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Accounting for change in declarative memory: A cognitive neuroscience perspective

Jenny Richmond and Charles A. Nelson

Harvard Medical School And Developmental Medicine Center Laboratory of Cognitive Neuroscience, Children's Hospital Boston

Abstract

The medial temporal lobe memory system matures relatively early and supports rudimentary declarative memory in young infants. There is considerable development, however, in the memory processes that underlie declarative memory performance during infancy. Here we consider age-related changes in encoding, retention, and retrieval in the context of current knowledge about the brain systems that may underlie these memory processes. While changes in infants' encoding may be attributed to rapid myelination during the first year of life, improvements in long-term retention and flexible retrieval are likely due to the prolonged development of the dentate gyrus. Future studies combining measures of brain and behavior are critical in improving our understanding of how brain development drives memory development during infancy and early childhood.

In 1953, as part of a drastic treatment for severe and intractable epilepsy, patient H.M. underwent a temporal lobe resection, and subsequently became unable to store new information in memory (Scoville & Milner, 1957). Although memories from before his surgery remained largely intact, H.M. had no recollection of his everyday life since the surgery. He no longer remembers people that he meets, he cannot learn the route to his new house, and he will read magazines over and over again without any sense of familiarity (Milner, Corkin, & Teuber, 1968). Hundreds of researchers have studied his impairment and demonstrated that despite his profound amnesia, H.M.'s ability to learn, under certain conditions, remains intact (Corkin, 2002). H.M. performs well on priming and conditioning tasks, and is able to acquire perceptual and cognitive-based skills at the same rate as controls.

To explain the specific pattern of impairment associated with hippocampal amnesia, Cohen and Squire (1980) suggested that there may be a dissociation between remembering "that" and remembering "how". Although the idea that there may be more than one kind of memory was not new (Tulving, 1972), the fact that damage to a specific area of the brain caused a specific pattern of impairment led these researchers to suggest that different kinds of memory might be subserved by different brain systems. It is now generally accepted that structures in the medial temporal lobe (see Figure 1), including the hippocampus and parahippocampal cortex, underlie the conscious recollection of facts and events (i.e. explicit or declarative memory). In contrast, parts of the striatum, cerebellum and brain stem are responsible for the implicit or procedural learning that is evident in priming, conditioning, and skill-learning tasks.

The idea that there may be multiple memory systems led to obvious questions among developmental psychologists studying memory: How do memory systems develop? How does the maturation of the brain regions that underlie these memory systems contribute to their

development? Schacter and Moscovitch (1984) were the first to argue that the memory systems that are dissociated in amnesia are also dissociated during the course of typical development. According to their view, implicit memory, or the unconscious learning that is expressed by changes in task performance as the result of experience, is controlled by an early-developing system, which may be present at birth. In contrast, the development of explicit memory is quite protracted, emerging when a late-developing neural system matures around 8- to 10-months of age. Schacter and Moscovitch (1984) suggested that performance on “early-system tasks” (i.e. habituation/novelty preference and conditioning) precede the development of performance on “late-system tasks” (i.e. delayed non-match to sample, object search, and cross-modal recognition).

In a similar theoretical vein, Nelson (1995) proposed that the striatum, cerebellum, and brain stem, which are functional at birth, allow even very young infants to demonstrate learning on visual expectation, operant conditioning, and classical conditioning tasks. In contrast, tasks such as the visual paired-comparison (VPC) procedure, which depend on the hippocampus, are controlled by a “pre-explicit” memory system, which gives way to adult-like explicit memory capabilities around 8-months of age (see Figure 2). Although the early-developing hippocampus can sustain performance on novelty preference tasks over short delays, further maturation of limbic (e.g. dentate gyrus) and cortical areas are required for performance on traditional versions of the delayed non-matching to sample (DNMS) task, deferred imitation, and cross-modal recognition. Nelson (1995) suggested the development of successful performance on these tasks between 8- and 12- months of age is the result of a transition from reliance on a pre-explicit system to use of an adult-like explicit memory system.

In contrast to Schacter and Nelson, some researchers argue that there is no evidence for a qualitative change in the nature of infants’ memory late in the first year of life. Rovee-Collier and colleagues have shown that when infants who span the proposed critical age period are tested on the same procedure, there is little evidence of a sudden improvement in performance around 8-months of age (Hartshorn et al., 1998). Rovee-Collier (1997) suggests that performance on the mobile conjugate reinforcement paradigm, an operant conditioning procedure that is often considered to be a measure of implicit memory, is subject to all the same variables that affect adults’ performance on measures of declarative memory. Infants’ performance on the mobile task is affected by changes in study time, retention interval, and context in a way that is more consistent with measures of declarative memory than measures of procedural memory. Rovee-Collier, Colombo and Hayne (2001) suggest that explicit and implicit memory systems develop in parallel, gradually and continuously from early in life.

On the whole, there is little debate about the development of implicit or procedural memory. Areas of the striatum, cerebellum, and brain stem are functionally mature very early in life, and evidence of simple conditioning can be seen in newborn infants (DeCasper & Fifer, 1980). In contrast, there is much debate as to the relative development of declarative memory. Studying the development of declarative memory is inherently difficult because traditional definitions do not apply to preverbal infants. For example, it is difficult to evaluate whether infants are consciously aware of their memories (i.e. possess conscious recollection). Because infants are unable to express their memories explicitly, researchers must indirectly infer memory from changes in infants’ behavior as a function of their experience. As a consequence, much research has been focused on first determining whether a given infant memory task qualifies as a measure of declarative memory, and then determining the earliest age at which infants can perform the task. This largely paradigm-driven approach has focused the field more on determining when performance on a given “task” develops, rather than considering the processes underlying developmental change (Ornstein & Haden, 2001).

In this review, we will explore the merit of taking a cognitive neuroscience approach to understanding how declarative memory emerges and changes early in development. We will focus primarily on declarative memory during infancy, first considering what we know about the development of performance on declarative memory tasks, in the context of current knowledge about the brain systems responsible for task performance. We will then review the fundamental changes in memory processes that occur during infancy and consider the development of brain systems involved in encoding, retention, and retrieval. By considering the development of memory processes that underlie memory tasks, and integrating current knowledge of brain development, we hope to provide a comprehensive account of age-related changes in declarative memory during the first two years of life.

