Memory

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Introduction

Memory comprises a variety of abilities and skills. In this entry, we focus on episodic memory, which can be defined as the ability to remember past events with details about time, place, and other unique contextual features (Tulving, 1983). The development of episodic memory has traditionally been considered to be distinct and dissociable from that of other forms of memory. For example, semantic memory, which refers to the acquisition, retention, and use of general world knowledge, has been proposed to be a distinct memory system, despite both episodic and semantic memory being declarative, or available for conscious access (Tulving, 1983). From this perspective, the capacity to remember a specific episode relies on fundamentally different behavioral and neural mechanisms from the capacity to learn facts. Recent research, however, has suggested that the mechanisms involved in episodic memory contribute to knowledge acquisition (e.g., Preston & Eichenbaum, 2013), emphasizing the contribution of episodic memory for the development of semantic memory.

The contribution of episodic memory is also critical for the emergence and development of autobiographical memory, which is the capacity to form and maintain a coherent narrative about the self in time. Autobiographical memory clearly extends beyond episodic memory in that it integrates memory of past episodes with self-representations, including one's subjective evaluations, internal states, and attribution of personal meaning to past events. However, it is clear that without a capacity to remember specific episodes, one would lack the capacity to retain past episodes long enough to be reflected upon and integrated in one's life history.

Even newborns show signs of functioning memory systems. For example, very young infants can successfully discriminate their mother's voice from other voices. However, episodic memory continues to develop dramatically from infancy throughout childhood and adolescence. In the following sections, we discuss the potential mechanisms underlying this development. Improvements in episodic memory are closely related to the development of learning and semantic memory, and we integrate the discussion of how these processes mature in our overview of episodic memory development.

Most of the present discussion is devoted to the mechanisms supporting the typical development of learning and memory. We then go on to review recent findings regarding atypical development and how our understanding of the typical developmental trajectory of episodic memory may help unravel the causes and consequences of altered memory functioning. Finally, we discuss potential implications of episodic memory development for learning and instruction.

Typical development of episodic memory

The first months of life are associated with rapid improvements in memory functioning: By 3 months, infants can form associations among simultaneous events after a single exposure to these events, and the ability to retain memories over longer periods of time continues to improve during the first year of life (Bauer, 2006). Although there is still considerable debate about the extent to which memory manifestations within the first year of life actually reflect episodic memory, it is clear that by the second year of life, toddlers are clearly able to retain information about the associations between events and the arbitrary features of the context in which they initially appeared. Episodic memory continues to develop further throughout early childhood, middle and late childhood, and adolescence, with children becoming increasingly better at remembering details about the past and strategically learning novel information.

The typical developmental trajectory of episodic memory can be related to the maturation of relational binding and mnemonic control processes (Ghetti & Bunge, 2012). In the following discussion of these processes, we integrate behavioral findings with current understanding of the possible neural mechanisms supporting relational binding and mnemonic control, and their maturation.

Relational binding processes

Memories of our past experiences typically contain multiple features, including event information (i.e., what), spatial information (i.e., where), and temporal information (i.e., when). Therefore, episodic memory functioning is crucially dependent on the ability to bind together information about an event with information about the surrounding spatiotemporal context. At the neural level, the encoding and retrieval of arbitrary associations is supported by regions of the medial temporal lobe (MTL), and the hippocampus in particular. The structural and functional maturation of MTL regions may therefore be expected to foster episodic memory development during childhood.

Some research has highlighted the early emergence of relational binding processes. For example, research using eye tracking to measure infants' gaze patterns during remembering suggests that 9-month-olds are capable of binding together unfamiliar faces with an arbitrary scene context (Richmond & Nelson, 2009). Infants were presented with a series of three scenes each paired with a different face. During a subsequent recognition test, they were presented with three familiar faces on the background of a studied scene such that only one of the faces had been previously presented with this particular scene. In this task, 9-month-olds looked longer at the matching face that was previously studied with the corresponding scene than at the familiar lure faces, indicating that infants formed memories for the arbitrary associations between faces and scenes. Critically, comparable looking behavior is observed in typically developing adults performing a similar task, but not in patients with damage to the hippocampus, who fail to look preferentially at the matching face.

