct instruction (e.g., learning how clocks work in school), knowledge of global temporal patterns is learned from repeated or related episodic experiences.

Because across-event integration links temporally distant experiences, the first step in this process must be the reinstatement of past experiences (Figs. 2**C,** 4**B**). As such, the ability to form knowledge of global temporal patterns places greater demands on long-term memory than within-event binding, because the relevant experiences must be retrieved from memory rather than being available in the current environment. By reinstating related past events, individuals can compare current experiences with their knowledge of past experience, allowing them to remember both local instances and commonalities between events that are separated in time.

Though local temporal memory abilities are largely present by middle childhood (Guillery-Girard et al., 2013), interactions between local temporal experience and global temporal patterns continue to develop, such that memory for temporal patterns and generalities becomes more extended and flexible over time. One example of how across-event integration gives rise to knowledge of global temporal patterns is the formation of scripts (e.g., what happens when you visit a restaurant). Notably, children can form rudimentary scripts at early ages, but these tend to be more constrained and less flexible than those of older children. Beginning even in early childhood (3–5 years), children form "scripts" for events that repeatedly occur in the same order, such as a bedtime routine (Hudson et al., 1992). However, throughout childhood, children's understanding of such temporal regularities is bound to specific contexts and lacks the flexibility to be extended to future decisions or environments (Hudson and Nelson 1983a, 1983b). For example, younger children struggle to understand conditional events that only occur in certain contexts and are less likely than older children to organize their knowledge in a hierarchical event structure, instead tending to recall only direct sequence relations or the most important actions within an event (Ratner et al., 1986; Hudson and