Declarative memory in infancy

As discussed above, a major stumbling block in the study of declarative memory in infants is the difficulty in determining whether infant memory tasks tap declarative or procedural memory. There are at least two strategies that are typically used to assign memory tasks to memory systems. In adults, declarative and procedural memory tasks can be dissociated both in the degree to which patients with temporal lobe amnesia are impaired on the task and in the effect of certain independent variables on the performance of normal adults (Rovee-Collier et al., 2001). For example, amnesic patients exhibit impairments on tasks requiring declarative memory but perform well on procedural memory tasks. By applying the *amnesia filter*, it is possible to determine whether performance on a given task recruits the medial temporal lobe memory system, and thus taps declarative memory. Similarly, normal adults' performance on declarative memory tasks is affected by changes in study time, retention interval, and context change, while performance on procedural memory tasks is relatively immune to the effect of these specific variables. By applying the *parameter filter*, it is possible to determine whether a given task measures a process that closely resembles other declarative memory tasks. For the purpose of this review, we will restrict our discussion to infant memory tasks for which studies applying both the amnesia filter and the parameter filter have been conducted¹.

Visual paired-comparison task

Although originally considered to measure early-developing implicit memory (Schacter & Moscovitch, 1984), recent research has shown that novelty preferences are dependent on the hippocampus and may reflect a form of pre-explicit memory (Nelson, 1995). The visual paired-comparison (VPC) task typically involves two phases, a familiarization phase and a test phase. During the familiarization phase, infants are exposed to a pair of stimuli for a fixed amount of time or until a fixed amount of looking time is accumulated. Following a delay, infants are shown another pair of stimuli, this time one is the same as the familiarization stimulus and one is novel. Memory is inferred if infants exhibit a *novelty preference*, spending a greater proportion of time fixating the novel stimulus than the familiar stimulus during the test.

The VPC task passes both the amnesia filter and the parameter filter and is considered to measure declarative memory. Patients with damage to the medial temporal lobe fail to exhibit novelty preferences when tested on the VPC task after delays longer than 2 minutes (McKee & Squire, 1993). Even patients with lesions restricted to the hippocampus proper only exhibit novelty preferences when tested on the VPC task immediately (Pascalis, Hunkin, Holdstock,

¹Historically, our understanding of the brain systems underlying infant memory performance has been constrained by our ability to adapt infant memory tasks for use with adult amnesic patients. It is important to note that the "amnesia filter" relies on the assumption that there is continuity across development in the brain systems that are responsible for performance on a given task (i.e. if performance on a task depends on the hippocampus in adults, then it must also depend on the hippocampus in infants and children). This assumption has proven correct in the case of the deferred imitation task, however, prospective studies of infants and children who have incurred early damage to the hippocampus are required to determine whether this assumption also holds for other infant memory tasks.

Isaac, & Mayes, 2004). In addition, studies with infants and adults have demonstrated that performance on the VPC task is affected by study time, retention interval, and context change in the same way that these variables affect adults' performance on other measures of declarative memory (Bahrick & Pickens, 1995; Richmond, Sowerby, Colombo, & Hayne, 2004; Robinson & Pascalis, 2004; Rose, Gottfried, Melloy-Carminar, & Bridger, 1982).

There is also considerable evidence from primate lesion studies, that the medial temporal lobe memory system generally, and the hippocampus specifically, are involved in VPC performance. Monkeys with lesions to the hippocampus are impaired on the VPC task in a delay-dependent fashion. While lesioned monkeys are able to exhibit novelty preferences when tested immediately, their performance relative to control animals is impaired when they are tested after a delay (Bachevalier, Brickson, & Hagger, 1993; Nemanic, Alvarado, & Bachevalier, 2004; Pascalis & Bachevalier, 1999; Zola et al., 2000). Most recently, Nemanic, Alvarado, and Bachevalier (2004) report that monkeys with damage restricted to the hippocampus exhibit novelty preferences when tested after short delays but exhibit null preferences when tested after delays longer than 30s. This result suggests that extrahippocampal areas may support the expression of novelty preferences in the short term, but that the hippocampus is critical when delayed recognition is required (Nelson, 1995). These results are also consistent with data from adult amnesics showing that the effect of hippocampal damage is most apparent during delayed VPC testing (McKee & Squire, 1993; Pascalis et al., 2004).

It is important to note that several studies have now reported dissociations between performance on the VPC task and other recognition tasks, suggesting that novelty preferences tasks may be more sensitive to the effects of hippocampal damage than are other measures of recognition memory. For example, Nemanic, Alvarado, and Bachevalier (2004) showed that monkeys with lesions to the hippocampus who were impaired on the VPC task did not exhibit impairments on a delayed nonmatching to sample (DNMS) task. Patients with damage to medial temporal lobe systems also show impaired VPC performance but relatively intact recognition (McKee & Squire, 1993; Pascalis et al., 2004). These results suggest that the hippocampus may be critical for the expression of novelty preferences specifically, rather than performance on visual recognition tasks generally. Recognition memory in a general sense is likely mediated by extrahippocampal structures (Nelson, de Haan, & Thomas, 2006a).

Taken together, there is substantial evidence that the VPC task depends on the medial temporal lobe memory system. In addition, performance on the VPC task in infants, children, and adults is susceptible to changes in study time, retention interval, and context change in a manner that is consistent with a measure of declarative memory.

Deferred imitation

The deferred imitation task assesses infants' ability to encode, retain, and reproduce a sequence of novel actions following a delay. During the demonstration phase, the experimenter shows the infant a sequence of actions, however, the infant is not permitted to touch the props or to practice the actions prior to the test. Following a delay, the infant is given the opportunity to reproduce the actions seen earlier. Although long considered a hallmark of sophisticated mental representation (Piaget, 1962), recent studies have shown that the deferred imitation task passes both the amnesia filter and the parameter filter and can be considered to measure declarative memory.

McDonough, Mandler, McKee and Squire (1995) tested adult amnesics with bilateral medial temporal lobe damage on an age-appropriate version of the deferred imitation task. The deferred imitation problems were demonstrated incidentally as distractors between the study and test phase of a word-learning paradigm. Spontaneous and cued reproduction of the target

actions was assessed after a 24-hour delay. While controls produced more target actions spontaneously and during cued testing than during the baseline phase, amnesic patients were no more likely to use the objects to produce target actions than were inexperienced controls, who had not seen the target actions demonstrated the previous day. Patients with “developmental amnesia”, who incurred hippocampal damage early in life, also exhibit impairments on the deferred imitation task, although their impairment is restricted to the recall of the temporal order of actions (Adlam, Vargha-Khadem, Mishkin, & de Haan, 2005). Infants who are at risk for damage to the medial temporal lobe memory system because of adverse fetal environments, also exhibit impairments in recalling the temporal order of imitation sequences (DeBoer, Wewerka, Bauer, Georgieff, & Nelson, 2005).

