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Infant memory development: Implications for childhood amnesia[☆]

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Abstract

When asked to recall their earliest personal memories, most children and adults have virtually no recollection of their infancy or early childhood. This phenomenon is commonly referred to as childhood amnesia. The fate of our earliest memories has puzzled psychologists for over 50 years, particularly in light of the importance of early experience in human development. Empirical research has shown that infants can both learn and remember very early in development, making the ultimate fate of early memories even more mysterious. The theoretical explanation of childhood amnesia outlined here relies on age-related changes in encoding, retention, and retrieval that occur during infancy and early childhood. Data obtained using a host of different memory tasks support the conclusion that quantitative changes in these basic memory processes can account for the decline of childhood amnesia during the third or fourth year of life. © 2003 Elsevier Inc. All rights reserved.

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Historical perspective

The first three years of a child's life are characterized by a remarkable degree of physical, social, emotional, and cognitive change. At no other time is the rate of

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development so rapid or so dramatic. Historically, most theorists have placed special emphasis on infant experience, arguing that events that occur early in life have a greater and more lasting impact than the same events or experiences encountered during adulthood. The relative importance of early experience was the cornerstone of Freudian theory and was also reflected in a number of subsequent theories of social and emotional development (for review, see Ainsworth & Bowlby, 1991). Early empirical research on infants who were raised in partial or total social isolation clearly demonstrated the profound effects of early social experience on subsequent development (Harlow, Harlow, & Suomi, 1971; Skeels, 1966).

Recent advances in neuroscience have shown that early experiences also play a fundamental role in brain development. At birth, the human infant brain weighs approximately 350 grams but it more than quadruples its size by the time of adulthood. Most of the neurons that make up the human brain are present at the time of birth; the fourfold change in weight is due primarily to an increase in the connections between the neurons. These connections are established very rapidly during infancy and are contingent, at least in part, upon experience (Greenough, Black, & Wallace, 1987). Although both deprivation and enrichment influence the structure and function of the mammalian brain throughout the lifespan (Black & Greenough, 1998; Winocur, 1998), these experiences may be particularly important early in development when the brain is initially taking shape (Kolb, Forgie, Gibb, Gorny, & Rowntree, 1998; Perry, 1997; Wickelgren, 1999).

In light of the pervasive effects of infant experience on both behavioral and neural development, it is somewhat perplexing that most adults have little or no recollection of these early, formative experiences. Freud coined the term *infantile or childhood amnesia* to describe the inability of adults to remember events from their infancy and early childhood. He originally identified the phenomenon by asking his patients to describe their earliest personal memories in the context of therapy. On the basis of these patient reports, Freud argued that the period of childhood amnesia extended into the 6th or 8th year of life (1953). Subsequent normative studies of adults' earliest memories have shown that Freud may have overestimated the period of childhood amnesia. There is now a general consensus that adults' earliest autobiographical memories are for events that occurred when they were approximately 3 to 4 years of age or even slightly younger (e.g., MacDonald, Uesiliana, & Hayne, 2000; Mullen, 1994; Usher & Neisser, 1993). Although this empirical research has forced us to revise Freud's estimates of the boundary for childhood amnesia, it has not eliminated the phenomenon *per se*. The fact remains that much, if not all, of our infancy is inaccessible to recall later in development.

There have been numerous attempts to identify the mechanism(s) responsible for childhood amnesia. Freud's notion of repression has been largely discounted. Recent theories of childhood amnesia have been couched in cognitive, rather than psychoanalytic, terms. Current explanations for childhood amnesia include neurologically based transitions from one memory system to another (Bachevalier, 1990), age-related changes in children's self concept (Howe, 2003; Howe & Courage, 1993, 1997a) and theory-of-mind (Perner & Ruffman, 1995), or the development of language and conversational skills (Nelson, 1993).

The phenomenon of childhood amnesia raises critical questions about the continuity of memory processing across the life span. Are there fundamental changes in memory during development? If so, what are they and when do they occur? Spear (1979) was one of the first memory experts to argue that the key to childhood amnesia might emerge through systematic studies of memory development. Consistent with Spear's view, our recent attempts to understand the mechanism responsible for childhood amnesia have focussed on age-related changes in memory processing during infancy and early childhood.

The goal of the present paper is threefold. First, I will outline the practical problems encountered by researchers who try to study memory development during the infancy period. Second, I will describe a range of experimental tasks that have been used to document infants' memory skills, highlighting some of the seminal findings that have been obtained with each task. Finally, I will discuss the implications of current studies of infant memory for the phenomenon of childhood amnesia.

Obstacles to the study of infant memory

The empirical study of memory development during the infancy period presents researchers with some significant challenges. First, the memory tasks that are commonly used with children and adults are generally inappropriate for use with infants. Even within the infancy period, tasks that are appropriate for one age group are not necessarily appropriate for another. For this reason, research on infant memory is often remarkably nondevelopmental, focusing on a single age group or a very limited age range. This practice has severely limited our ability to draw conclusions about memory development *per se*.

Second, the preverbal nature of the human infant requires researchers to "build" nonverbal instructions into a given memory task. Furthermore, researchers must rely on the infant's nonverbal behavior as the primary index of memory. Researchers who study memory in nonhuman participants encounter these same problems and, in fact, some researchers who are interested in memory development in human infants have borrowed techniques that were originally developed for use with monkeys or rats. In both nonhuman animals and in preverbal human infants, the nonverbal nature of the memory response makes it impossible to experimentally validate the conscious nature of participants' memories (Rovee-Collier, Hayne, & Colombo, 2001). Because researchers have yet to overcome this obstacle, we must live with the ambiguity inherent in our current measures of infant memory processing.

Third, not only are the tasks that can be used with infants limited by factors related to language, they are also limited by factors related to motor skill. The immature motor competence of the human infant, particularly during the first 6–12 months of life, severely constrains the kinds of tasks that can be used to study memory. Tasks used to measure memory in older infants are typically longer and more motorically complicated than tasks used to measure memory in younger infants. Even some of the nonverbal reaching tasks that were originally developed for use

with nonhuman primates (e.g., Bachevalier & Mishkin, 1984) are too motorically difficult for young human infants.

Finally, the neonatal period is characterized by extremely rapid changes in behavioral state (Clifton & Nelson, 1976). Although older infants' state regulation is more stable, changes in interest and motivation continue to fluctuate rapidly. As such, any memory task that is to be used with infants must be relatively quick to administer. When session duration increases, subject loss rate is typically high. Furthermore, tasks that require multiple sessions are likely to have extremely high attrition rates given that they provide multiple opportunities for participant loss.

Tasks used to study infant memory

Despite the methodological difficulties that characterize the empirical study of infant memory, a number of experimental procedures have been devised that circumvent some, if not all, of the problems outlined above. To date, the most comprehensive analyses of infant memory development have been obtained using visual recognition memory, operant conditioning, and deferred imitation procedures. In addition to these tasks, a host of other procedures have been used to document particular aspects of infants' memory skills.

Visual recognition memory procedures

The two visual recognition memory (VRM) procedures that are most commonly used with infants were derived from procedures originally developed by Fantz (1958) and Berlyne (1958) to study infant perception. In the *paired-comparison task*, infants are initially exposed to a particular stimulus for a fixed duration or until they have accumulated a specified amount of time looking at that stimulus. Following this familiarization period, infants are then tested with two stimuli that are presented simultaneously. One of the test stimuli was present during the familiarization period and the other stimulus is novel. The proportion of time that the infants spend looking at the familiar and the novel stimulus is assessed during this test period. When this task is used to study memory, a delay is inserted between the end of the familiarization trial and the beginning of the test.