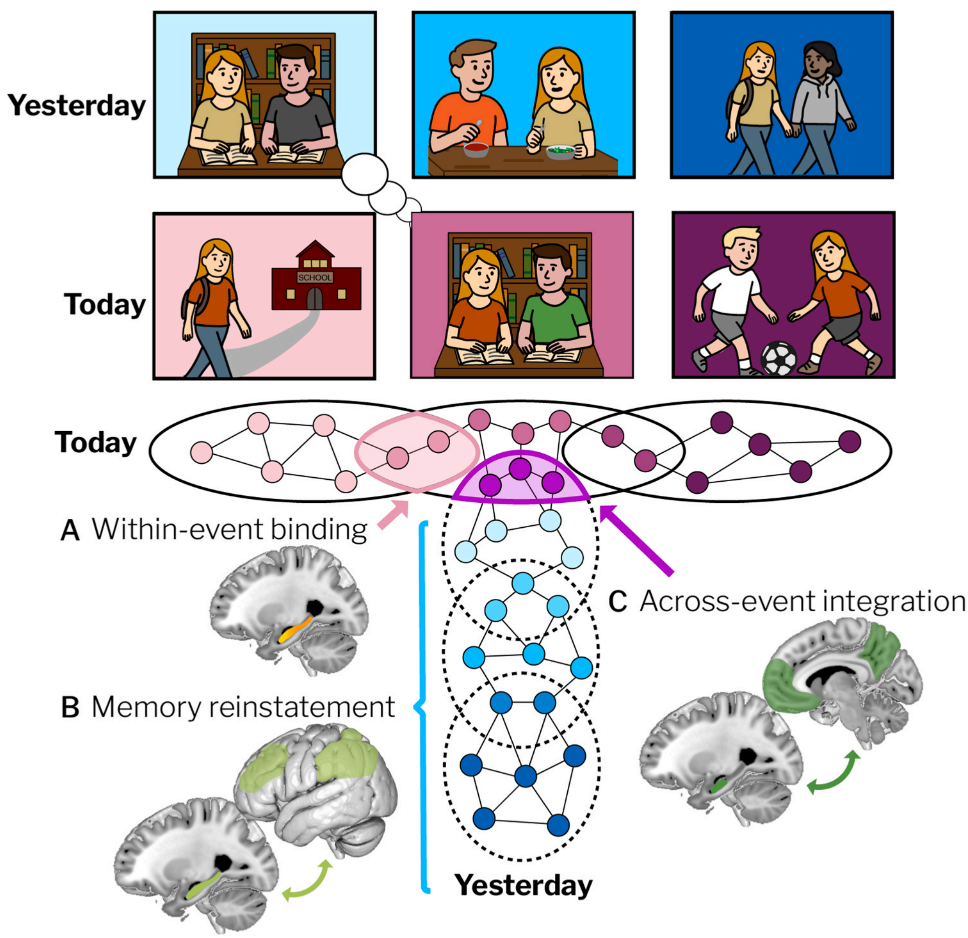

Fig. 4. Development of within-event binding, memory reinstatement, and across-event integration mechanisms enable hierarchical representation with age. In the mature brain, hierarchical memory representation provides behavioral flexibility by simultaneously representing information at multiple levels of specificity. Imagine that "yesterday" (in blue shades) comprises a sequence of events, including studying with a classmate, having lunch with a friend, and then walking home with one's roommate. In turn, the sequence of events for "today" (in pink shades) is walking to school, studying with the same classmate, and then playing soccer. A hierarchical representation of these event sequences will include the representation of details that are specific to individual events (i.e., walking to school today is represented by the lightest pink nodes) as well as event relations including: **A)** Binding of elements that occur within the same temporal context, e.g., two events from "today" are represented by overlapping neural populations within hippocampus. For instance, walking to class and studying with the classmate "today", as adjacent temporal events, may be represented more similarly in hippocampus (as depicted by the rose colored intersection of the two individual event representations); **B)** Reinstatement of prior experiences (memories of yesterday) supported by hippocampal interactions with lateral frontoparietal regions. For instance, studying with your classmate today may evoke your memory for your study session "yesterday" (the lightest blue nodes) as well as other things you did following your study session (the medium and dark blue representations); and **C)** Integration of information across days (between today and yesterday) supported by anterior hippocampal–medial frontoparietal cortex interactions. In particular, your study sessions with your classmate "today" and "yesterday" may be represented in overlapping neural populations (depicted as the bright purple intersection of the representation of the two individual events) within the anterior hippocampus and medial frontoparietal cortex.

Slackman, 1990; Smith et al., 1987; Hudson et al., 1992). Younger children (e.g., 4-year-olds) also form less flexible knowledge of routines, finding it challenging to retrieve even highly familiar relations in the backwards direction (e.g., meals of the day; "night" before "morning"; Scales and Pathman, 2021). Thus, while children do understand regularities in time to an extent, the knowledge of general temporal patterns that they form remains under-developed and inflexible. In other words, the local nature of temporal memory during childhood does not mean that children are completely insensitive to regularities, but rather that even the general temporal pattern knowledge that they form remains highly localized to specific temporal contexts, becoming more global and flexible through childhood and into adolescence. We propose that this shift depends on the maturation of neural systems that support the reinstatement and integration of information across episodes.

One reason children's script knowledge may be less flexible is because they struggle to reinstate prior memories and integrate them with their new experiences, and studies of autobiographical memory may reveal how these abilities develop. For example, while children aged 6–8 years can reliably remember the order of distinct experiences like a vacation relative to a birthday party (Pathman et al., 2013b), the ability to remember when those individual instances occurred within more conventional time frameworks like the month or season does not develop until late childhood (8–9 years), highlighting developmental constraints in relating discrete episodes to broader temporal knowledge (Friedman, 1992; Friedman and Lyon, 2005). For example, while even young children can recall the order and content of events (i.e., local event information), their ability to situate these events within broader temporal regularities, such as holidays or routines, improves substantially during adolescence (Friedman and Lyon, 2005; Friedman et al., 2011; Jack et al., 2016). Moreover, from childhood to adolescence, children demonstrate increased access to knowledge of temporal landmarks (e.g., holidays), suggesting not only a greater capacity for forming knowledge of regularities, but a greater ability to reinstate that knowledge during new experiences (Jack et al., 2016). Thus, temporal landmarks serve as memory cues to reinstate prior knowledge/experiences in the same temporal context. Developmental improvements in memory reinstatement may also explain constraints in young children's script knowledge, because when demands change (i.e., the temporal context changes), children struggle to use memory cues to retrieve relevant prior knowledge. Together, these findings highlight a gradually expanding capacity to organize memories hierarchically by integrating both local and global temporal relations between events.

2.2. Increasing connectivity between hippocampus and lateral frontoparietal cortex supports the reinstatement of related memories during new experiences

We propose that age-related improvements in the scale and flexibility of global temporal patterns (e.g., event relations, scripts, routines) are supported by the emergence of neurobiological reinstatement mechanisms. A key developmental milestone in the shift from local to global temporal memory is the emergence of the ability to retrieve and reinstate memories that share structural similarities with new experiences (Figs. 2**C,** 4**B)**. This capacity depends on interactions between hippocampus and lateral frontoparietal cortex, regions whose functional connectivity strengthens across development (Chang et al., 2016; Tang et al., 2020). As these connections mature with age, children become increasingly capable of reactivating relevant prior knowledge during ongoing experience, a mechanism that enables them to draw connections across distinct experiences in memory (Schlichting et al., 2022). Therefore, we propose that these hippocampal–lateral frontoparietal interactions explain the developmental shift from inflexible, event-specific temporal memory in early childhood to more abstract global knowledge of temporal patterns in adolescence and beyond.

