Trends in Cognitive Sciences

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Review

The ubiquity of episodic-like memory during infancy

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Considerable progress has been made in understanding early memory development. However, much of this research pre-dates contemporary theories of memory systems in the mature brain. This review provides a refresher on these conceptual frameworks and proposes a common theoretical foundation for reconciling adult and infant studies. This foundation enables a critical analysis of infant studies that have directly tested memory and suggests that they may not capture the full nature and extent of episodic memory abilities in infancy. The analysis is extended to infant studies that are ostensibly focused on cognitive domains other than memory and finds that many such tasks require episodic-like memory. Thus, there may be substantially more evidence for episodic-like memory in infants than previously recognized.

Highlights

Although humans lack memories from infancy later in life (infantile amnesia), infants may still have at least basic episodic-like memory abilities.

This review synthesizes current theories of memory and proposes an updated conceptual framework to help understand the early development of these abilities.

This framework uses a component process perspective to decompose the most commonly used tasks in studies that are overtly about infant memory.

This framework can also be applied to tasks in other domains of infant cognition, revealing that many such tasks have hidden demands on episodic-like memory.

These tasks could be added to the memory development literature and they suggest that episodic-like memory is more ubiquitous in infancy than previously recognized.

Infant memory development

The inability of older children and adults to recall specific events from infancy – or **infantile amnesia** (see Glossary) – has puzzled researchers for more than a century [1]. Efforts to better understand infantile amnesia span Sigmund Freud's ideas about memory repression to recent work in rodents using optogenetic stimulation to retrieve 'forgotten' memories from infancy at maturity [2–5]. This recent work suggests that infants may have the capacity to encode memories, placing the blame for infantile amnesia on post-encoding mechanisms such as a failure of retrieval [3,5]. In direct support of this theory are recent findings from fMRI in awake human infants demonstrating one-shot encoding of visual events in the hippocampus starting around 12 months of age [6].

Behavioral studies in the 20th century have also revealed that even very young infants possess some rudimentary memory abilities [7–9]. These results were interpreted through the lens of theories of memory that were dominant at the time [10,11], which emphasized a taxonomy of modular brain systems each associated with a different behavioral expression of memory (e.g., conscious recollection of a past event versus facilitated perception of previously seen stimuli). However, these hypothesized dissociations between memory types and systems were based primarily on neuropsychological studies in adults, raising questions about their appropriateness for understanding infant memory [12,13].

Perspectives on human memory have since evolved. Brain systems are now considered in terms of the computations they perform rather than the specific psychological constructs they implement [14–16]. Different types of memory are distributed across multiple systems rather than instantiated by a single, modular system [17,18]. Important insights have come from behavioral and brain imaging studies in children and infants [19,20]. These advances provide a new theoretical foundation for interpreting studies of infant memory.

This article has three goals: first, to review the current understanding of human memory functions and how recent perspectives provide a framework for interpreting behavioral studies on infant

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memory. Second, to review the behavioral paradigms most commonly used to assess infant memory and how results from these studies can be interpreted with recent theories. Third, to review a broader suite of behavioral infant tasks that were not designed to assess memory and yet place demands on memory for successful performance. These findings provide a more complete view on infant memory and suggest useful constraints when developing theories of memory development. The audience for this paper includes researchers of infant cognition and human memory, as well as developmental psychologists and cognitive neuroscientists.

Evolving perspectives on human memory systems

This section describes how the conceptualization of memory systems has changed over time, focusing on the three predominant theories that have guided empirical research on human memory. Although centered on adult memory, this section also reflects upon the implications of these theories for understanding infant memory development.

Multiple memory systems

The dominant theory in the adult memory literature is the multiple memory systems framework. This theory posits that memory is not unitary but instead consists of multiple types that each rely upon a distinct neural circuit [21–23]. These types can be organized into a hierarchy, with the distinction between short-term and long-term memory at the top. The former is responsible for temporary maintenance and manipulation of limited information (i.e., **working memory**), whereas the latter is a heterogeneous group of functions that support the acquisition and retention of information over longer durations and across interruptions [24,25].

Long-term memory systems are divided into declarative (explicit) and non-declarative (implicit). Declarative memory depends upon the hippocampus and supports conscious recollection of facts (semantic memory) and events **(episodic memory)** [21]. Non-declarative memory includes non-conscious learning and memory abilities that are preserved in amnesic patients with hippocampal damage [26]: habituation and sensitization, priming and perceptual learning [27–30], procedural skill learning [31], and conditioning [32,33] (Figure 1).