Infants’ performance on the deferred imitation task is affected by the same variables that influence adults’ performance on declarative memory tasks. Using a deferred imitation task in which a set of actions are demonstrated with an animal hand puppet, Hayne and colleagues have shown that infants’ imitation is enhanced by increasing the amount of demonstration time, performance declines as a function of increasing retention interval, and retrieval is disrupted by a change in context (Barr & Hayne, 2000; Hayne, Boniface, & Barr, 2000; Herbert & Hayne, 2000a).

Taken together, data from adults and children with amnesia and from typically-developing infants converge to suggest that performance on the deferred imitation task depends on the medial temporal lobe memory system, and may reflect declarative memory. In the following section, we will consider what is known about the development of brain systems that subserve performance on declarative memory tasks in infancy.

Brain development

Brain development occurs in a predictable sequence of events, beginning with the proliferation of new cells (i.e. neurogenesis) and ending with the insulation of fibers that connect cells and circuits within the brain (i.e. myelination). Along the way, new neurons journey to their final home in the brain (i.e. cell migration) and must develop in a way that allows them to seek out connections (i.e. axon and dendritic arborization). Synapses, which in many cases connect the axon of one neuron to the dendrite of another neuron, are initially produced in excess during infancy (i.e. synaptogenesis) but their numbers are gradually reduced during childhood and early adulthood via experience-dependent mechanisms (i.e. synaptic pruning) (Nelson, de Haan, & Thomas, 2006b).

Studies of medial temporal lobe development in humans have shown that while much of the hippocampal formation is formed early in gestation, development of the dentate gyrus lags behind the development of other hippocampal subfields (Seress & Abraham, in press). Like the rest of the brain, neurogenesis in the hippocampal region occurs largely prenatally. Several subfields of the hippocampal formation (i.e. entorhinal, subiculum, Ammon’s horn) can be distinguished by the 10th week of gestation and cell formation is largely complete by 14–15 weeks (Humphrey, 1967; Seress, Abraham, Tornoczky, & Kosztolanyi, 2001). Cell migration is also rapid; the cytoarchitecture of the hippocampal formation resembles that of the adult by the end of the second trimester (Seress & Abraham, in press).

In contrast to the majority of the hippocampal formation, the dentate gyrus undergoes a more protracted period of development, as is illustrated in Figure 3. Although the granule cell layer of the dentate gyrus is present by the 12th week of gestation (Humphrey, 1967), cell formation in this area continues until at least 28 weeks. Seress and Abraham (in press) report that migration of cells in the dentate gyrus continues after birth; clusters of immature granule cells are evident in the dentate gyrus in infants up to 11-months of age. The cytoarchitecture of the dentate gyrus appears adult-like by the end of the first postnatal year.

While the dentate gyrus in infants resembles that in adults around 1 year of age, Seress and Abraham (in press) suggest that inhibitory interneurons within the hippocampal formation do not appear adult-like until sometime between 2- and 8- years of age. The late development of these GABA-ergic interneurons may play an important role in memory and cognitive development because these cells have been implicated in gamma oscillations that originate in hippocampal cell networks. Gamma-band oscillatory activity (30–80 Hz) has been shown to increase during performance of the DNMS task (Tallon-Baudry, Bertrand, Peronnet, & Pernier, 1998; Tallon-Baudry, Kreiter, & Bertrand, 1999) and has been implicated in attention and memory processes (for review, see Kahana, 2006).

In summary, Seress and Abraham (in press) argue that while much of the hippocampal formation develops early, the prolonged development of the dentate gyrus, along with the development of inhibitory interneurons precludes adult-like function during infancy and much of early childhood. There are few human data addressing the development of the remainder of the hippocampal region (i.e. entorhinal, perirhinal, and parahippocampal cortices), however, anatomical data from primates suggests that these areas are also cytoarchitecturally adult-like and may be functional at birth (Alvarado & Bachevalier, 2000; Berger & Alvarez, 1994).

The development of declarative memory

While much of the hippocampus is formed prior to birth, postnatal development of the dentate gyrus along with maturation of inhibitory interneurons, prolong the functional maturity of the medial temporal lobe memory system until at least 2 years of age (Seress & Abraham, in press). These data are consistent with the extant behavioral database, which suggests that while rudimentary declarative memory is evident early, prolonged development of encoding, retention, and retrieval processes contribute to age-related changes in declarative memory performance throughout infancy. In the following section, we will discuss the key characteristics of infant memory development and suggest how brain development may contribute to age-related changes in memory processes during infancy.

Encoding

As a rule, older infants encode information faster than younger infants (Hayne, 2004). When tested on the VPC task, the length of familiarization phase required for infants to exhibit novelty preferences decreases as a function of age (see Rose et al., 1982), so much so that researchers working with different age groups often use infant-controlled familiarization procedures (Diamond, 1995; Pascalis, de Haan, Nelson, & de Schonen, 1998), or design studies allowing younger infants longer familiarization times than older infants (Colombo, Mitchell, & Horowitz, 1988; Jacobs, 2000; Rose, Feldman, & Jankowski, 2001). Similarly, when tested on a deferred imitation task, 6-month olds require a demonstration period that is twice the length of that used with 12-month-old infants, in order to exhibit equivalent imitation performance after a delay (Barr, Dowden, & Hayne, 1996).

Age-related differences in encoding become less apparent after 12-months of age. Studies using the VPC task with 1- to 4- year olds have shown that children in different age groups will exhibit equivalent novelty preferences given the same familiarization period (Hayne, 2004). Similarly, while some studies using the deferred imitation paradigm report equivalent levels of encoding in 14- and 24-month olds (Meltzoff, 1985), others report age-related changes in immediate imitation until at least until 30-months of age (Hayne, Herbert, & Simcock, 2003; Herbert & Hayne, 2000a).

Taken together, these data suggest that while declarative memory emerges early in the first year of life, age-related changes in performance on declarative memory tasks may be related to the development of encoding processes. How can we account for age-related changes in

encoding during infancy? As discussed above, lesions to the hippocampus typically do not impair performance on the declarative memory tasks when the test occurs immediately. For this reason, it is unlikely that the maturation of the hippocampus proper contributes greatly to age-related differences in infants' encoding.