In the *habituation task*, a single stimulus is repeatedly presented until the infant's attention to it has declined to some absolute (e.g., McCall, Kennedy, & Dodds, 1977a) or relative level (e.g., Cohen, DeLoache, & Pearl, 1977). At this point, the infant is presented with a novel stimulus and his or her looking time to this stimulus is compared to looking time to the familiarization stimulus at the end of the habituation period. Again, this task can be used to study memory by inserting a delay between the habituation and the test phases.

The interpretation of infants' distribution of looking during the test in the VRM procedure was originally based on Sokolov's (1963) model of habituation of the orienting response. According to Sokolov, participants construct a memory representation, or an engram, of the stimuli they encounter. Attention to a particular stimulus

at any given moment is determined by the discrepancy between that memory representation and the external stimulus. The more complete the representation, the smaller the discrepancy, and the less attention allocated to that stimulus. When the internal representation is complete, participants attend more to a novel stimulus than to the familiar stimulus during the test. If a delay is inserted between the original familiarization and the test, there is an opportunity for forgetting to occur. As the delay increases and the representation presumably decays, participants will again re-orient toward the original stimulus to the degree that the representation no longer matches the stimulus.

In light of Sokolov's model, "retention" in the VRM paradigm was traditionally inferred only when participants looked longer at the novel stimulus than at the familiar stimulus during the test (i.e., novelty preference). Using this operational definition, early research provided evidence for visual recognition memory by 3- to 12-month-old infants (for review, see Olson & Sherman, 1983). Although most studies employed delays on the order of minutes or hours, at least one study yielded novelty preferences by 5-month-olds who were tested after a delay as long as 2 weeks (Fagan, 1973).

Following a surge of studies during the 1970s, many researchers abandoned the VRM procedure in favor of other techniques to study infant memory. Exclusive reliance on novelty preference as an index of retention was deemed inadequate by some researchers because a number of factors (e.g., age, prior experience) might lead infants to look longer at the familiar rather than the novel stimulus during the test (Hunter & Ames, 1988; Sophian, 1980). For other researchers, selective looking procedures confound measures of acquisition (i.e., encoding) and measures of memory (Rovee-Collier, 2001). Furthermore, the finding that novelty preferences often disappeared within seconds or minutes did not make the VRM procedure a viable candidate for the study of long-term memory during infancy (Rovee-Collier & Hayne, 1987). Although the VRM procedure continued to provide valuable information about infant attention, cognition, and information processing (for review, see Campbell, Hayne, & Richardson, 1992), its use in memory-related research virtually disappeared.

At least four factors have contributed to a recent renaissance in the use of the VRM paradigm to study infant memory development. First, research with nonhuman primates (Bachevalier, Brickson, & Hagger, 1993; Pascalis & Bachevalier, 1999) and brain-damaged human adults (McKee & Squire, 1993) has shown that novelty preferences in these tasks are dependent upon the integrity of the hippocampus. In contrast to earlier views about the kind of memory that was tapped by the VRM procedure (Schacter & Moscovitch, 1984), studies conducted with brain-damaged adults have been used to argue that this paradigm taps the kinds of higher-order memory processes that are disrupted in amnesia, increasing interest in the task as a tool to study memory development.

Second, the way in which "retention" is defined in the VRM procedure has changed, expanding the range of situations in which it can now be used. Consistent with the traditional Sokolovian perspective, infants sometimes look reliably longer at the novel stimulus during the test (i.e., novelty preference), but there are also conditions

under which infants look reliably longer at the familiar stimulus during the test (i.e., familiarity preference). Familiarity preferences are commonly seen when the stimuli are biologically significant, the infant is very young, or the familiarization time is very brief (Bushnell, Sai, & Mullin, 1989; Field, Cohen, Garcia, & Greenberg, 1984; Hunter & Ames, 1988; Pascalis, de Schonen, Morton, Deruelle, & Fabre-Grenet, 1995; Rose, Gottfried, Melloy-Carminar, & Bridger, 1982). Furthermore, although 3- to 6-month-olds typically exhibit novelty preferences when they are tested after short delays, as the retention interval increases, they are more likely to exhibit familiarity preferences (Bahrick & Pickens, 1995; Bahrick, Hernandez-Reif, & Pickens, 1997; Courage & Howe, 1998, 2001; for similar findings with auditory stimuli, see Spence, 1996). A shift away from an exclusive reliance on novelty preference has made it possible to use the VRM paradigm to study memory in newborns and in older infants who are tested after very long delays.

Third, although the VRM paradigm is typically used with infants, it may be the ideal tool to study memory development across the lifespan. A clear understanding of age-related changes in basic memory mechanisms (e.g., encoding, retention, retrieval) has been impossible to date because participants of different ages have always been tested using different experimental procedures. With the appropriate stimuli, however, the VRM paradigm can be used to study age-related changes in encoding, retention, and retrieval in infants, children, and adults who are tested under exactly the same experimental conditions (Morgan & Hayne, 2002; Sowerby & Hayne, 1999).

Finally, in addition to studies of memory development, VRM procedures have also been used to assess cognitive continuity from infancy through childhood. Although traditional tests of infant development have been relatively poor predictors of long-term outcome, novelty preferences obtained between 6 and 12 months of age provide a reliable predictor of childhood IQ in both normal and at-risk populations (Fagan, 1984, 1990; Rose & Feldman, 1995, 1997; Rose, Feldman, McCarton, & Wolfson, 1988; for reviews, see Colombo, 1993; McCall & Carriger, 1993). These findings suggest that the VRM procedure taps a fundamental component of central nervous system functioning during development.

Operant conditioning paradigms

Operant conditioning methods have also been used extensively to study infant memory. In a typical operant conditioning paradigm, infants alter their behavior when it is followed by the presentation of a particular consequence. Under most conditions, the target response is already part of the infant's behavioral repertoire (i.e., nonzero baseline), but the frequency or the pattern of the response changes as a function of the conditioning experience. Initially, operant conditioning procedures were used to document the *learning* abilities of human infants. Learning was inferred when the frequency of a particular behavior increased (or decreased) over successive trials (Fagen & Rovee, 1976; Lipsitt, 1963; Sameroff & Cavanaugh, 1979). Although it is generally assumed that operant conditioning leads to extremely slow and gradual changes in behavior, acquisition in these tasks can also occur quite rapidly and is

determined, in large part, by the age of the infant (Hartshorn et al., 1998a; Hill, Borovsky, & Rovee-Collier, 1988).

The three operant conditioning techniques that have been used most often are described below. In all three techniques, the version of the task that is used to study learning is altered when the task is used to study memory.

High-amplitude sucking

In the high-amplitude sucking procedure, infants suck on a nipple to produce visual (Siqueland & DeLucia, 1969) auditory (Eimas, Siqueland, Jusczyk, & Vigorito, 1971), or gustatory consequences (Sameroff, 1965). The nipple is attached to a pressure transducer that allows the experimenter to measure the baseline characteristics of the infant's sucking pattern (e.g., rate, timing), and to monitor changes in that pattern during conditioning. When this task is used to study memory, the value of the reinforcer is manipulated through prior experience that typically occurs outside the context of conditioning. The infant's ability to remember that reinforcer is then assessed by examining the degree to which he or she is willing to work for it relative to another reinforcer that is novel.