This work in infants aligns well with early evidence from animal models, suggesting that the anatomical maturation of the MTL, and the hippocampus in particular, is completed relatively early in postnatal life. Analyses of the postnatal development of primate hippocampal formation reveals that the hippocampus may be reaching adult-like dimensions by the second half of the first year of life, except for the dentate gyrus and the cornu ammonis area 3 (CA3) of the hippocampus, which seem to mature later and are fully functional after 7 years of age. Indeed, the protracted maturation of the dentate gyrus may be an important factor in infantile amnesia, a phenomenon that refers to the fact that children and adults have only scarce and fragmented memories from the first years of their lives. It has been recently proposed that the continued production of new neurons in the dentate gyrus after birth may prevent memories consolidating and stabilizing, resulting in less persistent memories and infantile amnesia (Josselyn & Frankland, 2012). Furthermore, accumulating neuroimaging evidence discussed in the upcoming sections suggests that the hippocampus exhibits a more protracted developmental trajectory than initially thought, and may therefore play a key role in the development of memory abilities well beyond infancy.

With age, the ability of infants and children to retain and retrieve relational information over longer time delays improves considerably. For example, Wenner and Bauer (1999) demonstrated that memory for individual target actions was comparable between 20-month-olds and 16-month-olds, but only the 20-month-olds were able to reliably reproduce sequences of arbitrarily ordered actions, indicating that the capacity to encode and retain information about the actions and their temporal context continues to develop in infancy. The number of actions retained and the interval over which this information is remembered gradually increases further during late infancy and the toddler years.

Age-related improvements in memory for item–context associations continue to be evident later in childhood. For example, age differences have been reported between 4- and 6-year-olds in memory for the associations between animals and arbitrary background scenes (Sluzenski, Newcombe, & Kovacs, 2006). In this study, 6-year-olds were more likely than 4-year-olds to correctly remember the specific association between an animal and a corresponding background. Of importance, the 4- and 6-year-old children did not differ in their capacity to remember the individual elements of the event (i.e., individual animals or scenes), indicating that it is specifically the binding of these elements that poses a developmental challenge.

Relational binding processes are important not only for the formation of integrated contextual representations but also for the retrieval of these representations. The ability to recollect past experiences with specific contextual details is associated with increased demand on relational binding processes compared to recognizing events as familiar. Accordingly, Ghetti and Angelini (2008) demonstrated age differences in recollection, but not in familiarity between 6 and 8 years of age. However, developmental improvements in recollection were only observed when children encoded content semantically. Recollection of perceptually encoded content did not change over childhood and adolescence. These findings suggest that recollection of qualitative details during middle and late childhood depends on additional factors, such as semantic processing and the ability to utilize it in the service of learning. In addition, evidence from neuroscience suggests that the neural substrates of relational bindings do continue to change during middle and late childhood.

Indeed, there is now considerable functional neuroimaging evidence demonstrating prolonged maturation in memory-related activation of the hippocampus, the structure that is primarily responsible for relational binding processes (Ghetti, DeMaster, Yonelinas, & Bunge, 2010). Across studies, differences in neural activity associated with successful memory for details have been observed when comparing children (ranging between 8 and 12 years) and adults, during both encoding and retrieval. Studies of structural integrity of the hippocampus have further corroborated the notion of protracted development of this brain structure and have started to uncover regional differences in the maturation of the anterior and posterior hippocampus, as well as in different hippocampal sub-fields. Altogether, these findings support the view that binding processes supported by the hippocampus continue to develop even in late childhood.