In relation to VPC performance at least, Rose, Feldman, and Jankowski (2004) suggest that developmental changes in encoding may be related to changes in the speed of information processing. Support for this idea comes from studies using a VPC procedure in which a familiar stimulus is paired with a new novel stimulus on each preferences trial. Speed of processing is measured by determining how many trials it takes for infants to consistently exhibit a novelty preferences. Between 5- and 9-months of age, the number of trials needed to reach the novelty criterion decreases systematically (Rose, Futterweit, & Jankowski, 1999). In addition, infants' attentional style points to a relation between visual recognition and speed of processing. During a pretest, infants who tended to accumulate 20 s of looking at a photograph by taking many brief looks (i.e. "short lookers"), required fewer trials to reach the novelty criterion in subsequent VPC testing than did infants who accumulated looking in fewer longer looks. Older infants exhibited shorter peak looks and mean look durations than younger infants, consistent with the idea that a short-looking style is a characteristic of more mature information processing and faster learning (Colombo, Freeseaman, Coldren, & Frick, 1995; Colombo, Mitchell, Coldren, & Freeseaman, 1991.)

Event-related potential (ERP) studies also lend weight to the role of processing speed in developmental changes in encoding. A recent longitudinal study showed that the latency to peak amplitude of ERP components decreases as a function of age (Webb, Long, & Nelson, 2005). In this study, ERPs were recorded in response to brief presentations of the infant's mother and a stranger and presentations of their favorite toy and a novel toy at 4-, 6-, 8-, 10-, and 12-months of age. As illustrated in Figure 4, age-related decreases in latency were evident in both early occipital components that are related to visual processing (Pb), and in mid-latency fronto-central components that are involved in attention (Nc). This result suggests that a domain-general mechanism, such as myelination may be responsible for age-related changes in processing speed.

Myelination of axons within the central nervous system allows for the efficient transmission of electrical impulses. Myelination begins in the fifth fetal month and continues throughout the first two decades of life, however, the most rapid changes in myelination occur during the first postnatal year (Paus et al., 2001). Myelination can be studied non-invasively by looking at the signal intensities of grey and white matter on T1 and T2 weighted magnetic resonance (MR) images. Signal intensities at birth and during the first 6-months of life are the reverse of that seen in the adult (Ballesteros, Hansen, & Soila, 1993; Gilmore et al., 2004). Unmyelinated white matter has a lower signal intensity and thus appears darker than the grey matter in T1-weighted images. An isotense transition period occurs between 8 and 10- months of age during which time white and grey matter are difficult to differentiate. The "early adult pattern" in which white matter has a higher signal intensity than grey matter in T1-weighted images becomes evident by 12-months of age (Ballesteros et al., 1993) (see Figure 5).

Myelination occurs in a predictable temporal sequence beginning with the brain stem structures responsible for basic functioning and moving in a deep to superficial, posterior to anterior pattern (Ballesteros et al., 1993; Barkovich, 2005). Myelination progresses most quickly in areas of the brain that are responsible for the basic functions that are used in early life. At birth, myelin is evident in the pons and the cerebellar peduncles. Between 1- and 3-months of age, the posterior limb of the internal capsule, optic radiation, and the splenium of the corpus callosum also myelinate. While the anterior limb of the internal capsule and the genu of the corpus callosum are myelinated by 6-months of age, white matter of the cerebral cortex is the

last to myelinate. Myelination of the occipital cortex occurs first, closely followed by the white matter of the frontal and parietal lobes around 8-months of age and the temporal lobe by 12-months (Ballesteros et al., 1993). Recent studies using diffusion tensor imaging (DTI) have confirmed that the most rapid changes in myelination occur within the first 6-months of life, with slower change between 6- and 24-months and relative stability thereafter (Hermoye et al., 2006; Miller, McKinstry, Philip, Mukherjee, & Neil, 2003; Prayer & Prayer, 2003).

We suggest that the rapid myelination that occurs during the first year may account for age-related changes in processing speed, decreases in the latency of infant ERP components, and ultimately changes in encoding. Webb, Long and Nelson (2005) report that age-related decreases in ERP latency plateau between 8- and 10-months of age. Age-related differences in encoding are also less apparent late in the first year. Thus, both behavioral and electrophysiological measures point to rapid myelination during the first 12 months followed by slower developmental change thereafter.

Retention

Given equivalent levels of encoding, older infants will remember for longer than younger infants (Hayne, 2004). Using the VPC task, Rose (1981) has shown that when tested after delays ranging from 90 and 160 s, while both 6- and 9-month olds displayed novelty preferences when tested immediately, only 9-month olds exhibited evidence of retention when they were tested after a delay. Age-related changes in retention on the VPC task continue into early childhood. When tested on the VPC task, 1-year olds will only exhibit retention when tested immediately, 2-year olds will exhibit novelty preferences for 1 day, 3-year olds for 1 week and 4-year olds for 1 month (Hayne, 2004).

Similarly, studies using the deferred imitation paradigm have shown that when levels of immediate imitation are held constant, older infants are able to remember the actions for longer than younger infants. Barr and Hayne (2000) showed that despite equivalent levels of immediate imitation, 6-month olds will only remember the puppet task for 24 hours, while 12-month olds will remember the task for 1 week. As with performance on the VPC task, age-related changes in retention continue into the second year of life. While 18-month and 24-month olds will exhibit equivalent imitation when tested immediately, 18-month olds will remember the task for a maximum of 2 weeks, while 24-month olds will remember the task for a maximum of 12 weeks (Herbert & Hayne, 2000b). Similarly, Bauer (2005) has shown that during the second year of life, younger infants are more susceptible to forgetting after long delays than are older infants, even when levels of initial learning are matched. Bauer (2005) suggests that the fact that older infants exhibit greater savings upon relearning than do younger infants provides evidence for age-related differences in storage rather than retrieval processes.

Support for the storage account comes from studies combining event-related potentials and imitation tasks over long delays (Bauer et al., 2006; Bauer, Wiebe, Carver, Waters, & Nelson, 2003; Carver, Bauer, & Nelson, 2000). In one such study, Bauer et al. (2003) exposed 9-month-old infants to three elicited imitation sequences during three demonstration sessions. At the end of the final demonstration session, immediate recognition was assessed by recording ERPs in response to pictures of the familiar sequences and pictures of novel sequences. One week following demonstration, delayed recognition was assessed using ERPs, and behavioral imitation was tested 1 month later. ERPs at both the immediate and delayed recognition test were analyzed as a function of whether infants subsequently exhibited ordered recall at the 1 month behavioral test. At the immediate recognition test, Nc amplitudes were larger in response to familiar sequences than in response to novel sequences, irrespective of whether infants subsequently remembered at the 1 month test. This result suggests that individual differences in subsequent imitation performance could not be accounted for by differences in initial

encoding. At the delayed recognition test, the Nc component also differentiated between novel and familiar sequences, but only for infants who subsequently exhibited ordered recall. Bauer (2005) suggests that continued development of the dentate gyrus late in the first year of life may account for changes in infants' ability to consolidate memories into long-term storage.