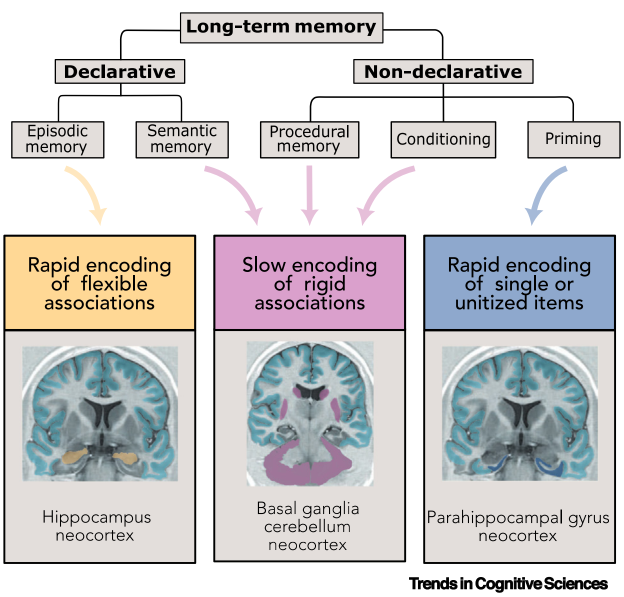

Figure 1. Evolution of classifications of human memory systems. The upper portion of the figure depicts how various types of memory are classified using the multiple memory systems framework. The lower portion demonstrates how these various systems map onto the cognitive operations central to component process models of memory. Adapted from [14].

Glossary

Deferred imitation: a method used to assess cognition in young children wherein they observe an action and are tested on their ability to repeat the action after a delay.
Episodic memory: a form of long-term memory that allows for recall of autobiographical experiences that happened at a specific moment in time and location in space.
Infantile amnesia: the inability of adults and older children to recall memories of events they experienced when they were an infant or toddler.
Occlusion events: a part of a task in which an object is hidden behind another larger object to probe the ability of infants to understand what can happen to objects out of view.
Relational binding: the ability to form associations between an object and other arbitrary features across space and time.
Social cognition: the ability to interpret and predict the behaviors of others and to use that information to adapt one's own behavior during a social interaction.
Violation of expectation: an experimental design in which an infant's understanding of an event is examined by presenting them with event outcomes that contradict what an adult would expect.
Visual paired comparison (VPC): a method of assessing infant cognition by measuring looking behavior to familiar relative to novel stimuli.
Working memory: a form of short-term memory in which limited quantities of information can be maintained and manipulated in the mind over brief intervals of time.

Though initially formulated for adults, the multiple memory systems framework also has utility for understanding development. Different memory systems have unique developmental trajectories that underlie the protracted emergence of learning capabilities. The earliest forms of learning include priming and classical conditioning in newborns [34–36]. Perceptual learning and operant conditioning are evident by 3 months [37–40]. Procedural learning has been documented at 9 months but is hypothesized to develop earlier and contribute to motor development [31,41].

The developmental trajectory of declarative memory remains debated, with estimates ranging across the first several years of life [13,20,42]. This debate is further complicated by the difficulty of assessing memory in infants, especially the conscious/non-conscious distinction between declarative and non-declarative memory, respectively. Indeed, preverbal infants cannot report conscious awareness of a remembered event [43]. However, an inability to speak does not necessarily mean a lack of awareness [44] and not all declarative memories are consciously accessible [45], leaving unclear the extent of declarative memory in infants.

Relational memory

The relational view of memory helps address this gap by focusing on the functional role of the hippocampus in declarative memory rather than on consciousness [46,47]. It posits that the hippocampus is necessary for encoding memories that require binding arbitrarily related information. This ability is critical for episodic memory because the individual elements of an episode (who, what, where, when) may not have an inherent relationship but need to be bound into a unified representation. In relational memory theory, the content matters most: memory for relations requires the hippocampus, whereas memory for the constituent items does not [48–50]. Item recognition is instead supported by adjacent cortical regions of the medial temporal lobe [51,52]. This distinction remains nuanced, as relational memory can but does not always involve multiple items; binding a single item to a context requires the hippocampus [53].

In some respects, relational memory theory is better suited for studying early development than multiple memory systems theory. Namely, removing the consciousness criterion for declarative memory theoretically motivates the assessment of episodic-like memory in preverbal infants. Relational memory theory also formalizes the basic building blocks of episodic memory, such as **relational binding**, which bridges the gap from simple (e.g., item recognition) to complex (e.g., vivid recollection) abilities, and may thus be important throughout memory development. Although humans may not have permanent memories of detailed episodes from infancy, the capacities required for forming these memories are developing during this period.

Component processes

Component process models focus less on psychological constructs like 'episodic memory' and more on atomic cognitive operations shared by tasks that test these constructs [54]. By one account [14], there exist three such operations. The first operation is rapid encoding of flexible associations by the hippocampus and neocortex, which links the different aspects of an episode over space and time (i.e., who, what, where, when). The second operation is slow encoding of rigid associations, which lies at the heart of procedural learning, conditioning, and the acquisition of semantic knowledge across multiple exposures. The third operation is rapid encoding of single/unitized items, which can support priming and familiarity; this formalizes the idea from relational memory theory that recognition of single items warrants its own class (Figure 1).