While the discussion above demonstrates the importance of relational binding for the development of episodic memory, these processes and their neural substrates may also contribute to children's ability to make inferences about past events and to acquire new knowledge. Specifically, novel events are interpreted and integrated in the context of existing knowledge structures, or schemas. Such knowledge structures include mental representations of the relations or commonalities among different events. Frequently, they are based on extracting the regularities across multiple events and forming a 'gist' representation that is deprived of specific details of the separate events. Research with rodents and human adults suggests that the hippocampus may play a critical role in the formation of a schema through its involvement in the extraction of relations across multiple events. This process would foster the development of children's knowledge and semantic memory.

Mnemonic control processes

Relational binding processes constitute the key building blocks of episodic memory and lie at the heart of the ability to re-experience our past and imagine the future. However, developmental changes in these processes and their neural correlates cannot fully account for the observed developmental changes in episodic memory during childhood. In addition to binding, higher-order control operations direct and facilitate the learning of new information and the retrieval of bound representations. Mnemonic control processes include the use of effective encoding and retrieval strategies, the monitoring of learning and memory in the context of current goals and task demands, as well as decision-making processes to regulate learning and remembering. The latter aspects are referred to as metacognition, the knowledge about one's cognition, and the ongoing monitoring and control of learning and memory.

Learning and memory strategies

With increasing age, the use of elaborative strategies becomes an increasingly important part of children's learning behavior, especially between the preschool years and adolescence (Schneider & Pressley, 1997). In general, even though younger children exhibit goal-directed behaviors geared toward learning success, their strategy repertoire is limited compared to that of older children. Younger children are less likely to produce complex learning and retrieval strategies spontaneously. Even after they are instructed in a strategy, their performance is often less likely to benefit from the new strategy compared to older children and adults. Direct comparisons of memory performance after intentional and incidental encoding instruction clearly demonstrate that age differences in memory accuracy are magnified in situations when children deliberately attempt to learn new information, even when comparing 7- to 8-year-old children and adults. Furthermore, even at the age of 7, the degree to which age differences persist under incidental encoding (i.e., when memory is tested without an explicit instruction to learn) depends on the extent to which an orienting task promotes the encoding of meaning of the presented information. Thus, younger children may be less likely to self-initiate and engage in control processes to promote learning, thereby affecting later performance. In contrast, the use of elaborative and organizational strategies in older children is considerably less situation dependent and more flexible (Schneider & Pressley, 1997).

Longitudinal research in 6- to 10-year-olds has revealed phases of rapid change in strategy use, with the majority of children changing from not using a strategy to near perfect use within time periods as short as six months (Schneider & Pressley, 1997). These general developmental trends are accompanied by considerable individual variability in the specific strategies that children use. This variability is likely due to the idea that, at any given point in time, children use a number of different strategies and combinations of strategies to facilitate learning and remembering in a particular situation.

There are a number of factors contributing to individual differences in the development of strategy use in the preschool and elementary school years. First, strategy use requires more effort and places greater demands on working memory and executive functioning; these processes also undergo pronounced developmental changes during this lifespan period. Second, environmental factors are crucial for creating opportunities to acquire and maintain novel learning strategies. For example, in early childhood, children's strategic behavior at 52 months has been related to maternal strategic behavior observed when the children were 40 months old (Güler, Larkina, Kleinknecht, & Bauer, 2010). Specifically, this study showed that during a free-recall task, 52-month-old children were more likely to strategically sort items according to their categories if their mothers emphasized organization of the items rather than focusing on repetition at the earlier time point. Third, research has demonstrated that the kind of elaborative encoding experts engage in when they process information within their domain of expertise selectively promotes recollection of specific details. Increased knowledge of a topic also facilitates the learning of novel information related to this particular topic. Thus, children's experience with and knowledge of a particular domain may facilitate the flexible use of more complex learning and retrieval strategies, suggesting that the degree to which children can effectively utilize different strategic behaviors may depend on the development of the semantic memory system. In line with this idea, research which examines knowledge effects in domains of child expertise has demonstrated that children outperformed adults in recall measures for content specific to these domains.