This hypothesis is consistent with the data from adult neuroimaging studies which show greater activation of the hippocampus and medial temporal lobe structures during the encoding of items that are subsequently recalled relative to items that are subsequently forgotten (for review, see Henson, 2005). Within the hippocampus, high resolution fMRI studies have shown that CA2/3 subfields and the dentate gyrus may be disproportionately activated during the consolidation of new associative memories (Zeinab, Engel, Thompson, & Bookheimer, 2005). The CA 2/3 and dentate activation during learning trials was most apparent early in the session and decreased in magnitude as recall performance improved from block to block. In contrast, learning-related decreases in activation in the subiculum occurred primarily during retrieval. These results suggest that subfields of the hippocampus may play different roles in the formation of new memories, with the CA fields and dentate playing an important role in storage and consolidation (Zeinab et al., 2005).

In summary, age-related changes in retention occur throughout infancy and into early childhood. Electrophysiological studies suggest that failures in storage may account for age-related changes in retention, and point to the prolonged development of the dentate gyrus as a possible mechanism. This hypothesis is consistent with adult neuroimaging studies implicating the hippocampus generally and dentate gyrus specifically in storage and consolidation.

Retrieval

According to Tulving's encoding specificity hypothesis, the likelihood that a given memory will be retrieved depends on a match between the cues present at the time of encoding and the cues present at the time of the test (Tulving & Thomson, 1973). Infant memories are extremely specific; retrieval will only occur if the cues available at encoding are identical to those available during the test.

Studies using the deferred imitation task have shown that at least until the middle of the second year of life, infants' memory retrieval is disrupted if they are tested with different, but functionally equivalent props. As is illustrated in Figure 6, Hayne, Boniface and Barr (2000) showed that 6- and 12-month olds fail to reproduce the target puppet actions after a 24-hour delay if the central cue (i.e. puppet) is changed between the demonstration and the test. It is not until 18-months of age that infants will exhibit retention if the actions are demonstrated with the grey mouse and tested with the pink rabbit, or vice versa. This is not to say that by 18-months of age memory is no longer constrained by specific retrieval cues. If the similarity of the puppets is manipulated (i.e. black cow to yellow duck), 18-month olds are also unable to retrieve their memory when tested with a new puppet stimulus (Hayne, MacDonald, & Barr, 1997). It is not until 24-months of age that infants can generalize the actions they learned with the cow to the duck, or vice versa.

Infants' memory for the puppet task is also specific to the retrieval cues present in the learning context. Using the same deferred imitation task, Learmonth, Lamberth and Rovee-Collier (2004) demonstrated the puppet actions to 6- and 9-month old infants while they sat on a distinctive colored mat and then changed either the mat, the room in the house, or both the mat and the room prior to the test. Both 6- and 9-month olds were able to imitate the actions after a 24-hour delay if the test occurred either on a different mat or in a different room of their house. Only 9-month olds exhibited retention if both the mat and the room in their house were changed at the time of the test (Learmonth et al., 2004). As is illustrated in Figure 6, by 12-months of age, infants tested on the puppet task are able to cope with large changes in the

retrieval cues available at the test (Hayne et al., 2000). Twelve-month-old infants who learn about the puppet in their home and are tested 24 hours later in the lab (or vice versa) are able to reproduce the target actions despite the change in context.

Similarly, until at least 12-months of age, infants' performance on the VPC task is also constrained by retrieval cues available at the test. Robinson and Pascalis (2004) familiarized 6-, 12-, 18-, and 24-month-old infants with objects that were presented on a colored background. When tested immediately with the same proximal context, infants in all age groups exhibited significant novelty preferences. When the color of the background was changed between the familiarization and the test, however, only 18- and 24-month olds exhibited evidence of retention.

In summary, infants' memories are highly specific. Relatively small changes to either the central stimulus cue or the environmental context disrupt retrieval and cause memory to fail. With age, however, infants' memory retrieval becomes less constrained and they develop the ability to retrieve memories in increasingly novel situations. This age-related change in infants' ability to use their memories flexibly is a hallmark of declarative memory development.

How can we account for age-related changes in the infants' memory retrieval? According to Eichenbaum's (1992) relational memory account, declarative memory can be applied to nonverbal organisms if it is considered in terms of two fundamental features, *relational representations* and *flexible expression* (Eichenbaum, 1992; Eichenbaum, Otto, & Cohen, 1992). By this definition, the hippocampus is critically involved in forming memories that are made up of networks of items that are linked together by causal, logical, or temporal relationships (Eichenbaum, 1999). Flexibility of expression is a natural consequence and advantage of this type of representational coding; relational networks can be used to make inferences about items that are only indirectly connected. In contrast, the regions outside the hippocampus proper, including the entorhinal, perirhinal, and parahippocampal cortices, can support representations of individual items in memory, however, these representations are "hyperspecific". Hippocampal-independent memories can only be expressed when the specific conditions that were present at learning are reinstated (Eichenbaum, 2002).

There is now considerable support for the relational memory hypothesis in both animals and humans. Eichenbaum and colleagues have shown that rats may exhibit hippocampal-dependent memory that is analogous to declarative memory in humans (Bunsey & Eichenbaum, 1995, 1996; Dusek & Eichenbaum, 1997). Rats have demonstrated transitive inference (TI), a classic example of relational representation and flexible use of knowledge (Dusek & Eichenbaum, 1997). In this task, rats are trained on a series of odor-based discriminations in which they dig in a pair of scented chow dishes to retrieve a cereal reward. The rewarded odor of any given pair is determined by an arbitrary hierarchical series. For example, when odor A and B are paired together, A is reinforced; when odor B and C are paired together, B is reinforced etc. A series of five odors is used ($A > B > C > D > E$), and a B–D probe test is applied to test for transitive inference. Odor B and D are never presented together and are rewarded (B–C, D–E) and punished (A–B, C–D) equally often during the course of training. If rats are able to use their memory flexibly, they should infer from the series that odor B is the correct choice.

Dusek and Eichenbaum (1997) trained rats with fornix transection, rats with perirhinal and entorhinal lesions, and control animals on this TI paradigm. Control animals and those with hippocampal disconnection, whether by fornix or perirhinal/entorhinal lesions, learned the series of odor discriminations at the same rate. Control animals also exhibited transitive inference, as evidenced by high levels of performance on the B–D probe trial. Animals with lesions that disconnected the hippocampus from its subcortical or cortical inputs, however, were unable to use their knowledge flexibly, performing at chance on the B–D probe trial.