The component process model's most notable departure from prior theories is the grouping of semantic memory with conditioning and procedural learning. Proponents justify this grouping as follows [14]: first, conditioning and procedural learning take place over extended timescales and so too does semantic knowledge acquisition [55]. Second, the associations learned via conditioning and procedural learning are fixed/rigid, as are those in semantic memory [56]. Finally, like conditioning and procedural learning, patients with hippocampal amnesia are able to complete semantic learning tasks [57].

An important aspect of component process models is that they allow for classification of the type of memory assessed by a task based on properties of the task and resulting knowledge, instead of hinging classification on reverse inference from the brain regions involved. This is especially valuable for studying infancy, when rigorous assessment of brain systems is methodologically challenging. Key task features for classification include the type of information encoded (items versus associations) and the temporal extent of encoding. Tasks presenting associative information across long and/or repetitive encoding opportunities lead to rigid associations, such as those characteristic of procedural learning and conditioning. By contrast, those with shorter/fewer encoding opportunities result in either flexible associations or unitized representations.

This review relies heavily on the component process perspective for evaluating the demands of a task, yet also employs the more traditional terms ‘episodic’ and ‘episodic-like’. Retaining these terms helps distinguish the most fundamental processes involved in this kind of memory – the rapid encoding of flexible associations (captured by ‘episodic-like’) – from additional, more sophisticated processes enabled by such encoding, including reinstatement, discrimination, inference, and prospection, which make up the full capacity (captured by ‘episodic’). The latter processes are difficult to verify in preverbal infants and non-human animals, hence why the behavior of these populations is described as episodic-like. Furthermore, whereas some accounts suggest that the more sophisticated episodic processes, such as the discrimination of similar memories, take place during encoding [58], others argue that additional retrieval processes are important [59]. The focus on episodic-like memory skirts this unsettled debate that cannot be easily resolved in infants.

Assessing episodic-like memory during infancy

There are many behavioral paradigms for assessing memory in adults, but far fewer appropriate for preverbal infants. The present section reviews these infant paradigms, discusses the type(s) of memory each is intended to test, and classifies the results using the frameworks described earlier. The primary focus is on long-term, episodic-like memory, defined based on component process models as involving: (i) rapid encoding after one or a small number/duration of encounters; and (ii) the learning of flexible, arbitrary associations.

Visual paired comparison

The **visual paired comparison (VPC)** paradigm was developed to assess recognition memory in infants [7]. The participant is first familiarized with a visual stimulus. After a delay, they are tested with this old stimulus alongside a new stimulus (Figure 2A). Longer looking at the new stimulus (or sometimes the old stimulus [60]) is interpreted as evidence of memory for the old stimulus [61,62].

Thinking about VPC in terms of component processes can help synthesize these discrepant findings into two types: (i) habituated VPC, where the duration of familiarization is determined based on how long it takes the infant to habituate to (i.e., show reduced interest in) the old stimulus; and (ii) rapid-encoding VPC, where familiarization is brief and lasts up to a fixed duration of 60 s (Box 1). This difference in encoding duration is an important factor in distinguishing underlying memory processes [14].

In component process models, habituated VPC would not qualify as having the processing requirements of episodic-like memory. Because infants are extensively exposed to a single item (or, in some cases, a category of items [63]) and there is no need to bind the item to a spatial/