Metacognition

Parallel to the development of more elaborative and efficient learning strategies, children demonstrate notable improvements in metacognitive abilities, in particular monitoring and control of learning and memory outcomes. Monitoring mechanisms are involved in the ongoing assessment of memory availability and accuracy, whereas metacognitive control mechanisms are involved in the regulation of behavior, for example through the decision to volunteer or withhold a response or to re-study novel information. Together, metacognitive monitoring and control enable the strategic regulation of learning and remembering, and are expected to make significant contributions to the development of core binding capacity and the efficiency with which children can acquire new knowledge and expertise.

With respect to the control of learning, studies with adult participants have demonstrated that they use metacognitive monitoring to guide decision-making and to choose which individual items to study and for how long, resulting in considerable improvements in memory performance. In contrast, developmental studies indicate considerable improvements in the degree to which children (7- to 10-year-olds) use their judgments of learning (i.e., subjective decisions about how well an item was learned) to guide decisions about which items to study again or how to allocate study time across items (e.g., Metcalfe & Finn, 2013). In addition, metacognitive knowledge of how learning and memory processes operate, or which strategies are more effective than others, plays an important role for the development and use of effective learning strategies. Metacognitive knowledge may therefore provide one of the key mechanisms mediating the effects of home or school environment on the development of learning strategies (Schneider & Pressley, 1997).

Developmental improvements are also observed in metacognitive processes involved during memory retrieval. Abundant evidence from studies with adult participants suggests that when given the opportunity to choose which memories to volunteer, adults discard less-confident responses, resulting in a superior performance compared to when no opportunity to withhold a response is provided. Similar effects have been demonstrated in children as young as 4 and 5 years (Hembacher & Ghetti, 2014). However, another study showed that while both younger and older children (6 to 10 years) reliably monitored memory retrieval by reporting subjective recollection of previous episodes that were recalled with contextual detail, only older children (9- and 10-year-olds) were more likely to select a sub-set of subjectively recollected items to be evaluated for a possible reward (Hembacher & Ghetti, 2013). These results suggest that the protracted development of metacognitive processes may involve the ability to engage in more fine-grained metacognitive distinctions, as well as in more complex choice behaviors (e.g., selecting a finite sub-set of most valuable items as opposed to reporting for every item whether individual memory is good enough for a future reward).

The nascent literature on developmental cognitive neuroscience highlights the role of the development of cortical regions within the prefrontal (PFC) and posterior parietal cortices to support age-related improvements in the strategic control of encoding and retrieval (DeMaster & Ghetti, 2013). Functional neuroimaging findings point to developmental differences in task-related activation in lateral PFC regions during encoding, regardless of whether participants attempted to learn new information intentionally or encoded it incidentally, though differences may be attenuated in the latter case. Age differences in PFC activation are also found between children and adults during retrieval, demonstrating maturational differences in the ability to engage monitoring processes in the service of current goals and task demands. Moreover, the existing neuroimaging studies of the development of episodic retrieval have consistently reported age-related differences in activation of the posterior parietal cortex across middle childhood and adolescence. The exact role of the posterior parietal cortex in memory retrieval is a subject of an ongoing debate, but this region may be involved in supporting the control and manipulation of retrieved representations. While studies focused on the contribution of the posterior parietal cortex to memory development are currently missing, they may play a critical role for understanding the development of strategic control abilities. Taken together, one main trend in the development of the neural mechanisms supporting mnemonic control may be an increasing selectivity and flexibility in fronto-parietal recruitment in service of current learning and retrieval goals.

Age-related differences in functional activations are accompanied by changes in the structural integrity of PFC and posterior parietal regions during childhood and adolescence; individual differences in cortical thickness and gray-matter volume of these areas have been associated with differences in the ability to remember detailed memory representations. Future research is needed to characterize the mechanisms by which fronto-parietal brain networks are involved in the emergence of more sophisticated control of learning and memory, for example to what extent structural and functional development in these brain areas may create the basis for the emergence and utilization of complex and elaborative learning strategies.