Perhaps the greatest strength of the high-amplitude sucking procedure is that it can be used to assess memory ability in newborns (DeCasper & Fifer, 1980; DeCasper & Spence, 1986; Walton, Bower, & Bower, 1992). In a landmark study, DeCasper and Fifer (1980) tested newborns in an operant procedure in which high-amplitude sucking on a nonnutritive nipple turned on a tape-recording of either the infant's own mother's voice or the voice of another infant's mother. For each infant, baseline suck rate was established during a 5-min period in which no voices were presented. Some infants were then required to increase the duration of the pause between successive sucking bursts in order to produce their mother's voice and other infants were required to decrease the pause between successive sucking bursts to produce their mother's voice. Although the infants were less than 3 days old, and had had less than 12 h postnatal contact with their mothers, they still exhibited a clear operant preference for their mother's voice.

The tentative conclusion put forward by DeCasper and Fifer (1980) was that infants' operant preference for their mother's voice was based primarily on prenatal, rather than postnatal, experience. Because the infants in the original DeCasper and Fifer studies had spent at least some time with their mothers following birth, however, the opportunity for postnatal learning and memory could not be ruled out.

In a highly provocative study that followed, DeCasper and Spence (1986) obtained striking evidence for retention of information encountered only prior to birth. In their study, pregnant women were asked to read one of three prose passages two times a day during the last 6 weeks of their pregnancy. The three passages were matched for length, number of individual words, and pattern. Two to three days after the infants were born, they were given the opportunity to alter their suck rate to produce the passage that their mother had read during her pregnancy or to produce another passage. DeCasper and Spence found that infants altered their suck rate to maintain contact with the familiar story irrespective of who read it during the test (i.e., their mother or another unfamiliar woman). In contrast, the control group

who had no prior prenatal experience with the passages displayed no preference. Taken together, these studies clearly reveal that the human central nervous system is capable of encoding information about complex speech sounds prior to birth and of retaining that information for at least 2–3 days after birth.

Mobile conjugate reinforcement

Without exception, the operant procedure that has been used most widely to assess infant memory is the mobile conjugate reinforcement paradigm. This procedure was pioneered by Rovee-Collier and has been used for almost 4 decades to document the learning and memory abilities of young human infants (Rovee & Rovee, 1969; for reviews, see Rovee-Collier & Hayne, 1987; Rovee-Collier, 1997). In the mobile conjugate reinforcement paradigm, infants learn to kick their feet to produce movement in an overhead mobile. Mobile movement is made possible by a length of ribbon that is secured to the infant's ankle and to a flexible stand that supports the mobile. The original task was designed for use with 2- and 3-month-old infants, however, subsequent modifications of the procedure have rendered it appropriate for infants as old as 6–7 months.

Each training session in the mobile conjugate reinforcement paradigm begins with a brief period of nonreinforcement. During this period, the mobile is visible, but the ankle ribbon is attached to an adjacent (empty) mobile stand rather than to the stand that supports the mobile. In this arrangement, the infant receives somesthetic feedback each time he or she kicks, but the mobile remains stationary, unaffected by the infant's behavior. Each training session also includes a period of reinforcement. During this period, the ribbon is moved to the stand that supports the mobile and the infant is given the opportunity to kick to produce mobile movement. The reinforcement schedule in this task is conjugate—that is, the rate and vigor of mobile movement is directly related to the rate and vigor of the infant's kicks.

During the first training session, the nonreinforcement period at the outset of the session provides a measure of the infant's baseline kick rate. Learning in this task is defined as a kick rate that exceeds baseline by a factor of 1.5 in two of any three consecutive minutes of reinforcement. The duration of the nonreinforcement and reinforcement periods vary as a function of the age of the infant. For 2- and 3-month-olds, each session typically consists of a 9-min period of reinforcement that is preceded and followed by a 3-min period of nonreinforcement. Because 6-month-old infants learn much more quickly, their training sessions are abbreviated (Hill et al., 1988). For 6-month-olds, each session typically consists of a 6-min period of reinforcement that is preceded and followed by a 1-min period of nonreinforcement.

When the mobile conjugate reinforcement paradigm is used to study memory, a delay is inserted between the conclusion of training and the test session that is scheduled days, weeks, or months later. Retention is assessed during a period of nonreinforcement at the outset of the test and is evaluated on the basis of two relative measures of responding—the baseline ratio and the retention ratio. The baseline ratio is calculated by dividing the infant's kick rate during the period of nonreinforcement at the outset of the test session by that same infant's kick rate during the period

of nonreinforcement at the outset of the initial training session (baseline phase). The baseline ratio expresses the degree to which an infant's kick rate during the test exceeds his/her baseline kick rate.

The second measure of relative responding is the retention ratio. The retention ratio is calculated by dividing the infant's kick rate during the period of nonreinforcement at the outset of the test session by that same infant's kick rate during the period of nonreinforcement at the end of the final training session. The retention ratio expresses the degree to which the infant's kick rate has declined during the retention interval.

Train task

Although the mobile conjugate reinforcement paradigm has been highly successful with 2- to 7-month-olds, age-related changes in interest, motivation, and motor skill make it substantially less effective with older infants. To extend their analysis of infant learning and memory beyond the first half-year of life, Rovee-Collier and her students developed a second task that can be used with 6- to 18-month-olds (Hartshorn & Rovee-Collier, 1997; Hartshorn et al., 1998a, 1998b). In this task, infants learn to press a lever to make a miniature train move around a track. Infants' baseline response rate is assessed during an initial period of nonreinforcement during which the apparatus is available and within reach, but lever presses are ineffective. At the end of this baseline period, each lever press produces a 1–2 s movement in the train. Following acquisition, there is a final period of nonreinforcement. As in the mobile conjugate reinforcement paradigm, learning in the train paradigm is defined as a response rate of at least 1.5 times above operant level during 2 of any 3 consecutive minutes of acquisition, all retention testing occurs during periods of nonreinforcement, and retention is evaluated in terms of two relative response measures, the baseline ratio and the retention ratio.

Unfortunately, two common misunderstandings have plagued secondary citations of research using the mobile conjugate reinforcement and train paradigms. First, the target behaviors in these tasks—a foot kick, a lever press—are emitted, not elicited. An increase in response rate during acquisition is not an obligatory reaction to the reinforcer, but rather reflects the contingency between a particular behavior and the outcome it produces; infants who are presented with a mobile or train that moves noncontingently, do not increase their response rate either within or across successive sessions (Hartshorn & Rovee-Collier, 1997; Rovee & Rovee, 1969). Furthermore, during the retention test, the mobile or the train do not elicit responding, but rather serve as a retrieval cue for a prior memory.

Second, the index of retention in these paradigms is not savings in the rate of relearning. Retention is always measured in the *absence* of reinforcement. During the retention test, the mobile or the train is visible, but remains stationary and is unaffected by infants' responding (nonreinforcement phase). Infants are given the opportunity to make the mobile or the train move at the conclusion of the test period—but their behavior during this final period of reinforcement is not used to index retention. Instead, infants' response rate during the reinforcement phase at the conclusion of the test allows researchers to confirm that infants' lack of responding during the test

was due to forgetting rather than to illness or to a change in motivation. Taken together, these two misunderstandings are often used to create barriers between research programs (Bauer, 1996; Bauer & Hertsgaard, 1993; Mandler, 1984, 1990; Nelson, 1995, 1997a); a better understanding of the methodology may help to build bridges.