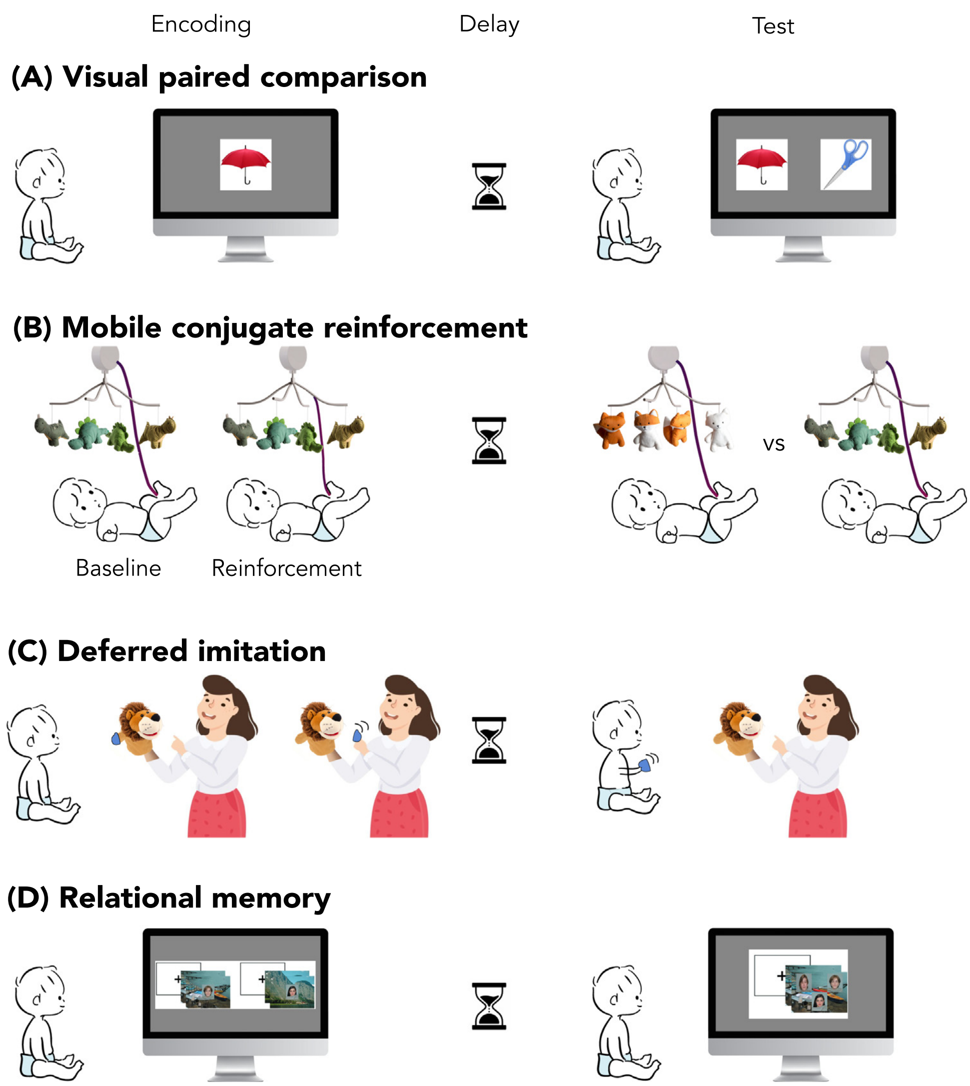

Figure 2. Task paradigms intended for assessing infant memory. (A) The visual paired comparison (VPC) paradigm involves an encoding phase (often to habituation) followed after a delay by a test phase that juxtaposes an item from encoding with a novel item; preferential looking to the new (or old) object is taken as evidence of memory. (B) The mobile conjugate reinforcement paradigm includes baseline and acquisition/reinforcement phases followed by a delayed test phase; increased kicking for the encoded versus a novel mobile and/or context is taken as evidence of memory. (C) The deferred imitation paradigm first exposes the infant to a demonstration in which the experimenter performs a target action; reproduction of the target action after a delay is taken as evidence of memory. (D) The relational memory paradigm involves an encoding phase in which faces are paired arbitrarily with scenes followed by a test phase in which encoded pairs are presented with two foil faces [79]; preferential looking to the paired face over the foil faces is taken as evidence of memory.

temporal context, novelty preferences are likely to be driven by familiarity [14]. In other words, looking-time preferences do not necessarily constitute evidence of episodic-like encoding and recognition [64]. By contrast, rapid-encoding VPC better aligns with the fast learning in component processes linked to episodic memory. Also in favor of episodic-like engagement, this task variant passes the 'amnesia filter', in that patients with developmental amnesia do not show novelty preferences after a limited familiarization period and a 2-min delay (for more on developmental amnesia, see Box 2) [65].

Box 1. Habituated versus rapid-encoding VPC

The infant memory development literature is dominated by habituated VPC studies. The habituation criterion is met when infant looking declines to an absolute level or to a relative value compared with the infant's initial viewing duration [60,107]. Although not always a habituation paradigm, this family of studies can also include studies with familiarization periods longer than 60 s, which exceeds the longest average peak look duration at 3 months [108]. Evidence from habituated VPC studies consistently suggests that memory for a habituated stimulus or category emerges at a very young age (as early as 3 days) and persists over a long duration (14 days between encoding and test in some cases) [7,63,107,109].

There are fewer rapid-encoding VPC studies. In these studies, novelty preferences have been reported after brief delays between encoding and test, up to 2 or 3 min [110–112]. Additionally, these novelty preferences emerge at a later age, between 6 and 9 months, relative to habituated VPC studies [110,112–114]. Taken together, these findings suggest that varying the encoding duration from rapid to habituated may engage different memory processes in infants, and that these memory processes have different developmental trajectories.

These findings can be reconciled using the component process model, as the duration of encoding is a key feature used for dissociating memory types. By comparison, these findings align less well with predictions of the multiple memory systems or relational memory theories, wherein encoding duration is not sufficient for memory classification.

Mobile conjugate reinforcement

The mobile conjugate reinforcement paradigm was initially developed to study operant conditioning in infants [39,66]. The task usually takes place in the infant's home. A distinctive mobile is hung over the infant's head with a ribbon that can be attached to the infant's ankle [67]. The first phase of the task is a baseline period when the ribbon is not yet attached and the infant's kicking rate is measured. This is followed by an acquisition period where the ribbon is attached and infants learn that their kicking moves the mobile (Figure 2B). After a delay, infants are placed back into the reinforcement context with the ribbon detached and the rate of kicking is again measured. Memory in this task is reflected in increased kicking during test versus baseline [68,69].