Developmentally, functional connectivity between hippocampus and lateral cortex increases from childhood through adolescence (Chang et al., 2016; Tang et al., 2020). These increases in connectivity may explain why memory retrieval becomes more flexible and robust with age, as enhanced connectivity may support more effective memory reinstatement (Vendetti and Bunge, 2014; Murty et al., 2016). Specifically, we propose that enhanced functional connectivity supports reinstatement by allowing prefrontal regions to guide hippocampal reactivation of prior experiences, enabling the retrieval of relevant information even when current cues are incomplete or only partially overlapping with past events. For instance, compared to adults, children are less able to reinstate prior knowledge from partial cues, and instead only reactivate prior knowledge when their current experience exactly mirrors a past experience (DeMaster et al., 2016; Ngo et al., 2018; 2019). In one task, children (8–10 years) and adults' hippocampal activity was measured while recognizing items either in an identical spatial arrangement to the initial exposure or flipped with other items (DeMaster et al., 2016). While children showed hippocampal reinstatement for items in the identical position, only adults demonstrated reactivation for items that changed positions, highlighting children's limitations in reinstating prior knowledge during distinct but related experiences. Adults also demonstrate reinstatement of temporal context for experiences spanning several months in hippocampal subfield CA1, suggesting a role for both temporally-extended representation and reinstatement of temporal context in the mature hippocampus (Zou et al., 2023).

Notably, recent work conceptualizes both encoding and reinstatement as dynamic, interactive processes that co-occur and engage both anterior and posterior hippocampus (Rugg et al., 2015; Persson and Söderlund, 2015; DeMaster et al., 2016; Hrybouski et al., 2019; Schlichting et al., 2022; Sullivan et al., 2024; Varga et al., 2025b). Accordingly, our framework does not attribute encoding or retrieval to either hippocampal subregion in isolation, but instead emphasizes representational organization over process-based distinctions. While limited, developmental evidence is consistent with this view, as existing findings do not support strong process-based dissociations along the hippocampal long axis. While one study reports greater posterior hippocampal reinstatement in children and anterior reinstatement in adults (Varga et al., 2025b), other work demonstrates engagement across both subregions during reinstatement (DeMaster et al., 2016; Schlichting et al., 2022). Accordingly, we treat reinstatement as a hippocampus-wide process in this framework (Fig. 2**C**).

Work across a broad developmental range (7–30 years) highlights additional age differences in knowledge reinstatement in hippocampus and lateral frontoparietal cortex (Schlichting et al., 2022). Specifically, children do not reactivate past experiences when their current observations overlapped with those experiences, whereas adolescents initially reactivate their prior experiences but then suppress them, suggesting that while they do reinstate their past experiences, they may struggle to relate those experiences to their current observations. Only adults show consistent reinstatement in service of integrating prior experiences with current ones, which further guides inference-based memory judgments. Moreover, hippocampal reactivation in this study did not vary as a function of age, while reinstatement in lateral parietal cortex and inferior frontal gyrus increased with age (Schlichting et al., 2022). This pattern has also been extended by developmental work assessing event-related potentials (ERPs) as children make temporal context judgments. Older children (10–12 year-olds) not only demonstrate improved behavioral accuracy for temporal context judgments relative to 7–9-year-olds, but the magnitude of ERP effects in parietal electrodes predicts individual differences in behavioral accuracy, suggesting a maturing ability to reinstate temporal context in parietal areas (Bettencourt et al., 2021). These frontoparietal regions are also strongly implicated in attentional processes (Vendetti and Bunge, 2014), suggesting that the ability to direct attention toward event features that relate to prior knowledge during encoding may further facilitate both reinstatement and the organization of temporal information for later retrieval. Thus, immature hippocampal–frontoparietal functional connectivity may limit children's ability to reinstate relevant prior experiences, requiring more repetition or a tighter contextual overlap to form and deploy knowledge of temporal regularities.