Neuroimaging studies of human participants have also shown that the hippocampus is activated during relational encoding (Davachi & Wagner, 2002; Henke, Buck, Weber, & Weiser, 1997) and flexible retrieval of memory (Giovanello, Schnyer, & Verfaellie, 2004; Heckers, Zalesak, Weiss, Ditman, & Titone, 2004; Preston, Shrager, Dudukovic, & Gabrieli, 2004). Preston, Shrager, Dudukovic, and Gabrieli (2004) trained participants to associate individual faces and houses. During the study phase, participants learned the association between one set of faces (A) and houses (B), between a new set of faces (C) and the same houses (B), as well as the association between pairs of faces (DE). Participants saw pairs of stimuli for 4 s during the study phase and were explicitly instructed to learn the association between them. Training occurred in three blocks (A/B then B/C then D/E), and participants were tested for recognition of the associations several times during each block. At the conclusion of training, participants were performing above 85% correct in forced choice recognition tests. During scanning, participants again made two alternative forced-choice recognition judgments about faces and houses that had been associated (A/B and C/B), faces that were directly associated during training (D/E) and faces that were indirectly associated, by virtue of being paired with the same house (A/C). Recognition of the associated faces and houses produced activation in both the hippocampus and parahippocampal cortex. Only activation of the anterior hippocampus, however, was greater during recognition of indirectly related face-face pairs (A/C) than during recognition of learned face-face pairs (D/E) or learned face-house pairs (A/B, C/B). This result suggests that while areas of the medial temporal lobe support paired associate learning, the hippocampus is critically involved in the inferential use of relational knowledge.

In a similar vein, Heckers et al. (2004) have shown the hippocampus is activated when adults are tested on a transitive inference task analogous to that used by Dusek and Eichenbaum (1997). In this study, adults learned pairs of visual stimuli that did not overlap (i.e. $A > B$; $C > D$; $E > F$) and pairs that formed an overlapping hierarchical sequence ($A > B > C > D > E$). During scanning, recognition of novel pairs from the overlapping sequence (including the critical BD pair) was associated with activation in the right anterior hippocampus. In contrast, recognition of non-overlapping paired associates produced activation in bilateral anterior parahippocampal cortex. Consistent with Dusek and Eichenbaum (1997), these results suggest that the parahippocampal cortex supports simple representations of individual items, however, the flexible use of such knowledge is critically dependent on the hippocampus.

By this account, we may attribute infants' failure to use their memories flexibly to an inability to form relational representations. According to Eichenbaum (2002), the hippocampus is necessary to extract consistencies from experiences and allows new memories to be encoded in relation to each other and in relation to previous knowledge, a property that allows for flexible expression. We now know that while much of the hippocampus is formed early, the protracted development of the dentate gyrus and inhibitory interneurons, precludes adult-like function until at least 2 years of age (Seress & Abraham, in press). This continued maturation of the hippocampus may account for the gradual loosening of cue and context constraints on memory throughout infancy and into early childhood.

Consistent with this explanation, some researchers have suggested that infants' memories fail under conditions in which the context or cue is changed because infants bind details of the central cue and the peripheral context into a unitary rather than a relational representation (Jones & Herbert, 2006). Jones and Herbert (2006) suggest that in the absence of mature hippocampal function, young infants fail to weight details of the cue and context in a hierarchical manner, such that small changes to incidental aspects of the environment result in retrieval failure.

How do we determine whether infants' memory representations are unitary or relational in nature? The approach that Eichenbaum (2002) has taken to testing declarative memory in

animals is equally applicable to studies of infants and may be useful in answering these questions. By training participants on a set of associated experiences, and testing whether acquired knowledge can be used inferentially to solve new problems, we are able to test whether the experiences have been linked in a relational manner. There are now several examples in the infant literature that take just this approach.

Using a sensory preconditioning paradigm, Barr, Marrott and Rovee-Collier (2003) showed that infants associate stimuli that co-occur in their environment and can use their knowledge about the relations among stimuli to support flexible memory. Six-month-old infants were pre-exposed to two animal hand puppets (a black cow and a yellow duck) that were paired together for 1 hour per day (paired preexposure) or presented for 30 min each at separate times of the day (unpaired preexposure). Following 7 days of preexposure to the puppets, infants saw a set of novel actions that were demonstrated using Puppet A. Twenty-four hours later, infants were tested for imitation of the target actions using Puppet B. Infants in the paired preexposure group reproduced the target actions when they were tested with a different puppet. Infants who had the same amount of preexposure to each puppet, but who did not have the opportunity to learn about the relation between the puppets (unpaired preexposure) did not exhibit retention. As discussed earlier, 6-month-old infants' memory for the puppet task is highly specific to the cues present during learning; changes in either the form or the color of the puppet will disrupt retrieval (Hayne et al., 2000). Typically, it is not until 24-months of age that infants are able to generalize their learning from the cow puppet to the duck puppet or vice versa (Hayne et al., 1997). Given paired preexposure, however, 6-month olds learned about the relation between the puppets and were subsequently able to use this knowledge to generalize their learning about the actions from one puppet to the other.

A recent paper in *Psychological Science* demonstrated that this kind of relational learning and flexible expression occurs not only independent of task, but may occur across tasks that have traditionally been considered to measure different kinds of memory (i.e. mobile conjugate reinforcement and deferred imitation). In this study, Cuevas, Rovee-Collier, and Learmonth (2006) preexposed infants to a pair of puppets (Puppet A and Puppet B) for 1 hour per day for two days. Following preexposure to the puppets, infants were then trained on the mobile task in the presence of a distinctive context. Having established an association between Puppet A and Puppet B, and then an association between the Mobile and the Context, infants were exposed to Puppet A in the presence of the Context for 2 minutes. Twenty-four hours later, infants saw a set of novel actions demonstrated with Puppet B were tested for imitation of the actions either 7, 14, or 21 days later. Although 6-month-old infants typically only remember the puppet task for 24 hours, Cuevas et al. (2006) showed that under these conditions infants exhibited deferred imitation for 14, but not 21 days, the exact retention interval that they will remember the mobile task.

The rationale for this experiment is as follows. While 6-month olds typically remember the puppet task for only 1 day, retention can be protracted if the puppet is associated with a longer enduring task, such as the mobile task or train task (Barr, Vieira, & Rovee-Collier, 2001, 2002). Cuevas et al. (2006) had infants learn the association between Puppet A and Puppet B, and the association between the Mobile and the Context. When infants are exposed to Puppet A in the presence of Context, representations of Puppet B and the Mobile were simultaneously activated and associated. Despite the fact that Puppet B and the Mobile were never seen together, by virtue of their indirect association, memory for Puppet B persists for as long as infants are able to remember the mobile (Cuevas et al., 2006).