Increased kicking in the basic mobile conjugate reinforcement paradigm is typically considered a conditioned response, as would be suggested from the multiple memory systems framework, rather than retrieval of an episodic-like memory [70]. However, later task variations attempted to use this behavior to examine episodic-like memory. For example, 3- and 6-month-old infants kick more to the original mobile than to a novel mobile (up to delays of 72 h), suggesting evidence of item memory [8,71]. Moreover, changing the surrounding environment [9] or parts of the mobile [72] between acquisition and test eliminates increased kicking relative to the baseline, suggesting the retrieved memory is bound to a specific spatio-temporal context, a key feature of episodic memory.

Box 2. Insights from developmental amnesia

Individuals with developmental amnesia show a selective deficit in episodic memory (with relatively preserved semantic memory) typically caused by hypoxic–ischemic events occurring within the first year of life that result in atrophy of the hippocampus [115,116]. When tested on paradigms similar to those used with infants, including item recognition [65] and, to a lesser extent, relational binding [117], these individuals are impaired relative to healthy controls. Such results suggest that these tasks may require hippocampal-dependent episodic-like memory.

It is an open question as to whether individuals with developmental amnesia would likewise be impaired on the broader range of infant tasks described throughout this review. If these tasks truly require episodic-like memory supported by the hippocampus, then performance on these tasks should be impaired as well. There are two challenges for assessing such impairments. The first challenge is that individuals are typically not diagnosed as having developmental amnesia until later childhood, when they start complaining about memory problems. As a result, the infant paradigms presented here may no longer be appropriate for them; moreover, successful performance could be achieved by relying on other abilities like language not available to infants. The second challenge is that individuals with developmental amnesia have broader deficits in object representation [118] and social cognition [119], two of the domains in which infant paradigms may often require episodic-like memory. These deficits would complicate the interpretation of findings, especially a negative result, as it would be unclear whether failed performance reflected impoverished object and social processing or the unavailability of episodic memory.

Whether the memories generated by these clever tasks are episodic remains debated [42]. Fueling skepticism is that these memories often show patterns of extinction expected in operant conditioning [70]. Furthermore, past mobile conjugate reinforcement studies involved 12–30 min of encoding time, often across multiple encoding sessions on separate days [8,71,72]. This slow encoding aligns with the component processes linked to procedural learning and conditioning and is inconsistent with the process-based definition of episodic-like memory as more rapid.

Deferred imitation

The **deferred imitation** paradigm was created to assess symbolic thought but is more commonly used to test non-verbal episodic-like memory [73,74]. In this task, infants observe an experimenter interacting with a series of objects and performing one or more target actions (Figure 2C). After a delay (e.g., 24 h), infants are observed when given an object from encoding to see if they spontaneously perform the target action; doing so indicates they are retrieving the experimenter's actions and the sequential order in which those actions occurred [74]. This paradigm is used beginning around 6 months when reliable reaching behaviors emerge [75]. After only a 20–30 s demonstration, infants aged 12, 18, and 24 (but not 6) months imitate the target action (s) 24 h later [75].

Evidence from amnesic patients with hippocampal damage suggests deferred imitation may rely on episodic-like memory. When compared with healthy controls, these patients performed as if they had never seen the target actions [76]. However, not all infant studies with deferred imitation align with the component process perspective on episodic-like memory as involving the rapid encoding of flexible associations. Some studies involve slower, extended encoding where the infant watches the experimenter perform the target actions many times or across many days; in other cases, the infant has the opportunity to interact with the objects and can practice the target action prior to the test phase [77].

Relational binding

The relational binding paradigm was first used in adults to test the role of the hippocampus in forming arbitrary associations between faces and scenes [45,78]. Adapted for early development, infants view three encoding trials (8 s each) in which a novel face is superimposed on an unrelated novel scene. After a brief delay, they are shown one of the previously viewed scenes with all three equally familiar faces from encoding superimposed (Figure 2D). Preferential looking to the face encoded with the tested scene is taken as evidence of relational memory (i.e., successful retrieval of the face–scene association) [79].

Results from this task have been inconsistent across infancy. At 9 months, infants look preferentially at the matching face in the first second of 5-s test trials. A similar pattern of results emerges at 6 months, though the timing and magnitude of the effect is variable [80]. However, at 12 months, infants show no preferential looking to the matching face [81]. In a variation of this paradigm with object–location associations, relational binding was observed at 18 and 27 months, but not at 9 months, where evidence for face–scene binding was clearest [82].

From a component process perspective, the relational memory paradigm is a good candidate for assessing episodic-like memory, as success requires rapid encoding and delayed recall of arbitrary associations. However, it remains unclear whether the retrieved associations are truly flexible. It is plausible that infants could be encoding the simultaneously presented faces and scenes as a single, unitized representation, and that this explains their looking behavior at test. Additional research using an object–location and/or object–time variant of this task may prove fruitful in disambiguating these explanations.