Finally, adult neuroimaging studies further support the argument that hippocampal interactions with lateral frontoparietal regions facilitate the formation and retrieval of global temporal patterns. For example, hippocampus and its interactions with lateral prefrontal and parietal cortices play a critical role in reinstating temporal structure during memory retrieval (DuBrow and Davachi, 2014; Zou et al., 2023). These frontoparietal regions facilitate reinstatement of global temporal patterns by co-activating with hippocampus to retrieve information that is not directly observable in the moment. For example, in one study, while medial temporal lobe activity tracked the position of individual items, lateral prefrontal regions tracked temporal context, suggesting maintenance of more global knowledge across distinct episodes (DuBrow and Davachi, 2014). Further, during continuous experiences, parietal cortex hierarchically organizes the temporal scale of information attended to from shorter to longer timescales, providing adults access to complementary representations of global temporal structure at varying scales (Hasson et al., 2008; Chang et al., 2022). In contrast, recent work assessing the same organization in children revealed that children primarily represent shorter timescales, suggesting that the development of parietal cortex may govern the scale at which temporal regularities are represented (Moraczewski et al., 2020). Additionally, mature prefrontal and parietal systems in adults track higher-order, temporal context while experiencing continuous sequences of events, providing not only a representation of what events were adjacent, but more abstractly, what experiences happened at a similar time regardless of sequence relations (Hsieh and Ranganath, 2015; Cohn-Sheehy and Ranganath, 2017).

Taken together, these findings suggest that maturation of hippocampus and its connectivity with lateral frontoparietal regions enable a critical developmental shift from representing local instances in isolation to forming knowledge by reinstating related past events during new experiences. This reinstatement, in turn, lays the foundation for the next critical developmental milestone, integrating information across separate, temporally-extended events.

3. Development of across-event integration in late childhood and adolescence

3.1. Across-event integration behaviors refine throughout adolescence

When prior experiences are successfully reinstated, the next step to forming knowledge of global temporal patterns is ***across-event integration***, the linking of related experiences across time (Figs. 2**D**, 4**C**). This linking across events allows individuals to form knowledge of commonalties or patterns across extended temporal contexts and progressively derive knowledge of regularities that are consistent or recur in one's environment (Schlichting and Preston, 2015; Morton et al., 2017a, 2017b). For example, linking memories of several school days may allow a child to derive relational knowledge of the typical structure of their routine, even when commonalities are typical but not shared across every single learning experience.

The development of across-event integration behaviors is typically assessed with inference paradigms (i.e., associative, transitive) in which children experience separate but overlapping associations (e.g., A-B, B-C) and are later tested on their ability to infer the relation between indirectly linked items (A-C). For example, a child that gets dressed before eating breakfast and eats breakfast before driving to school might link getting dressed and driving to school across time as part of the same routine knowledge despite those events not occurring directly in sequence. Notably, children often struggle to perform such across-event integration spontaneously even when they accurately remember the individual event elements, with gains in inferential reasoning extending throughout adolescence (Bauer and Souci, 2010; Bauer and Larkina, 2017; Schlichting et al., 2017; Varga et al., 2019).

Further, while adults can spontaneously integrate current observations with related memories at the time of encoding, children often do not show any behavioral evidence of such integration unless specifically instructed to do so (Varga and Bauer, 2013). When directed to integrate across episodes, children also require more time to make inference-based memory judgments, a pattern interpreted as children having to effortfully retrieve the direct associates (A-B and B-C) before inference, while adolescents and adults can successfully link A and C items during encoding (Schlichting et al., 2017; Shing et al., 2019). Collectively, this work suggests that the ability to link related experiences across time may develop later than the ability to reinstate prior knowledge during new experiences. While such approaches have not been applied to memory for time directly, the ability to spontaneously derive knowledge through across-event integration is critical to forming general knowledge (Bauer et al., 2024), suggesting this cognitive ability is essential to acquiring global knowledge of regularities regardless of domain.

3.2. Anterior hippocampus and medial prefrontal cortex facilitate across-event integration

We propose that across-event integration exhibits an extended developmental trajectory due to the protracted maturation of anterior hippocampus and its interactions with medial frontoparietal cortex. In adults, associative inference is predicted by increased functional connectivity between medial prefrontal cortex and hippocampus during the encoding of overlapping experiences, supporting both successful memory reinstatement and across-event integration (Zeithamova et al., 2012; Schlichting and Preston, 2015). During development, however, the immaturity of these regions may preclude such across-event integration, even when prior experiences are successfully reinstated.

While the scale of across-event integration abilities has not been tested at the representational level (see **Directions for direct investigation**), existing work has linked the structural maturity of anterior hippocampus to across-event integration, demonstrating that structural maturity of anterior hippocampus predicts integration in a broad sample of participants aged 7–30 years (Schlichting et al., 2017). In fact, even in younger children (5–8 years) the volume of medial prefrontal cortex and hippocampus relate to the ability to derive new knowledge through memory integration (Bauer et al., 2019). Thus, volumetric work provides important hints that the ability to link information across events depends on the maturity of hippocampus and medial frontoparietal cortex.