In summary, age-related changes in infants' ability to exploit retrieval cues in the service of flexible memory are a hallmark of declarative memory development. By 12-months of age, infants can retrieve memories across changes in context, however, changes in stimulus cue

continue to disrupt retrieval until late in the second year of life. While it is tempting to attribute inflexibility in memory retrieval during infancy to immature hippocampal circuitry, under certain circumstances, infants as young as 6 months are able to encode associations among items in memory in a relational manner and use these associations to support flexible retrieval (Barr et al., 2003; Cuevas et al., 2006). It is possible that even without the adult-like functioning of the hippocampus, the medial temporal lobe circuitry is sufficiently mature by 6-months of age to support simple relational associations between co-occurring stimuli and contexts, given certain experience.

What is the role of experience?

Several studies have now demonstrated that experience influences the development of memory flexibility. In some of these studies, experience is provided by the experimental situation. For example, Herbert and Hayne (2000a) have shown that the addition of verbal cues during the demonstration and test of a deferred imitation task allows 24-month olds to generalize the imitation actions from one set of props to another. Similarly, Hayne, Barr and Herbert (2003) have shown that the opportunity to practice the actions prior to the test, allows 18-month olds to generalize their memory to a new set of props. In addition, studies using the mobile conjugate reinforcement paradigm, have shown that even young infants' memories can appear to be context independent, if infants experience several contexts during training (Amabile & Rovee-Collier, 1991; Rovee-Collier & DuFault, 1991).

In other studies, infant gain experience outside of the experimental situation. For example, Herbert, Gross, and Hayne (2007) have shown that onset of independent locomotion is associated with increased memory flexibility. In this study, 9-month olds who were crawling were better able to imitate the target actions across a change in context than were their non-crawling counterparts. The question remains, how does experience interact with brain development? Although it is possible that perceptual, verbal, or locomotor experience directly influences maturational changes in the brain, we suggest that experience may influence memory flexibility via a more indirect route. Declarative memories are encoded in networks of representations that allow new memories to be linked to prior knowledge (Eichenbaum, 2002). Given the limited experience that infants have with the world, however, the nature of the knowledge networks to which new memories can be associated is initially sparse, but develops in an experience-dependent manner. Young infants are able to demonstrate relational memory when the relational network is explicitly provided by the experimental situation, however, they are unable to exhibit relational memory in situations where there is less representational support. For example, Barr, Marrott, and Rovee-Collier (2003) have shown that 6-month olds can imitate the puppet actions when the test occurs with a novel puppet, only if they are given experience prior to the demonstration that establishes a relational "puppet knowledge" network. In the absence of such experience, however, infants do not possess a sufficiently rich network of knowledge into which the memory for the puppet can be integrated, thus the memory is isolated and inflexible. With the onset of independent locomotion, infants are able to seek out new experiences; these experiences contribute to the complexity of the knowledge networks into which new memories can be related and integrated.

Concluding remarks

Behavioral studies suggest that although rudimentary declarative memory abilities develop early in infancy, the fundamental processes that underlie task performance undergo considerable development during infancy. This review highlights the potential of a cognitive neuroscience approach in enhancing our understanding of the relation between age-related changes in encoding, retention, and retrieval, and the maturation of brain systems that may underlie these processes. By addressing how changes in brain are related to changes in memory,

we may begin to move the field beyond simply describing early development to understanding the mechanisms that drive it.

In summary, there are at least three fundamental characteristics of memory development that are most apparent during infancy; each is independent of the task that is used to measure memory. First, older infants learn faster than younger infants. Second, older infants remember for longer than younger infants. Third, older infants are better able to exploit retrieval cues in the service of flexible memory than are younger infants (Hayne, 2004). The critical question of interest is how does brain development drive these age-related changes in memory processes?

Declarative memory depends critically on brain structures in the medial temporal lobe and age-related changes in retention and retrieval may, at least in part, be attributed to the prolonged maturation of hippocampal circuitry. We now know that the hippocampus and surrounding cortex can support performance on the VPC task and deferred imitation during the first half of the first year, however Seress (in press) suggests that adult-like function of the hippocampal region can not be expected until at least 2-years of age. Prolonged cell formation and migration in the dentate gyrus may explain the continued development of infants' long-term retention throughout infancy, as the hippocampus has been implicated in the consolidation of memories into long-term storage. Continued development of the dentate may also explain age-related changes in infants' ability to retrieve memories in new situations, as some research suggests that the hippocampus is critically involved in relational encoding and flexible retrieval (Eichenbaum, 2002). Age-related changes in encoding are likely attributable to rapid myelination during the first year of life, which allows for efficient transmission of electrical signals and faster information processing.

Many of the memory processes that exhibit age-related change during infancy are processes that we attribute to the hippocampus in adults (i.e. consolidation, relational encoding, and retrieval flexibility). Although it is possible that developmental changes in these processes are due solely to maturational changes in the hippocampus, we acknowledge that the hippocampus does not mature, or even operate for that matter, in isolation. Many of the tasks that we use to measure declarative memory during infancy likely recruit brain systems in addition to the hippocampus. For example, the deferred imitation task requires infants to encode, retain and retrieve a representation of a past event. In performing this task, however, infants also to encode the event as a sequence of ordered actions and map the appropriate motor response to the imitation props, processes which may recruit prefrontal and premotor cortices (Nelson & Webb, 2003). For this reason, we cannot rule out the possibility that developmental changes in deferred imitation performance, for example, are due to the maturation of frontal cortex and/or the development of connectivity between the medial temporal lobe and frontal brain regions.

Maturation of the connections between the medial temporal lobe and cortical areas, particularly prefrontal cortex, have been implicated in the development of strategy use in older children (Nelson et al., 2006a). Declarative memory performance continues to develop throughout early and middle childhood and children become increasingly able to use strategies to efficiently encode, retain, and retrieve memories. Recent neuroimaging data confirms that while MTL activation predicts subsequent story recall in 7–8 year olds, activation in both MTL and prefrontal regions is associated with successful recall in 10–18 year olds (Chiu, Schmithorst, Douglas Brown, Holland, & Dunn, 2006). Chiu et al. (2006) suggest that greater involvement of the prefrontal cortex in older children may be associated with age-related improvements in rehearsal and other encoding strategies during middle childhood.