Other infant tasks recruiting episodic-like memory

The infant cognition literature uses carefully designed behavioral tasks to assess a range of capacities across early development. This section presents some examples of tasks that may rely on episodic-like memory for successful performance. These studies require infants to: (i) rapidly and flexibly encode context-bound representations following only brief encounters with stimuli; (ii) maintain such bindings over extended durations and in the face of intervening events; and (iii) recall these memories to make sense of ongoing events or to take relevant actions (Box 3). Although far from exhaustive, these examples provide compelling evidence for episodic-like memory in infancy beyond the memory paradigms reviewed earlier.

Object representation

Studies examining how infants represent objects that are hidden from their view often require infants to bind feature, object, and context information during **occlusion events**, then retain this information in memory over extended durations and through distractions. These tasks use a **violation of expectation** approach [83] to examine infants' representations of objects in memory. In a typical trial, infants observe two objects with distinctive features (e.g., a disk and a triangle). The objects are then hidden sequentially behind separate occluders. After a delay of 5–10 s, memory for one of the objects is probed; one occluder is removed to reveal either the object that had been hidden in that location originally or the object that had been hidden in the other location. Looking time to these different outcomes is compared. To discriminate the outcomes, infants must bind what, where, and when information and store this information in memory for later recall. They must do so even when objects are hidden one at a time, and they therefore have to encode information about a new occlusion event while maintaining the previous occlusion event (Figure 3A). This method has revealed memory in infants as young as 6 months, with the robustness and durability increasing over the first 2 years of life [84–87].

Although infant behavior in these tasks has often been characterized as working memory, the pattern of performance and developmental change may be better explained as episodic-like memory. First, in line with the component process-based definition of episodic-like memory, infants must rapidly encode arbitrary associations between features, objects, and contexts in single trials. Second, the interval over which such associations are encoded and retained (e.g., 5–10 s) is longer than a typical working memory task (0.5–1 s [86]); moreover, the fidelity of the encoded information is not appreciably impacted by maintenance duration, with or without intervening distraction [88], unlike what would be expected of working memory. Third, looking behavior across multiple trials shows signatures of proactive interference [89], consistent with long-term rather

Box 3. Identifying hidden memory requirements

Studies that examine infant cognition often require infants to integrate multiple sources of information, store that information in memory, and recall it to respond systematically to experimental conditions. Being mindful of the hidden memory requirements of infant cognition tasks allows researchers to design experiments that attempt to equate memory demands across conditions, and to consider the interaction of memory with other cognitive domains of interest. The following are several dimensions along which the memory requirements of infant cognition experiments can be evaluated:

- Does the task require infants to encode and bind relations between stimuli, or between stimuli and contextual elements (e.g., where, when, or who)?
- Are those relations somewhat arbitrary or novel (e.g., an object with a specific color and shape in a location), or might they occur outside of the experiment (e.g., a dog in a doghouse)?
- Are infants required to maintain bound representations over extended durations? For how long?
- Are infants required to maintain bound representations while also encoding new relations or attending to new information or events?
- How many bound representations must infants encode and maintain in memory?
- Are infants required to recall bound representations to make sense of or respond to later stimuli?
- Are infants required to discriminate among multiple bound representations in memory?