Imitation paradigms

Imitation paradigms involve a “monkey see, monkey do” procedure that exploits infants’ natural tendency to reproduce the actions of other people in their environment. Naturalistic studies of imitation have shown that 12- to 18-month-olds acquire at least 1–2 new behaviors each day simply by watching and repeating the actions of others (Barr & Hayne, 2003). Piaget (1962) was the first to note the relevance of imitation for studies of memory. According to his theory, imitation that occurred following a delay signaled the infant’s ability to form a mental representation of the model’s behavior and to retain that representation over the retention interval (for a similar argument, see Meltzoff & Moore, 1998). Although empirical studies have now shown that Piaget underestimated the developmental emergence of imitation (Meltzoff & Moore, 1994), his views about the relation between imitation and memory continue to provide the theoretical cornerstone for research in this area.

Deferred imitation

Piaget’s theory of the development of imitation was based primarily on observations of his own three children. The first systematic studies of imitation under highly controlled, experimental conditions began to emerge during the 1970s and 1980s (McCall, Parke, & Kavanaugh, 1977b; Meltzoff, 1985). These initial studies employed procedures that were based on Piaget’s definition of *deferred imitation*—that is, they required infants to reproduce a modeled action, without prior practice, following a delay. In the deferred imitation paradigm, an experimenter demonstrates a novel action using an unfamiliar object. The infant’s ability to reproduce that action is assessed during a test that occurs either immediately or after delays ranging from 1 day to 4 months (Herbert & Hayne, 2000a; Meltzoff, 1995). During the demonstration, the experimenter does not label the object(s) or describe the target action(s) and the infant is not allowed to touch the object(s) during the demonstration or practice the target action(s) prior to the test. During the test, the infant’s behavior is scored from videotape by trained observers who are blind to the infant’s prior experience.

In the deferred imitation paradigm, stringent control procedures are used to assess the spontaneous production of the target action(s) in the absence of adult demonstration. In the *baseline control procedure*, the experimenter does not model the target action(s); the infant encounters the object for the first time during the test. In the *activity control condition*, the experimenter manipulates the object in some way during the demonstration session, but the target action(s) is never modeled. Retention is inferred when the imitation scores of infants in the demonstration condition exceed those of infants in the control condition. On the basis of this definition, infants as young as 6 months have been shown to exhibit deferred imitation when tested after

a 24-h delay (Barr, Dowden, & Hayne, 1996; Collie & Hayne, 1999; Hayne, Boniface, & Barr, 2000a).

In addition to imitation of actions with objects, infants also imitate adults' facial expressions (Meltzoff & Moore, 1977, 1983, 1989, 1994). In experimental studies of facial imitation, an adult models a unique facial gesture (e.g., mouth opening, tongue protrusion) and the infant's re-production of the same gesture is assessed immediately or after a delay. These studies have shown that even newborns exhibit imitation of adults' facial gestures when they are tested immediately (Meltzoff & Moore, 1983) and that 6-week-old infants exhibit imitation when they are tested after a 24-h delay (Meltzoff & Moore, 1994). This latter finding represents the lowest boundary to date for deferred imitation by human infants.

The finding that infants as young as 6 weeks of age imitate actions from memory challenges the Piagetian notion that the capacity for mental representation does not emerge until the end of the sensorimotor period (e.g., 18–24 months). In contrast to Piagetian theory, Meltzoff and Moore have argued that infants are born with some rudimentary representational capacity that is signaled by their ability to exhibit deferred imitation very early in development. Despite the precocious emergence of imitation, however, there are clear age-related changes in infants' memory for the modeled information (see below).

Elicited imitation

Bauer and her colleagues have developed a modified version of the deferred imitation paradigm that is frequently referred to as the *elicited imitation paradigm* (Bauer, 1996; Bauer & Mandler, 1989). This paradigm has been used to assess memory processing by infants ranging in age from 9- to 32-months of age (e.g., Bauer, Wenner, Dropik, & Wewerka, 2000; Carver & Bauer, 2001). The experimental procedures used in the elicited imitation paradigm differ from those used in the deferred imitation paradigm in a number of ways. First, in the elicited imitation paradigm, the duration of the baseline and test periods is not fixed, but rather is child-controlled. Both prior to and after the demonstration, infants are allowed to interact with the stimuli until they begin to mouth them or throw them on the floor. Across infants in the same study, the duration of the baseline and test periods can vary by as much as a factor of 7 (e.g., 20–145 s, Bauer & Hertsgaard, 1993).

Second, in the elicited imitation paradigm, infants are allowed to practice the target actions immediately following the demonstration prior to the retention interval. If an infant does not imitate the target behaviors during this practice period, the target behaviors are modeled again and the infant is given a second opportunity to imitate the actions prior to the retention interval (Bauer & Hertsgaard, 1993; Bauer, Hertsgaard, & Wewerka, 1995; Bauer & Mandler, 1992).

Finally, in the elicited imitation paradigm, infants are provided with a verbal description of the target actions and the outcome of the imitation sequence during the demonstration. Furthermore, during the practice phase prior to the retention interval, and during the retention test, infants are verbally encouraged to reproduce the target actions and are prompted to do so with verbal descriptions of the actions and

the goals of the target sequence (e.g., "can you give the dirty bear a bath?" Bauer & Shore, 1987, p. 330).

Recent empirical research has shown that some of the procedural differences between the deferred imitation and elicited imitation paradigms may be more important than others. Although the use of child-controlled baseline and test periods may have little or no effect on imitation scores, at least after a 24-h delay (Herbert, Barr, & Hayne, 2000), complications do arise when infants' baseline performance on one set of activities is used to benchmark their retention on another set of activities (e.g., Carver & Bauer, 1999, 2001). In studies of this kind, retention is evaluated by comparing infants' re-production of the target actions to their spontaneous production of a completely different set of actions.

Age-related and delay-related changes in baseline responding in the elicited imitation task have also led to erroneous conclusions about retention per se (e.g., Bauer et al., 2000; Carver & Bauer, 2001). In some studies of elicited imitation, for example, the only difference between groups occurs at the level of baseline. In these studies, an age-related *decrease* in baseline is erroneously used to draw conclusions about an age-related *increase* in retention (Bauer et al., 2000). This same interpretive problem also emerges when infants of the same age are tested after different delays. In the Carver and Bauer (2001) study, for example, 9-month-old infants who were tested after a 1-month delay imitated the same proportion of target actions as 9-month-old infants who were tested after a 3-month delay. Despite the similarity in their performance, the authors concluded that infants tested after 1 month exhibited retention, while infants tested after 3 months did not. This conclusion was based exclusively on a delay-related *increase* in baseline responding.

In studies of deferred imitation, on the other hand, care is typically taken to ensure that there are no age-related or delay-related differences in spontaneous production of the target actions (Barr et al., 1996; Hayne et al., 2000a, Hayne, MacDonald, & Barr, 1997; Herbert & Hayne, 2000a, 2000b); this practice precludes the interpretive problems that have plagued prior work on elicited imitation.

Two additional differences between elicited and deferred imitation procedures—the opportunity to practice the target actions prior to the retention interval and the provision of verbal cues—also lead to systematic differences in infants' memory performance, at least under some test conditions.