In further support of our proposed framework, recent evidence has also linked across-event integration abilities to developmental differences in knowledge acquisition and subsequent reinstatement. Specifically, whereas adults integrate related memories in medial prefrontal cortex, children and adolescents differentiate those same memories in hippocampus (Varga et al., 2025b). In other words, children tended to represent events that share content distinctly in memory, whereas adults represented them in overlapping representations within medial prefrontal cortex. Interestingly, children were better at reinstating memories when they formed differentiated hippocampal memories, whereas adults were more accurate at reinstatement when they formed integrated memories coding the relationships among experiences. These findings also align with the observation that adolescents may initially reactivate overlapping memories but later represent them as distinct, while only adults simultaneously reinstate and integrate (Schlichting et al., 2022). Together, these studies highlight that both memory reinstatement and across-event integration mechanisms are essential for the formation of global knowledge and that they develop both progressively and separately. Thus, the extended development of across-event integration mechanisms may confer behavioral gains in forming global knowledge about temporal patterns derived across multiple episodes.

4. Mature temporal memory can be flexibly expressed at multiple levels of specificity

4.1. Behavioral evidence for flexible access to local experiences and global temporal patterns

During late adolescence and emerging adulthood, the maturation of hippocampus, lateral frontoparietal regions, and medial frontoparietal regions collectively enables the flexible expression of temporal knowledge across multiple levels of specificity, adapting memory retrieval based on context and task demands (Fig. 4). While the ability to form and reinstate global temporal knowledge may primarily emerge during adolescence, the ability to access and flexibly express either local or global temporal information dynamically may not fully emerge until early adulthood. For example, adolescents demonstrate adult-like learning of complex temporal community structures wherein items share both local (sequential) and global (temporal context) relations. However, only adults extend this temporal community knowledge to infer novel relationships between items (Pudhiyidath et al., 2020). This distinction suggests that, while adolescents may form structured, hierarchical knowledge of both local and global temporal relations, the ability to flexibly express that knowledge to reason about new events (i.e., dynamically access different levels of the hierarchy) extends into adulthood.

The ability to flexibly access temporal knowledge based on task demands emerges progressively across development and into adulthood. For example, the flexible manipulation of temporal knowledge is more predictive of memory precision than age in children 7–11 years, highlighting the importance of increasing flexibility during development (Pathman et al., 2022). Further, assessments of conventional time knowledge in childhood reveal that children (9–10 years) tend to only recall sequences (e.g., months of the year) in the forward order, while adolescents and adults can make backward order judgments as well (Friedman, 1986). This shift has been interpreted as a late developmental transition from relying on direct serial associations to constructing abstract relational representations of event relationships (Friedman, 1986; 1989). Supporting this interpretation, autobiographical tasks show that although both children and adolescents can draw on global knowledge of temporal patterns to infer when past events occurred, adolescents are more effective at using that knowledge to guide precise inferences, reflecting not just greater knowledge of temporal landmarks but more flexible and targeted application of that knowledge in memory (Friedman and Lyon, 2005; Hudson and Mayhew, 2011; Jack et al., 2016).

Finally, related non-temporal studies of hierarchical knowledge reinforce the importance of flexible access to information at multiple levels of specificity, supporting our argument that hierarchical memory representations are necessary to provide maximal flexibility in navigating both familiar and novel contexts. For example, in reinforcement learning tasks, the ability to either prioritize (up-weight) or compress (down-weight) specifics or generalities to guide memory-based decision-making also increases into adulthood, indicating that developmental changes in memory include not just what is remembered, but how information is prioritized (Nussenbaum and Hartley, 2025). Adult work on structure learning further shows that the ability to construct coherent, structured mental representations predicts memory for both individual items and higher-order patterns (Bui and McDaniel, 2015; McDaniel et al., 2022). Together, these findings highlight the interaction of local and global information in memory, emphasizing that effective memory relies not just on the formation of local and global representations, but on the ability to integrate and flexibly shift between them.

4.2. Medial frontoparietal-anterior hippocampal integration supports flexible expression of local and global temporal information based on environmental demands

Converging neural evidence from children and adults suggests that connectivity between anterior hippocampus and medial frontoparietal cortex is critical for the flexible expression of both local and global temporal memory in novel contexts. This flexible expression is achieved by not only reinstating prior knowledge during new experiences, but by embedding new experiences into global knowledge structures across time, allowing one to access specific memories or relational knowledge depending on contextual demands **(**Fig. 4). As a result, one can hierarchically represent details unique to individual experiences (individual nodes in Fig. 4), elements that are bound within an episode (highlighted pink nodes in Fig. 4**A**), and integrated details shared across similar experiences (highlighted purple nodes in Fig. 4**B,C**).