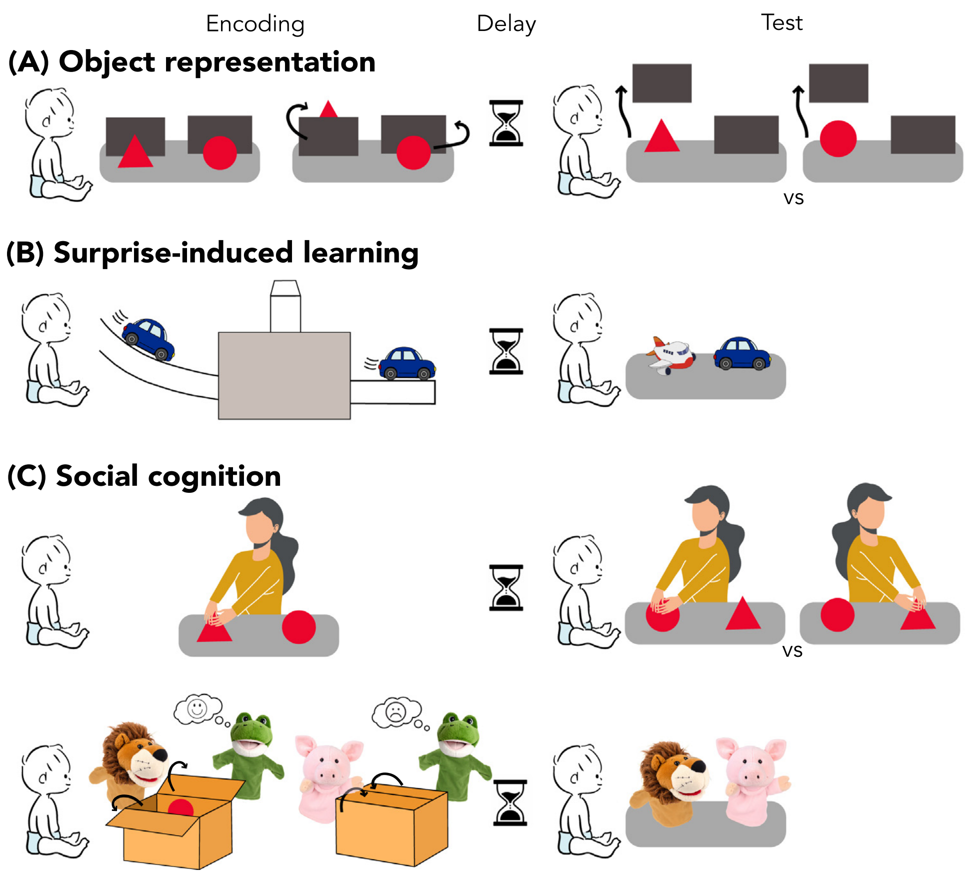

Figure 3. Task paradigms from other cognitive domains with memory requirements. (A) An object representation paradigm in which an infant is presented with two unique shapes, each associated with a specific location. The shapes are then occluded so that they are no longer in view of the infant. After a delay, one occluder is removed and infant looking to the congruent versus incongruent object–location pairing is measured. (B) A surprise-induced learning paradigm in which infants are presented with an object that seemingly violates the laws of physics. After a delay, they are presented with this object and a second control object and preference for the violation object is taken as evidence that the infant bound and remembered the surprising physical properties of that object. (C) Social cognition paradigms in which an infant encodes a social situation. Upper panel: the infant is tasked with encoding an agent's goal-related action. After a delay, the infant is presented with two scenarios, one congruent and the other incongruent with the goal-related action, and looking behavior to each is measured. Lower panel: the infant observes two agents taking distinct social actions (one prosocial, one antisocial) toward a third agent. After a delay, the infant is presented with both agents and preference for the prosocial agent is taken as evidence that the infant remembered the social actions of each agent.

than short-term memory. Finally, the developmental change observed in object representation tasks, from 6 months through the first several years of life, is more protracted than that observed in tasks that more closely resemble adult visual working memory tasks [86,90] and is consistent with the developmental change observed in tests of episodic-like memory [91].

Surprise-induced learning

Infants have robust expectations about how objects should physically interact with each other (e.g., they expect that an object cannot pass through another solid object). Violating these expectations can prompt new learning: 11-month-old infants who observe an object defying physical laws can learn a novel association between the object and an arbitrary property (e.g., a squeaking sound) after a single brief exposure (Figure 3B) [92]. Furthermore, infants who viewed an object defying physical laws and who were then given a choice between the violation object and a novel distractor were more likely to choose to play with the violation object. The resulting play also mirrored the violation they witnessed (i.e., they dropped an object that appeared to float and banged an object that appeared to pass through a wall) [92,93], suggesting that they recalled relevant details of the event and used these memories to guide exploratory behavior toward the object that had been featured in the event. Crucially, infants exhibited these behaviors 25–30 s after observing the physical violation event, and in a new context: the physical violation was displayed on a puppet stage, but infants were given the violation object and the novel object on their high-chair tray. Eleven-month-olds also could update their memory of an event in light of new information; for example, infants who viewed an apparent physical violation were able to update their memory of the event after finding out that what looked like a solid wall in fact contained a hole that an object could pass through [93]. According to the component process perspective, such behavior may be supported by episodic-like memory: infants need to associatively bind information about the specific object, its properties, and the event in which it was involved from a single, brief observation, retain that information over a delay, and recall that information in order to discriminate the object from other objects and to perform targeted, event-relevant, novel actions on the object.

Social cognition

The early development of **social cognition** is investigated with tasks that require infants to flexibly and rapidly integrate and store context-bound information in memory. These tasks typically use violation-of-expectation and/or anticipatory looking methods [83] to assess how infants understand the actions, goals, and beliefs of others, and their expectations about how people should interact. They usually require infants to form arbitrary associations between agents, objects, and actions from brief encounters, retain those associations across delays of 30 s to several minutes, or across intervening events, and recall those associations to make predictions about an agent's actions or to take actions themselves.

In studies of infants' understanding of the goals or intentions of others, infants typically observe an agent who preferentially grasps one of two objects across a few trials (Figure 3C, top). Infants as young as 6 months predict that the agent will continue to choose that object, even when the location of the object or the identity of the other object changes [94,95]. These goal-related predictions are bound to individual contexts and individual people: by at least 9 months, infants do not extend them to objects or people not previously involved in a relevant event [96]. By at least 7 months, infants can form these memories after only a single exposure [97], and by 12 months can integrate across multiple actions of an agent to represent these actions as causally related [98]. At 18 months, infants can retroactively update representations of an agent's beliefs after receiving new information about the agent's knowledge of events: infants who observed an object displaced to a new location without an agent present, but later learned that the agent had observed the event through a peephole, expected the agent to know the updated location of the object; infants who did not learn about the peephole expected the agent to be unaware of the object's updated location [99].