Long-term retention. Findings from at least three different laboratories have shown that long-term retention is unaffected by the opportunity to practice the target actions (albeit, briefly) prior to the test (Abravanel, 1991; Barr & Hayne, 1996; Meltzoff, 1995). Long-term retention is prolonged, however, by the provision of verbal cues (Herbert et al., 2000). Furthermore, the effect of verbal cues varies as a function of the length of the retention interval. In a study by Herbert et al. (2000), for example, an adult demonstrated a 3-step series of actions and 18-month-old infants were tested either immediately or after a 4-week delay. Half of the infants were tested in a traditional deferred imitation paradigm in which no verbal information was provided during the demonstration or at the time of the test. The other half of the infants were provided with a verbal description of the target actions and

the goal of the event during the demonstration and were provided with a verbal reminder of the goal of the event at the time of the test (e.g., “can you show me how we use these things to make a rattle?”). These verbal cues are identical to those that are typically provided in the elicited imitation paradigm.

Despite equivalent levels of performance when infants were tested immediately after the demonstration, or after a 24-h delay, only the infants who were provided with verbal cues exhibited superior retention when tested after a 4-week delay (see Fig. 1). Apparently, the verbal information provided during the demonstration yielded a more durable representation, the verbal information provided at the time of the test served as an effective retrieval cue, or some combination of both. Irrespective of the mechanism(s) involved, the addition of verbal cues altered infants’ memory performance when they were tested after a long delay.

Generalization. When young infants are tested in a traditional deferred imitation paradigm in which there is no opportunity to practice the target actions and no verbal information is provided, they do not generalize to stimuli that differ from those present during the original demonstration (Hayne et al., 2000a, 1997). Both the opportunity to practice and the provision of verbal cues have been shown to facilitate generalization (Barr & Hayne, 2000; Hayne, Barr, & Herbert, 2003; Herbert et al., 2000). To assess the effects of prior practice, independent groups of 18-month-old infants were randomly assigned to a practice or a no practice condition. For

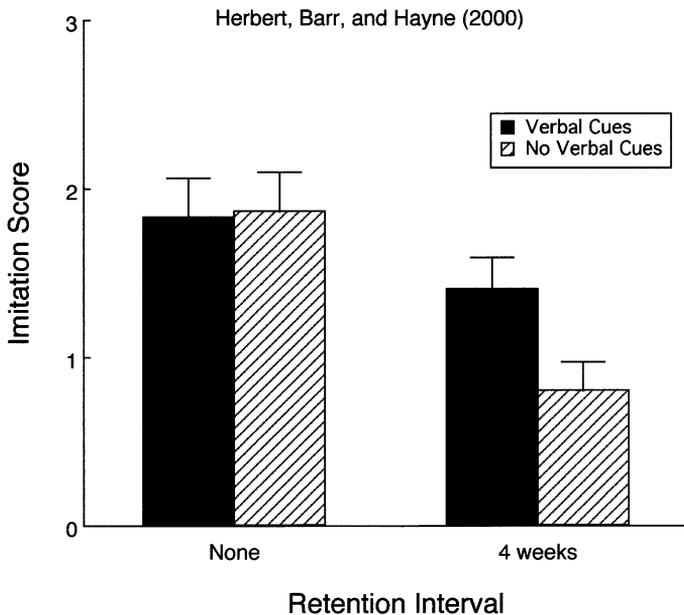


Fig. 1. Imitation scores of 18-month-old infants who were tested immediately after the demonstration or after a 4-week delay. Half of the infants received verbal cues during the demonstration and prior to the test and half did not.

infants in the practice condition, the experimenter demonstrated the target actions three times and the infant was given the opportunity to practice the target actions three times. For infants in the no practice condition, the experimenter demonstrated the target actions six times—the additional three demonstrations were added to provide infants in both conditions with equivalent duration of exposure to the stimuli and to the target actions.

All infants were tested after a 24-h delay. Half of the infants in each condition were tested with the same object that had been used during the demonstration and the other half were tested with a different object that could be used to perform the same actions. Although infants in both conditions exhibited excellent retention when they were tested with the same object, only infants who had been given prior practice exhibited retention when tested with the novel object. This finding has been replicated in two separate experiments using two different sets of stimuli and target actions (see Fig. 2).

Similarly, the provision of verbal cues also enhances generalization. For example, Herbert and Hayne (2000b) provided 18- and 24-month-old infants with a unique verbal label for the objects that were used during the demonstration and during the test 24 h later. Although the verbal labels had no effect on infants' performance when they were tested with the same stimuli that were used during the original demonstration, the verbal labels did influence infants' generalization to novel test stimuli. Furthermore, the effect of verbal cues varied as a function of age. The verbal labels increased generalization by 24-month-olds, but had no effect on generalization by 18-month-olds (see Fig. 3).

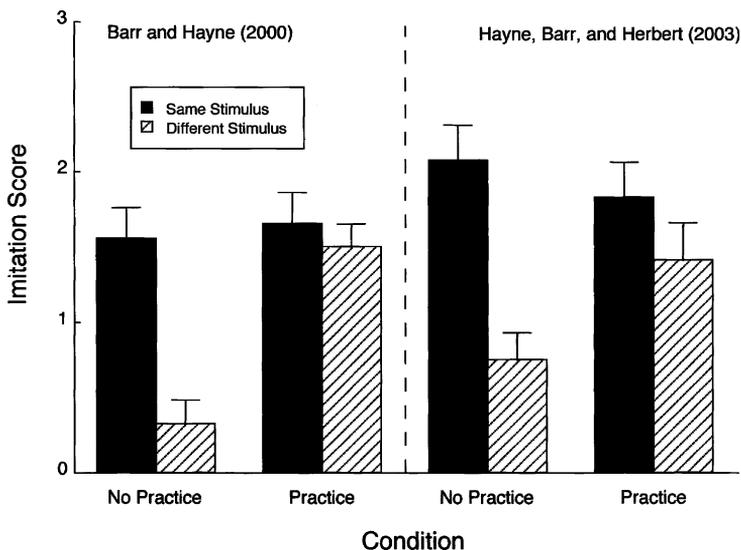


Fig. 2. Imitation scores of 18-month-old infants who were tested with the same stimuli that were used during the original demonstration or with different stimuli. Half of the infants were given the opportunity to practice the target actions prior to the test and half were not.

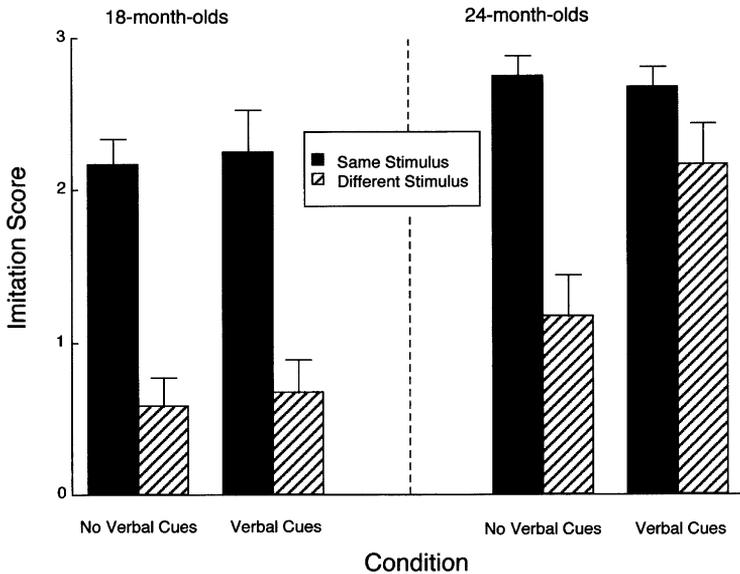


Fig. 3. Imitation scores of 18- and 24-month-old infants who were tested with the same stimuli that were used during the original demonstration or with different stimuli. Half of the infants were provided with a unique verbal label for the stimuli at the time of the demonstration and at the time of the test and half were not.