It is important to note that identifying a correlation between the relative maturation of brain systems underlying memory and age-related changes in behavior is only the first step to

improving our understanding of the mechanisms of development. For example, the coincidental timing of dentate maturation and improvements in memory flexibility only allows us to speculate about a possible association. Studies that combine multiple measures are critical, if we are to determine a causal link between brain and behavior development. So where do we go from here? Our understanding of the brain mechanisms underlying memory development will benefit from improvements in the armamentarium of neuroimaging tools that allow us to look inside the developing brain. There is much progress being made in customizing ERP source localization parameters for studies of infants and children (Reynolds & Richards, 2005; Richards, 2005). Several researchers are now using magnetic resonance imaging (MRI) and diffusion tensor imaging (DTI) to study structural brain development from infancy (Giedd et al., 1995; Giedd et al., 1996; Gilmore et al., 2006; Gilmore et al., 2004; Lenroot & Giedd, 2006). Methodological advances will allow younger children, although perhaps not infants, to participate in functional MRI studies (Casey, Tottenham, Liston, & Durston, 2005). Optical imaging techniques, like near-infrared spectroscopy (NIRS), also allow for the functional imaging of cortical activation in infants (Aslin & Mehler, 2005). Each of these techniques is not without its limitations, however, the advent of new technology allows us to use a converging methods approach to study brain-behavior relations during development.

The study of individual differences may allow us to more specifically understand the mechanisms by which brain and memory development are linked. To date, we know very little about the functional significance of variability in normal brain development. For example, what do individual differences in ERP latency tell us about myelination? What are the behavioral implications of individual differences in connectivity between MTL structures and frontal cortex? Most neuroimaging techniques use averaging to remove such “noise” from the data. Future research will develop methods by which we can make sense of the “noise”, and in doing so advance our understanding of developmental mechanisms.

Studies of infants who have had early damage to the brain systems involved in memory will also be critical in our understanding of the relation between brain and memory development (Vargha-Khadem, Gadian, & Mishkin, 2001). By designing prospective studies of infants who have experienced early insult to the hippocampus, and analyzing how early structural changes in the hippocampus give rise to behavioral deficits during development, we may gain a greater understanding of the mechanisms underlying memory development.

In summary, by considering the development of memory processes that underlie memory tasks, and integrating current knowledge of brain development, we have been able to speculate about the possible mechanisms by which brain development drives memory development during infancy. Technological advances in imaging methodology, along with studies of individual differences in both typical and atypical development will allow future research to go far beyond speculation. The field of developmental cognitive neuroscience, although in its infancy, is certainly beginning an exciting era.

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Figure 1.

The medial temporal lobe memory system. Source: From *Brain, Mind, and Behavior* (3rd ed.), by F. Bloom, C.A. Nelson, and A. Lazerson, 2001, New York: Worth Publishers.

Figure 2.

The major memory systems and associated memory tasks that are used with infants and children. Highlighted tasks indicate infant declarative memory tasks for which both the *amnesia filter* and the *parameter filter* have been applied. For a comprehensive review of the neural substrates of developmental memory tasks see Nelson and Webb (2003).

Figure 3.

Developmental changes in the hippocampal dentate gyrus between birth and two years of age. Cytoarchitectonic changes, including the completion of cell formation and migration, and morphological changes of individual neurons, such as increases in spine density, dendritic length, and synaptic connections characterize development during this period. In addition, the neurochemical characteristics of excitatory (granule cells) and inhibitory neurons (basket cells) change dramatically after birth (for further detail, see Seress & Abraham, in press). These schematic drawings do not show the real size of the structure, therefore the scale is not given. It is important to note that in parallel with the growth of the total brain volume the hippocampal dentate gyrus is much larger in the two year old than in the newborn.

Newborn In full-term newborns, most granule cells in the granule cells layer (red dots in g) do not express calbindin binding protein (CaBP-D28k); only the earliest born granule cells at the border with molecular layer (m) display calbindin immunoreactivity. Inside the hilus (h), a large number of granule cells migrate (green fusiform cells) toward their final position in the granule cell layer. The main excitatory cell of the hilus (h) is the mossy cell (black). Mossy cells have few spines and no thorny excrescences indicating sparse connection with granule cells (red line from granule cell represents an axon). Similarly, the mossy fiber bundle above the CA3 pyramidal cells is also sparse (red line) indicating the pyramidal cells of the CA3 area of Ammon's horn also receive few afferents from granule cells. Mossy cells project inside the hilus and above the granule cell layer (light brown zone) in the inner third of the molecular layer forming the association path that is present at birth. Inhibitory basket cells are present both in the hilus and in the CA3 area; only a few basket cells express parvalbumin-immunoreaction (blue) and their axon arborization is sparse among the excitatory granule cells and CA3 pyramidal neurons.

Two year old By two years of age, the development of the dentate gyrus has reached a point that is close to the adult, although in a few fine details (number of immunoreactive axonal branches, synaptic density etc.) further changes occur. All granule cells are calbindin-positive (red dots) inside the granule cell layer (g) and their axons form a rich collateral network in hilus (h). They also form the mossy fiber bundle (red lines) in stratum lucidum of the CA3 area, innervating both inhibitory (blue) and excitatory cells (black). Hilar mossy cells (black) receive a large number of afferents from granule cells (red lines). In contrast to the newborn,

the morphology of the mossy cells displays large complex spines (thorny excrescences) characteristic of mossy cells in adults. Large number of inhibitory basket cells express parvalbumin (blue) and their axons (blue lines) form a rich network among the somata of excitatory cells inside the granule cell layer and in the CA3 area as well. Source: Figure courtesy of László Seress and Hajnalka Ábrahám, Pécs University, Hungary.

Figure 4.

Mean latency (ms) of the Pb and Nc components recorded over midline leads. ERPs were recorded in response to pictures of faces and objects at 4 months, 6 months, 8 months, 10 months, and 12 months of age. Source: Figure adapted from Webb, Nelson, and Long (2005).

Figure 5.

Myelination across the first year of life. These T1 weighted MR images illustrate that myelination begins in subcortical structures and progresses in a deep to superficial, posterior to anterior pattern. Note that myelin is present in the occipital cortex at 4 months. The genu and splenium of the corpus callosum are myelinated at 6 months of age. Myelinated fiber tracts are evident in frontal cortex at 12 months of age. Source: Images courtesy of P. Ellen Grant M.D., Massachusetts General Hospital.

Figure 6.

Age-related changes in generalization across cues and contexts by 6-, 12-, and 18-month-old infants who were tested in the deferred imitation paradigm. Source: Figure courtesy of Harlene Hayne, University of Otago, New Zealand.