Interactions between relational binding and mnemonic control processes

Improvements in episodic memory are expected to depend not only on regional brain changes but also, and perhaps even more critically, on the communication and efficiency of coordination among these regions. The parietal cortex is functionally and structurally connected with lateral PFC regions. Furthermore, both frontal and parietal regions have direct structural connections to MTL regions: parietal regions are connected to the posterior hippocampus through the *cingulum bundle*, whereas PFC is connected with to anterior hippocampus through the *uncinate fasciculus*. Increases in the white matter coherence in a number of white-matter tracts have been associated with a superior episodic memory in middle childhood.

Developmental changes in the connectivity between PFC and MTL regions may be particularly important for the integration and consolidation of novel information into existing knowledge and for the development of semantic memory. Together with feature integration in the MTL, medial PFC regions may be particularly relevant for schema development during learning and for the subsequent retrieval of memories that are appropriate in a particular context (Preston & Eichenbaum, 2013). Newly encountered information is unlikely to completely overlap with an existing knowledge structure, even if they share common elements. In these situations, medial PFC may be engaged to resolve the conflict between contradicting information in the newly encountered information and the existing knowledge structure (Preston & Eichenbaum, 2013), thereby promoting the development of semantic memory. Evidence of the role of PFC–MTL interactions for semantic memory improvement with age is scarce, but is largely consistent with the idea that these regions are involved in the protracted development of semantic memory. For example, in one study, lateral PFC activity related to the semantic elaboration of words from common semantic categories was attenuated in children between 8 and 12 years compared to adults (Paz-Alonso *et al.*, 2008). Given the prolonged development of the uncinate fasciculus connecting the anterior hippocampus with the medial PFC, an intriguing venue for future research is that this tract may play an important role in the development of semantic memory and the capacity to integrate novel information into existing knowledge. Another key question for future research concerns the extent to which changes in the individual contributions of PFC and MTL regions to episodic memory development depend on the increasing integration between these regions and systems.

Atypical development of episodic memory

The healthy development of episodic memory is fundamental for carrying out many basic daily activities, such as recalling the way home after a visit to a new friend's home or engaging more complex skills such as anticipating future actions. Thus, understanding the conditions under which episodic memory development goes awry is critical. Episodic memory deficits have been reported in association with a number of neuropsychiatric disorders, including depression, post-traumatic stress disorder, and schizophrenia. Neurodevelopmental disorders such as autism and fragile X syndrome are also associated with memory deficits. Furthermore, episodic memory deficits are observed secondary to acquired brain injury, ranging from the most severe, such as cases of developmental amnesia or severe traumatic brain injury, to milder conditions. Examples of the latter include more subtle memory deficits associated with mild forms of cerebral hypoxia or ischemia, and complications of Type 1 diabetes, asthma, or exposure to general anesthesia during infancy (e.g., Stratmann *et al.*, 2014). This non-exhaustive list should make it apparent that there are many situations that can alter memory functioning in childhood and that could potentially have significant consequences for children's lives.

Despite a growing body of research documenting these memory deficits, it is still not clear how the developmental trajectory of episodic memory is affected in these conditions (e.g., do memory deficits worsen over time? Are there periods of increased susceptibility or increased resilience to memory insult?). In addition, addressing how different conditions specifically affect relational binding or mnemonic control processes and their neural correlates would be central not only for comprehensive theories of episodic memory development but also to design interventions that are targeted at the specific memory mechanisms.

Relevance for learning

Uncovering the mechanisms that drive episodic memory development is relevant not only for addressing conditions in which memory goes awry but also for improving learning and knowledge acquisition in the classroom. While the role of effective strategy use and metacognitive knowledge is well recognized, the extent to which the development of relational binding processes is related to academic achievement has received substantially less attention. Furthermore, among mnemonic control processes, the connection between metacognition, especially the development of uncertainty monitoring, and knowledge acquisition has received comparably little attention.