Delayed-nonmatching-to-sample paradigm

As described earlier, some of the tasks currently used to study memory development in human infants were derived from procedures originally used to study memory in animals. The standard delayed-nonmatching-to-sample (DNMS) procedure used with human infants, for example, is based on a procedure originally used with nonhuman primates (Bachevalier & Mishkin, 1984). In the standard DNMS task, infants participate in two kinds of trials. On sample trials, an object (i.e., sample) is placed over a well that contains a reward. After the infant removes the object and finds the reward, a screen is lowered between the infant and the sample object. After a delay, the screen is raised revealing the sample and a novel object. On these test trials, the reward is always hidden under the novel object. If the infant responds correctly by displacing the novel object, then he or she is allowed to retrieve the reward. If the infant responds incorrectly, then the experimenter reveals the reward under the novel object but does not let the infant have it. Typically, a new pair of objects is used on every trial (i.e., trial-unique stimuli).

Human infants do not succeed on the standard version of the DNMS task until midway through their second year of life (Diamond, 1990; Overman, 1990). In most studies, they do not reliably choose the novel stimulus until approximately 15–21 months of age, even when the delay between the sample trial and the test trial is only 5–10 s (Diamond, Towle, & Boyer, 1994; Overman, Bachevalier, Turner, & Peuster, 1992).

The prolonged time course for the development of DNMS performance is somewhat surprising given that the retention interval between sample and test trials is extremely brief (i.e., 5–10 s). Clearly, infants as young as 2–6 months of age have been shown to remember over much longer delays when they are tested using VRM (Fagan, 1973), operant conditioning (Hartshorn et al., 1998a), or deferred imitation procedures (Barr et al., 1996; Collie & Hayne, 1999; Hayne et al., 2000a). These findings raise the distinct possibility that age-related changes in something other than memory is responsible for young infants' poor performance in the standard version of the DNMS task.

Research by Diamond and her colleagues (Diamond, 1995; Diamond, Churchland, Cruess, & Kirkham, 1999) has shown that minor changes in the behavioral requirements of the DNMS task can dramatically alter its developmental time course. For example, in the standard version of the DNMS task, infants are required to displace the novel test stimulus in order to retrieve a reward that is placed beneath it. Alternatively, when the infant's reward is simply the opportunity to play with the novel test stimulus (i.e., stimulus = reward), infants solve the task at 6 months of age and perform significantly above chance after delays as long as 10 min (Diamond, 1995). Similarly, infants' performance on the task is also enhanced when verbal praise of the correct choice is used as the only reward (Diamond et al., 1999).

Taken together, these findings have led Diamond (1990, 1995; Diamond et al., 1999) to conclude that memory development is not the rate-limiting step in DNMS performance. Rather age-related changes in infants' ability to grasp the relation between the stimulus and the reward and their ability to inhibit a previously rewarded response make it extremely difficult for young infants to master the standard task. When these aspects of the tasks are removed, then infants' mastery of DNMS falls directly in line with their ability to master other memory tasks.

Classical eyeblink conditioning

Classical conditioning paradigms have been used for decades to study learning and memory in both human and nonhuman adults (for review, see Woodruff-Pak & Steinmetz, 2000a, 2000b). In a typical experiment, a neutral stimulus, such as a tone or a light (CS), is paired with an unconditioned stimulus, such as a shock or a loud noise (US). Prior to conditioning, the US elicits a response (UR), but the CS does not. Over successive CS–US pairings, however, the CS begins to elicit a response (CR) even when it is presented prior to or in the absence of the US.

There are two versions of the classical conditioning paradigm. In the *delay-conditioning* version of the paradigm, the presentation of the CS precedes presentation of the US, however, both overlap at some point and co-terminate. In the *trace-conditioning* version of the paradigm, the CS also precedes the US, however, it terminates prior to onset of the US. Furthermore, there is a brief temporal gap between the termination of the CS and the onset of the US. The most widely used classical conditioning task involves eyeblink conditioning. In this task, the neutral stimulus (CS) is paired with a puff of air delivered to the cornea (US). Prior to conditioning, only the US elicits a reflexive eyeblink, but over successive pairings, presentation of the CS alone is sufficient to elicit the eyeblink response.

A small, but growing body of research has documented evidence of classical eyeblink conditioning in human infants (Clafin, Stanton, Herbert, Greer, & Eckerman, 2002; Fitzgerald & Brackbill, 1976; Herbert, Eckerman, & Stanton, 2003; Ivkovich, Collins, Eckerman, Krasnegor, & Stanton, 1999; Little, Lipsitt, & Rovee-Collier, 1984). In Ivkovich et al. (1999), for example, 4- and 5-month-olds experienced repeated pairings of a tone and an airpuff in a delay version of the eyeblink conditioning task. Although infants of neither age exhibited evidence of conditioning within the first session, they did exhibit a high percentage of CRs at the outset of the second session that was conducted one week later. Subsequent research has also shown that 5-month-olds exhibit evidence of conditioning in the trace version of the procedure, however, their performance is inferior to that of adults who are tested under the same conditions (Herbert et al., 2003).

Although systematic studies of the ontogeny of human eyeblink conditioning are still in their infancy, this task, like the VRM task, has considerable potential for a systematic analysis of human memory development. Because eyeblink conditioning does not rely on verbal instructions or responses and because the motor requirements of the task are extremely minimal, it should be possible to use the task to trace memory development across the lifespan. Furthermore, because the neural circuitry required for the task has been clearly established (Ivkovich & Stanton, 2001; Thompson, 1986), the ontogeny of human eyeblink conditioning may provide a unique window into the development of the human brain.

Event-related potentials

Event-related potentials (ERPs) may also help us to establish the link between memory development and maturation of the human central nervous system. ERPs are defined as transient voltage changes in the brain that occur in response to discrete visual or auditory events. In studies conducted with human adults, ERPs are recorded through scalp electrodes while the participant is engaged in some kind of memory task. There are a number of components to the neural response that is invoked under these conditions, but there is an emerging consensus that the P300 component of the response yields at least one neural measure of memory.

Unlike other *in vivo* measures of human brain function (e.g., fMRI, PET), ERPs can be studied in human infants (Carver, Bauer, & Nelson, 2000; Nelson, 1997b; Nelson & Collins, 1992; Nelson, Thomas, de Haan, & Wewerka, 1998). In the infant version of the task, ERPs are recorded through scalp electrodes while infants view a series of brief, visual or auditory stimuli—some of these stimuli have been encountered before and some are novel. Although infants do not show the P300 component that is commonly seen in adults, they do show a positive slow wave component that occurs selectively in response to familiar stimuli. On the basis of these findings, Nelson has speculated that this positive slow wave is the developmental precursor to P300. This speculation is bolstered by the finding that this slow-wave activity is related to other, behavioral indices of memory (Carver et al., 2000). When and if this slow wave evolves into a P300 component has yet to be determined, but age-related changes in the topography of ERP continue to occur until at least middle childhood (Thomas & Nelson, 1996).

What kind of memory each task measure?