Projections from anterior hippocampus to medial neocortical regions are some of the latest to develop, maturing into young adulthood (Spear, 2000; Calabro et al., 2020). Importantly, these late-developing connections are thought to underlie several important cognitive functions, including the ability to reinstate prior knowledge to integrate new observations, infer connections between related events, and link events across broad windows of time (Hwang et al., 2010; 2016; Ghetti and Bunge, 2012; Murty et al., 2016; Schlichting et al., 2017). Thus, prior work suggests that the maturation of medial frontoparietal regions into young adulthood shapes not only the representation of memories but, critically, access to those memories in novel contexts (Güler and Thomas, 2013). As such, we argue that the maturation of medial frontoparietal-anterior hippocampal connectivity enables the flexible expression of temporal memory in real-world contexts by allowing individuals to retrieve and apply either specific or general information based on environmental demands.

A central function of medial prefrontal cortex is to dynamically modulate hippocampal memory representations based on behavioral goals. For example, hippocampal and prefrontal activity during temporal memory judgments varies based on the temporal scale of the information being retrieved. Specifically, activity in both regions increases when individuals recall temporal relations across distinct events, suggesting that prefrontal cortex facilitates the integration of temporal information between events by linking information from earlier and later parts of an experience (Swallow et al., 2011; DuBrow and Davachi, 2016). Furthermore, hippocampus and PFC demonstrate increased functional connectivity when encoding temporal information within events, suggesting prefrontal cortex may also facilitate the organization of continuous experiences into coherent, structured hippocampal representations (DuBrow and Davachi, 2016; Baldassano et al., 2017; Ben-Yakov and Henson, 2018).

Medial prefrontal cortex's dynamic modulation of temporal memory representation based on environmental demands additionally aligns with its role in co-activating with anterior hippocampus to compare current observations to prior knowledge and update that knowledge accordingly (Schlichting and Preston, 2016). For example, in category-learning tasks, medial PFC actively emphasizes task-relevant dimensions while compressing irrelevant information, suggesting medial prefrontal cortex may similarly tune hippocampal representations towards the most goal-relevant dimensions of temporal memory (Mack et al., 2020). In support of this proposed modulatory mechanism, in sequence-learning tasks, category knowledge is reinstated when recalling event sequences, consequently facilitating hippocampal linking of items sharing serial relations (DuBrow and Davachi, 2014). Critically, that this resulting hippocampal linking only happens as a result of knowledge reinstatement is a critical example of how we propose adolescents differ from adults; while adolescents may be able to reinstate prior knowledge, only adults will flexibly embed their current experiences within that knowledge to refine future behavior. Together, these findings highlight the dynamic role of the mature prefrontal cortex in modulating hippocampal representations to meet task-specific demands. As such, in children we would predict weaker task-specific modulation of hippocampal representations, consistent with protracted behavioral gains in the flexible expression of local and global temporal information across adolescence and into adulthood.

Finally, the mature brain enables flexible memory expression by directly representing hierarchies of local temporal relations and global temporal patterns across hippocampus and neocortex. This organization is hierarchical because local representations are embedded within higher-order temporal structure that spans multiple events or episodes, rather than existing as independent codes. Critically, this nesting allows information about the same experiences to be expressed at multiple levels of specificity (i.e., event details or temporal patterns) depending on current demands. Evidence for such hierarchical representation in the mature brain demonstrates this integrated coding across regions and timescales. For example, medial prefrontal cortex and inferior frontal gyrus preferentially respond to either temporal context (medial prefrontal cortex) or sequences of items (inferior frontal gyrus; Schapiro et al., 2013), while complementary representations in anterior hippocampus and precuneus, within medial parietal cortex, separately represent temporal relations between items at shorter and longer timescales (Pudhiyidath et al., 2022). Crucially, these distinct representations enable inference in novel contexts by providing access to relational information at either timescale depending on environmental demands (Pudhiyidath et al., 2022). Thus, hierarchical representation in anterior hippocampus and medial frontoparietal cortex provides a dynamic mechanism by which local and global temporal information can be flexibly expressed to facilitate reasoning in new environments.

Our framework proposes that, during development, immaturity in these anterior hippocampal–medial frontoparietal networks constrains reasoning abilities by limiting the flexible expression of temporal knowledge in novel contexts. Importantly, this constraint aligns with behavioral work demonstrating protracted gains in inferential temporal reasoning into young adulthood (Pudhiyidath et al., 2020). Again, this provides a critical example of maturation which extends through adolescence and into adulthood: while both adolescents and adults form structured knowledge of temporal regularities, only a fully mature cognitive system enables dynamic updating and expression of that knowledge based on current goals and environments. Together, this work suggests that the maturation of hippocampus (anterior hippocampus in particular) and the medial frontoparietal cortex network progressively enables flexible expression of temporal information based on environmental demands. As a result of anterior hippocampal and medial frontoparietal maturation, hierarchical representations can be formed which embed local experiences into global knowledge, allowing for representations of both commonalities and differences between experiences which enable flexible behavior in both familiar and novel contexts.