Relational binding processes might influence learning across different domains by directly supporting the ability to form detailed representations of newly acquired information. For example, in adults the ability to (implicitly) extract regularities in temporal sequences or spatial configurations, referred to as statistical learning, has been related to relational binding and supporting structures in the MTL. Infants as young as 2 months are able to detect regularities in the visual input, and further improvements in statistical learning play an important role in supporting the acquisition and development of language. Furthermore, a recent study with 11-month-old infants found that experiencing an unexpected event, such as an action outcome that contradicted infants' previous experience with a particular object, resulted in increased learning outcomes and exploration (Stahl & Feigenson, 2015).

Later in childhood, one important milestone in the development of arithmetic problem-solving skills is the transition from inefficient strategies such as counting to the use of memory-based strategies. Accordingly, a recent neuroimaging study demonstrated that this strategic shift in the elementary school years is related to maturation of the hippocampus and is accompanied by reorganization of the functional connectivity patterns between the hippocampus and fronto-parietal regions (Qin *et al.*, 2014). These initial results indicate that the degree to which children are able to build rich contextual representations of their experience in a given domain may strengthen learning processes.

Mnemonic control processes might influence children's learning behaviors in the classroom or in other educational settings through their effects on the ability to monitor learning success and strategy effectiveness. For example, awareness of uncertainty in a particular memory may lead a child to ask for additional clarification from a teacher or to re-study an item. An intriguing venue for future research is examining the extent to which developmental differences in the ability to make more subtle uncertainty distinctions might drive learning and the exploration of novel information and strategic behavior. There is already evidence that feelings of uncertainty guide such decisions as refraining from volunteering a response or selecting it as a viable candidate (Hembacher & Ghetti, 2014). However, many questions are unanswered. For example, it is not clear whether there exists an optimal level of uncertainty that guides the exploration of novel learning behaviors, and more generally behaviors that maximize learning given the current state of knowledge.

Of course, when we examine the learning process, both relational binding and controlled processes are involved. Assessing how these interactions affect classroom learning may be particularly promising for addressing outstanding questions regarding the effects of different instruction styles on learning success, as well as for identifying populations who need help in the classroom. For example, while the literature on adult learning has repeatedly revealed an advantage for self-guided learning over directed instruction, the findings in childhood are mixed. This could be related to differences in basic relational abilities. Specifically, the ability to encode and recollect past events with rich contextual detail may affect the ability to detect subtle differences among items and contexts, resulting in less success when learning is guided by children's choice and greater benefit from directed instruction. Alternatively, the prolonged development of the ability to monitor uncertainty and regulate memory may result in less effective choice of what, when, and how to learn.

Taken together, the developmental trajectories of relational binding and mnemonic control may affect learning in a nuanced and rich way that needs to be explored in futures studies. In turn, schooling provides an important context for the acquisition and maintenance of new strategies. It also has profound effects on the formation of metacognitive knowledge and beliefs about one's memory ability and learning style that may affect memory development.

Conclusions

In the present entry, we sought to integrate behavioral and neuroimaging findings in order to elucidate the development of episodic memory and learning during early and middle childhood. This lifespan period is marked by profound changes in relational binding and control processes that support memory formation and retrieval, along with maturation of their neural substrates. Furthermore, these general trends for improvements in relational binding and mnemonic control are accompanied by marked individual differences. Examining the factors contributing to changes in the components of the brain networks that support episodic memory is a fundamental venue of future research. Taking an individual difference approach in interaction with contextual, personality, and motivational factors is a key to understanding how developmental trajectories affect learning processes and are modified by adverse events.

See also

Learning theories; Experimental methods; Magnetic resonance imaging (MRI); Longitudinal and cross-sectional designs; Cognitive development during infancy; Cognitive development beyond infancy; Executive functions; Brain and behavioral development; Autism; Fragile X syndrome; Connectomics; Systems neuroscience

Further reading

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