Despite the fact that all of the methods described above are used to measure infant memory, there is often heated debate about the kind of memory that each task measures (Nelson, 1995; Schacter & Moscovitch, 1984; Rovee-Collier et al., 2001). At the center of this debate is the notion that “memory” consists of at least two, dissociable systems. The idea that there is more than one memory system grew out of studies conducted with human adults who had suffered damage to the hippocampal formation and its associated medial temporal-lobe structures (Milner, Corkin, & Teuber, 1968; Scoville & Milner, 1957). Although these individuals experienced dense anterograde amnesia, they showed near normal retention when tested on tasks of motor-skill learning or perceptual priming. These spared memory skills gave rise to the notion that memory is not a unitary process, but rather is composed of two (or more) dissociable systems that serve different functions and operate according to different principles (for review, see Squire & Schacter, 2002).

A number of different theoretical distinctions have been proposed to describe these hypothetical memory systems, but the two that are most commonly cited are *declarative* versus *nondeclarative* memory (Squire, 1994) and *explicit* versus *implicit* memory (Graf & Schacter, 1985; Schacter, 1994). Although these two dichotomies are not identical, they share the fundamental assumption that one memory system supports higher-order memory processes and conscious recollection (i.e., declarative memory and explicit memory), while the other system supports lower forms of memory like habit formation, skill learning, and priming (nondeclarative memory and implicit memory). These distinctions were originally established through studies conducted with human adults, however, there has been ample speculation that these multiple memory systems might also emerge at different rates during the course of normal development.

Given the nonverbal nature of infant memory, how can we ever determine if infants have access to one memory system or the other? In studies conducted with adults, at least two strategies have been used to assign memory tasks to memory systems. The *amnesia filter*, pioneered by Squire and his colleagues, uses the performance of human adults with temporal-lobe amnesia as the benchmark for task assignment (for review, see Squire & Schacter, 2002). For example, memory tasks that amnesiacs can solve are considered to require nondeclarative or implicit memory, while memory tasks that amnesics fail are considered to require declarative or explicit memory.

If we apply the amnesia filter to studies conducted with human infants, then many of the tasks described above would be assigned to the declarative or explicit category (see Table 1). For example, human adults who suffer from temporal-lobe amnesia fail when tested using VRM (McKee and Squire, 1983), imitation (McDonough et al., 1995), trace eyeblink conditioning (Clark & Squire, 1998), and ERP procedures (Olichney et al., 2000) similar to those that have been used with human infants. In contrast, human adults who suffer from temporal-lobe amnesia perform normally when tested on the standard version of the DNMS paradigm (Squire et al., 1988). They also perform normally on the delay version of the classical eyeblink conditioning paradigm (Clark & Squire, 1998; Weiskrantz & Warrington, 1979).

Table 1
Amnesia filter for tasks used to study infant memory

Infant task	Pass filter	Sample references
VRM	+	McKee and Squire (1993)
Mobile and train tasks	*	
Imitation	+	McDonough, Mandler, McKee, and Squire (1995)
DNMS	-	Squire, Zola-Morgan, and Chen (1988)
ERP	+	Olichney et al. (2000)
Eyeblink conditioning		
Delay	-	Weiskrantz and Warrington (1979)
Trace	+	Clark and Squire (1998)

+ Adults with temporal lobe amnesia fail these tasks.

- Adults with temporal lobe amnesia pass these tasks.

* No relevant data available.

On the basis of these findings, at least four of the tasks used to assess infant memory processing would pass the amnesia filter and be assigned to the declarative or explicit memory category (VRM, imitation, trace version of classical eyeblink conditioning, ERP). Two additional tasks, DNMS and the delay version of classical eyeblink conditioning, would not. For obvious reasons, human adults have not been tested using the mobile conjugate reinforcement or train paradigms, so the amnesia filter is agnostic with respect to these particular tasks.

Some researchers have argued that the amnesia filter is an inappropriate way to assign infant memory tasks to memory systems (for reviews see Rovee-Collier, 1997; Rovee-Collier et al., 2001). From a developmental perspective, there has been considerable concern about the validity of drawing analogies between brain-damaged adults and normally developing human infants. In light of this concern, the other strategy that has been used to assign memory tasks to memory systems is to assess the independent variables that influence performance in a particular task. According to this *parameter filter*, retention on tasks that are thought to tap declarative or explicit memory are influenced by independent variables that do not influence performance on tasks that are thought to tap nondeclarative or implicit memory, and vice versa.

Tulving (1983) referred to the relation between tasks and independent variables as the *rule of experimental dissociation*. Rovee-Collier (1997) was the first to apply the rule of experimental dissociation to memory research conducted with human infants. As shown in Table 2, infants' memory performance in the mobile conjugate reinforcement and train paradigms is influenced by the same independent variables that influence adults' performance on declarative or explicit memory tasks. That is, consistent with studies conducted with normal adults, infant retention in the mobile and train paradigms is influenced by age, retention interval, context change, interference, study time, levels of processing, and the serial position of the target item (see Rovee-Collier, 1997 for a complete review). On the basis of these findings, Rovee-Collier has argued that if there are two distinct memory systems, then they both emerge early in ontogeny and develop in parallel, not sequentially, during the infancy period.

Table 2

Parameter filter for the mobile conjugate reinforcement and train tasks (see Rovee-Collier, 1997)

Independent variable	Pass filter	Sample references
Age	+	Davis and Rovee-Collier (1983); Hill et al. (1988)
Retention interval	+	Hartshorn et al. (1998a); Rovee-Collier, Sullivan, Enright, Lucas, and Fagen (1980)
Context change	+	Borovsky and Rovee-Collier (1990); Butler and Rovee-Collier (1989); Hartshorn et al. (1998b)
Interference	+	Amabile and Rovee-Collier (1991); Boller and Rovee-Collier (1994)
Study time	+	Ohr, Fagen, Rovee-Collier, Hayne, and Vander Linde (1989)
Level of processing	+	Adler, Gerhardstein, and Rovee-Collier (1998)
Serial position	+	Gulya, Galluccio, Wilk, and Rovee-Collier (2001)

+ Performance is influenced by the same variables that influence adults' performance on declarative or explicit memory tasks.

- Performance is not influenced by the same variables that influence adults' performance on declarative or explicit memory tasks.

Since the publication of Rovee-Collier's analysis of infant memory based on the the two experimental procedures developed in her laboratory, data collected using two other experimental procedures have emerged that support her conclusions. As shown in Table 3, infants' performance in the VRM and deferred imitation paradigms is also influenced by at least some of the same independent variables that influence adults' performance in declarative or explicit memory tasks. For example, retention in the VRM paradigm is influenced by participant age, retention interval, and contextual change (Bahrick & Pickens, 1995; Bahrick et al., 1997; Courage & Howe, 1998, 2001; Morgan & Hayne, 2002; Pascalis & Robinson, 2001). Similarly, retention in the deferred imitation paradigm is influenced by participant age,

Table 3

Parameter filter for other tasks used to study infant memory

Infant task	Pass filter	Sample references
VRM	+	Morgan and Hayne (2002) ^{a,b} , Courage and Howe (2001, 1998) ^b , Pascalis and Robinson (2001) ^c
Imitation	+	Barr et al. (1996) ^a , Barr and Hayne (2000) ^b , Herbert and Hayne (2000a) ^b , Hayne, Gross, Hildreth, and Rovee-Collier (2000b) ^c
DNMS	-	Diamond et al. (1994) ^{a,b} , Diamond (1995) ^b
ERP	*	
Eyeblink conditioning	*	

+ Performance is influenced by the same variables that influence adults' performance on declarative or explicit memory tasks.