5. Directions for direct investigation

While our proposed neurocognitive framework is grounded in existing behavioral and neural literature, many of the key neural mechanisms it highlights have not yet been directly tested within temporal memory paradigms, particularly in developmental samples. As such, the framework lays out specific and testable hypotheses regarding how hippocampal and frontoparietal systems contribute to different temporal memory behaviors across age. Each neural mechanism within our developmental model (Fig. 2) can be empirically examined.

First, the temporal scale over which within-event binding occurs at different ages should be directly tested during late childhood and early adolescence by measuring hippocampal representations of adjacent vs. non-adjacent event elements, including elements that span longer temporal intervals within an episode. Such work would clarify how hippocampal maturation supports more extended temporal integration and whether anterior–posterior differences in representational scale account for developmental shifts in within-event binding (e.g., Schlichting et al., 2017; Forest et al., 2023). Moreover, future research may relate experiences with time in infancy and early childhood to the development of within-event binding, particularly through longitudinal designs that capture change within the same participants, given infants' ability to remember sequences and the early engagement of the posterior hippocampus (Yates et al., 2025), extending the proposed developmental mechanisms across a broader age range.

Second, the reinstatement of past experiences and their integration with current observations to form global temporal knowledge should be directly tested during late childhood and adolescence as lateral frontoparietal cortex undergoes significant functional and structural changes (Vendetti and Bunge, 2014). Future work can examine how differences in reinstatement-related activity in lateral prefrontal and parietal cortices correspond to adolescents' ability to extract and apply temporal regularities across distinct, temporally extended episodes, particularly in response to partial memory cues (e.g., Schlichting et al., 2022; Varga et al., 2025b).

Third, the flexible expression of hierarchical temporal knowledge and ability to represent both specific details of events times and higher-order temporal regularities simultaneously should be evaluated in both adolescents and adults. Neural measures should assess if and how individuals at different ages represent both local event details and global temporal structure across sequences of events, and whether representations at both levels of specificity can be identified in anterior hippocampus and medial prefrontal cortex (e.g., Pudhiyidath et al., 2020; Bellmund et al., 2022). Directly quantifying developmental changes in the representational scale, reinstatement capacity, and hierarchical integration of temporal information will provide critical evidence for how neural maturation gives rise to the shift from local to global temporal memory across development.

Finally, although the focus of the present review is on temporal memory, the mechanisms we propose - information binding, reinstatement, integration, and hierarchical representation - likely contribute to the maturation of memory behaviors across multiple domains. Indeed, prior work examining the development of spatial cognition (Nazareth et al., 2018; Varga et al., 2025a), reinforcement learning (Hartley et al., 2021), and emotional memory (Rosenblau et al., 2021) hypothesize similar neurodevelopmental mechanisms, suggesting that these developmental changes are not unique to temporal memory, but may scaffold cognitive development and flexible memory behavior more broadly. As such, future work should extend the proposed framework beyond the domain of time to evaluate which mechanisms are more general to episodic memory, and whether any mechanisms are unique to specific domains.

6. Implications outside of laboratory settings

Understanding how neural development shapes memory behaviors is critical in real-world contexts. Although real-world scenarios naturally require specific behaviors and underlying neural activity is less observable, examining how the brain supports these behaviors is essential for understanding: 1) when particular behaviors emerge across development and 2) why behaviors may differ across children of different ages. Here, we describe several important real-world behaviors and speculate as to how neural development may contribute to their emergence, highlighting directions for future applied research that links neural development to behavior to facilitate positive outcomes in high-stakes, real-world scenarios.

6.1. Child investigative interviewing

Understanding how children access and organize their memories is critical in forensic contexts for which the ability to provide temporal information can significantly impact eyewitness credibility and case outcomes. For instance, child abuse victims often recall what happened during abuse episodes but struggle to provide specific temporal details about when the abuse occurred (Wandrey et al., 2012). This pattern - accurate memory for episodic details but limited temporal information - aligns with the first level of our proposed hierarchy, reflecting highly localized memory for individual events and underdeveloped global knowledge of temporal patterns. According to the proposed framework, these behavioral patterns may reflect the extended development of neural systems that support across-event integration, suggesting that younger children may be more successful at describing event details than at placing events in time.