The literature on complex social cognition in infancy, including reasoning about morality or fairness, can be contentious in terms of whether the richest interpretation of the findings is warranted. However, the fact that infants respond systematically in these tasks suggests that they may recruit episodic-like memory. For example, 10-month-old infants who observe two agents taking different actions toward a third recipient agent in an event (e.g., events presented on a puppet stage in which a blue pig puppet helps a cow open a box, while a green pig prevents the cow from opening a box) show distinct behaviors toward the agents after approximately 30 s, selecting the 'helpful' agent for themselves when presented with the objects in a new context (i.e., on a tray) and expecting the recipient agent to also prefer the helping agent (as evidenced by increased looking toward a display in which the recipient approaches the hindering agent) (Figure 3C, bottom) [100,101]. By early in their second year, infants can remember, after a brief observation, which agents performed which actions in a variety of social contexts that require tracking who, what, and when (e.g., which agent distributed a resource evenly to other agents, which agents contributed effort to help another agent complete a task, etc.) [102].

In the context of the component process perspective, these findings provide suggestive evidence for episodic-like memory in infancy. Infants rapidly encode and maintain associations between specific agents (and their identifying features), their specific actions, and the specific objects or agents (and their identifying features) that are the recipients of those actions. These associations, while meaningful in the context of understanding social behavior, are ultimately somewhat arbitrary. They are also formed briefly, sometimes after only a single observation of an event, and can be updated to include relevant information acquired after the event. And infants recall these memories to make specific predictions about an agent's future actions or to guide their own actions. Furthermore, evidence from these tasks suggests that at least some components of episodic-like memory may be evident by 6 months, with the complexity and durability of such memories increasing across the first 2 years of life, consistent with developmental predictions based on the component process model.

Although the examples included here are not exhaustive, they suggest that careful evaluation of memory demands in infant cognition tasks can provide critical insights into the capacity of infants to deploy episodic-like memory across a range of cognitive domains for which such memory is critical for making sense of, and learning from, events.

Concluding remarks

Tasks used to assess infant memory were designed contemporaneously with the multiple memory systems taxonomy, which researchers then used to classify the types of memory being assessed by these tasks. As a result, the infant memory literature contains conflicting results about the developmental trajectories of various memory types. This review attempted to address these discrepancies by relying mainly on the component process model as a conceptual framework for assessing infant memory and applying it to existing infant memory paradigms. According to this framework, deferred imitation and relational binding tasks provide the most rigorous assessment of episodic-like memory because they require infants to encode arbitrarily related pieces of information rapidly. In comparison, the results of VPC and mobile conjugate reinforcement tasks should be interpreted with caution, and only after careful assessment of the necessity for infants to rapidly bind and later recall flexible associations. In particular, many task variants provide infants with repeated encoding opportunities over which they can slowly encode the information, which would not meet the rapid encoding requirements of component processes linked to episodic-like memory.

This review also aimed to expand the infant memory literature to include cognitive tasks that were designed to test the development of other cognitive domains but that actually require episodic/episodic-like memory. Reassessment of such studies suggested that additional evidence for episodic-like memory in infants can be found in studies of object representation, surprise-induced learning, and social cognition. Importantly, the list provided here is not exhaustive and could be expanded to include a host of other studies that require infants to rapidly encode flexible context-bound representations, maintain the representations across delays and interruptions, and later recall those memories.

Outstanding questions

At what age does the earliest evidence of episodic-like memory emerge?

How do behavioral changes in memory across the first two years of life relate to the development of the hippocampus and associated brain systems?

How can functional brain imaging be used to disentangle the memory systems and component processes underlying the behavior of preverbal infants?

How durable are episodic-like memories in infancy, how does this durability change across development, and how do such changes relate to infantile amnesia?

What new infant memory tasks could be designed in light of contemporary theoretical frameworks?

How do the memory requirements of infant tasks in other cognitive domains influence the conclusions drawn about the emergence or development of these domains?

How can memory demands be disentangled from the study of domain-specific infant cognition?

What is the relationship between episodic-like memory in infancy and other types of memory like working memory and statistical learning?

How could the component process model influence the interpretation of findings from non-human animals?

This additional evidence also aligns with what is known about memory development in non-human animals. Evidence across species, particularly in rodents [3,5] and more recently in humans [6], indicates that infants do have the capacity to encode memories even if those memories are no longer accessible by maturity [103]. In line with the human developmental trajectories discussed here, there is also support from non-human animals for the idea that some aspects of memory emerge earlier than others. Namely, memory for single or unitized objects is evident earlier than memory for associations, and the flexibility of these associative representations increases across early development [13]. Other aspects of adult-like episodic memory also emerge across early development, such as retrospective updating and mnemonic discrimination [104–106].

Beyond providing researchers with additional evidence for episodic-like memory in infants, this perspective also raises several questions for future research, including the developmental trajectories of these abilities and their interactions with other cognitive domains (see Outstanding questions). Although the answers to such questions will surely have important implications for infantile amnesia, evidence from within and beyond the traditional memory development literature suggests that episodic-like memory is more ubiquitous in infancy than previously thought.

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