Unfortunately, however, child victims are often asked to estimate when episodes of abuse occurred, and when children cannot produce specific temporal details, they can be perceived as less credible witnesses (Wandrey et al., 2012). This issue is particularly significant in cases of repeated abuse or delayed disclosure for which reasoning about time patterns is crucial, underscoring the need to understand how the development of hippocampal and frontoparietal systems constrains or enables children's ability to accurately encode, organize, and report temporal information (Malloy et al., 2007; McWilliams et al., 2023). Recent research also shows that child witnesses struggle to interpret temporal language (Friend et al., 2022) and often guess when asked to locate events in time, which may further undermine their credibility as witnesses (Merriwether et al., 2023; Cameron et al., 2024), especially for younger children whose temporal reasoning abilities are less mature. Moreover, childhood maltreatment has been linked to disruptions in hippocampal development, which may further limit the accuracy and scale of temporal memory during childhood (Teicher et al., 2012). Thus, understanding how neural function supports or constrains temporal memory across development is critical for interpreting children's temporal reports in a developmentally informed manner, particularly in forensic contexts where inaccurate expectations about temporal reasoning can have serious consequences.

Importantly, the evidence reviewed here does not suggest that children are incapable of making accurate temporal judgments in forensic contexts. Rather, it underscores that how we prompt children for temporal information, and what kinds of information we expect children to report about event times, must be tailored to their developmental stage. Indeed, children as young as six years can make above-chance judgments about the order and recency of two distant events (Friedman, 1991; Pathman et al., 2013b), and general location in conventional time (i.e., month; Friedman and Lyon, 2005) of their past experiences in some tasks, depending on the type of information that is probed. However, because methods for studying temporal memory are heterogeneous (see Fig. 1) and rarely compare children's performance directly to adults - who themselves are often imprecise at locating past events in time (Rubin and Baddeley, 1989) - it remains an open question what kinds of temporal information are appropriate to request from children at different ages in forensic settings and whether children are less reliable than adults. Lab-based memory studies also may underestimate children's ability to recall real-world experiences (Pathman et al., 2011), suggesting that children may actually be more accurate in describing their own past experiences than laboratory tasks imply. We argue that one way to better understand what kinds of temporal information children can produce across development is to understand how developing neural systems support different memory processes with age.

Together, these gaps highlight the need to better understand the temporal information that children can remember and report at different ages, and how these abilities compare to adults. While this review focuses on understanding neurodevelopmental mechanisms rather than their applied implications, understanding how local and global temporal memory abilities change with age may inform future applied research and practice which directly improves outcomes for child witnesses.

6.2. Educational success and knowledge generalization

In educational contexts, the ability to integrate information across learning episodes to form knowledge over time is critical (Bauer et al., 2012; Esposito and Bauer, 2017). Shing and Brod (2016) propose that shifts in processing from the medial temporal lobe to the neocortex with age support educational success by enabling the increased use of prior knowledge during learning. This account aligns with our proposed neurocognitive framework, which proposes that increased functional connectivity between hippocampus and frontoparietal regions facilitates integration of information across broader timescales with age. Temporal memory is also closely tied to key cognitive domains relevant to academic performance such as working memory and vocabulary (Pathman et al., 2022), suggesting that shared mechanisms may relate to the development of several important cognitive abilities. Additionally, the extent to which learning episodes are spaced over time is linked to the ability to generalize new knowledge, suggesting that age differences in the temporal window of memory integration may affect educational success (Vlach, 2014). Finally, in adults, the capacity to organize information into cohesive relational structures predicts comprehension and learning outcomes, emphasizing the importance of integrating events over time into global, structured knowledge representations (McDaniel et al., 2022). Thus, the maturation of hippocampal–cortical circuits that support temporal memory may explain individual differences in learning and academic achievement. Together, these findings highlight how developmental improvements in temporal memory and integrative processes may play a central role in educational success, and suggest that directly studying these mechanisms can reveal how learners build coherent, structured knowledge over time.

7. Conclusion

Understanding how children structure their experiences in time is critical to understanding episodic memory development. While adults form hierarchical knowledge of both temporal specifics and regularities, children often display more constrained memory for both event details and time patterns. This review proposes a unified neurocognitive account of this developmental transition grounded in the protracted and non-uniform development of hippocampus and frontoparietal cortex. Integrating behavioral and neural literatures of both children and adults, we demonstrate how the representational capacity of the developing brain gradually enables local, global, and flexible memory behaviors. Future work should directly test this unified neurocognitive framework to directly relate the representational capacity of the developing brain to different temporal memory behaviors across development.

Data Statement

The present manuscript is a review article and therefore does not contain any original data.

CRediT authorship contribution statement

Thanujeni Pathman: Writing – review & editing, Visualization, Conceptualization. **Alison R. Preston:** Writing – review & editing, Visualization, Conceptualization. **Owen W. Friend:** Writing – review & editing, Writing – original draft, Visualization, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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