- Performance is not influenced by the same variables that influence adults' performance on declarative or explicit memory tasks.

* No relevant data available.

^a Effects of age.

^b Effects of retention interval.

^c Effects of context change.

Table 4

The age at which infants first solve tasks that might measure declarative or explicit memory

Infant task	Infant age	Sample references
VRM	Newborns	Pascalis et al. (1995)
Mobile Task	2 months	Hayne, Greco, Earley, Griesler, and Rovee-Collier (1986)
Train Task	6 months	Hartshorn and Rovee-Collier (1997)
Imitation		
Facial expressions	6 weeks	Meltzoff and Moore (1994)
Actions with objects	6 months	Barr et al. (1996), Collie and Hayne (1999), Hayne et al. (2000b)
ERP	4–8 months	Nelson and deRegnier (1992)
Eyeblink conditioning	5 months	Herbert et al. (2003)

retention interval, and contextual change (Barr & Hayne, 2000; Hayne et al., 2000a; Herbert & Hayne, 2000b).

Taken together, studies conducted using three of the infant memory procedures described here have shown that retention in these tasks is influenced by the same factors that influence retention in other tasks of declarative or explicit memory. In contrast, once infants can acquire the standard DNMS task, their performance appears to be relatively insensitive to age (Diamond et al., 1994) or retention interval (Diamond, 1995; Diamond et al., 1994). These findings suggest that the DNMS task may yield a measure of nondeclarative or implicit memory. To date, systematic work on the effects of these independent variables on other measures of infant memory have yet to be conducted.

Thus, if we apply the same strategies that are typically used to assign memory tasks to memory systems in adult participants to work conducted with human infants, then we are forced to conclude that very early in development, infants exhibit higher-order memory skills that meet the definition of declarative or explicit memory. Table 4 shows the youngest age at which infants have been shown to solve a given memory task. As shown in Table 4, many of these tasks are accomplished very early in development. Thus, if we are going to argue that there is more than one memory system (but see Roediger, 1990; Tulving, 1985), then we also have to argue that infants have at least rudimentary access to both systems by the age of 6 months, and perhaps even earlier.

Principles of infant memory development

Data collected with human newborns clearly shows that the capacity for memory is a nascent skill (DeCasper & Fifer, 1980; DeCasper & Spence, 1986; Pascalis et al., 1995). Despite the precocious emergence of memory, however, there are a number of important differences in the memory skills exhibited by newborns and those exhibited by older infants and toddlers. On the basis of data collected using the VRM, operant conditioning, and imitation paradigms, it is now possible to outline four general principles of memory development during the infancy period. These principles are derived from adult models of human memory that include encoding, retention, and retrieval as their central mechanisms (Estes, 1976; Spear, 1978; Tulving,

1983). Age-related changes in these mechanisms may provide important clues about the source of childhood amnesia.

Principle 1: Older infants encode information faster

Although James (1890) is well recognized for his characterization of infant mental life as a “blooming, buzzing confusion,” even newborns can encode information about their environment and distinguish that information from novel information that they subsequently encounter. The speed with which original encoding occurs, however, increases dramatically as a function of age, at least during the first year of life. In the VRM task, for example, older infants exhibit novelty preferences following shorter familiarization periods than do younger infants (Hunter & Ames, 1988). Similarly, in the mobile conjugate reinforcement paradigm, the time it takes infants to meet the initial learning criterion decreases as a function of age: 2-month-olds typically meet the learning criterion within 3–6 min (Davis & Rovee-Collier, 1983), 3-month-olds typically meet the learning criterion within 2–3 min (Greco, Rovee-Collier, Hayne, Griesler, & Earley, 1986), and 6-month-olds typically meet the learning criterion within 1 min (Hill et al., 1988).

Finally, older infants have also been shown to encode information faster than younger infants in tests of deferred imitation. In two different published reports, 12-, 18-, and 24-month-old infants exhibited deferred imitation following a 24-h delay after observing the target actions modeled only three times over a single 20- to 30-s period; 6-month-olds, on the other hand, required twice as much exposure to the same target actions in order to exhibit imitation following the same delay (Barr et al., 1996; Hayne et al., 2000a).

Principle 2: Older infants remember longer

Without exception, the most complete picture of age-related changes in long-term retention during the infancy period has been obtained using the mobile conjugate reinforcement and train paradigms. The primary advantage of these paradigms is that, because all infants are trained to the same criterion, it is possible to assess age-related changes in retention that are independent of age-related changes in original encoding (see also, Howe & Courage, 1997b). A similar, unambiguous analysis of long-term retention has been much more difficult to obtain in studies using other procedures where age-related changes in performance prior to the retention interval often preclude conclusions about age-related changes in retention per se (Bauer et al., 2000).

When infants of the same age are tested in the mobile conjugate reinforcement and train paradigms, their performance is virtually identical (Hartshorn & Rovee-Collier, 1997). This finding has provided the unique opportunity to assess age-related changes in long-term retention in infants who range from 2- to 18-months of age. In Hartshorn et al. (1998a), 2- to 18-month-old infants were tested in either the mobile task (2- to 6-month-olds) or the train task (6- to 18-month-olds). Independent groups of infants of each age were then tested after delays ranging from 24 h to 15 weeks. As shown in Fig. 4, the maximum duration of retention increased linearly

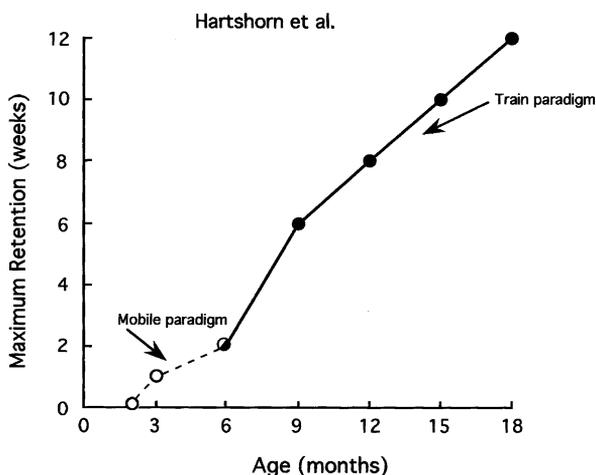


Fig. 4. Age-related changes in the duration of retention by 2- to 18-month-olds tested in the mobile conjugate reinforcement and train paradigms. Copyright © (1998). Reprinted by permission of John & Wiley Sons, Inc.

as a function of age. The absolute difference in retention was also striking—although 2-month-olds only exhibited retention when they were tested after a 24-h delay, 18-month-olds exhibited retention for as long as 13 weeks.

Despite the difficulty in establishing equivalent levels of initial encoding by infants of different ages, at least two studies of deferred imitation have yielded evidence for an age-related increase in the duration of retention. For example, Barr and Hayne (2000) found that 6- and 12-month-olds exhibited equivalent imitation scores when they were tested immediately after the demonstration, but 12-month-olds remembered significantly longer (see Fig. 5). For 6-month-olds, the maximum duration of retention was 24 h while for 12-month-olds, the maximum duration of retention was 1 week. Similarly, Herbert and Hayne (2000a) found that although 18- and 24-month-olds exhibited the same level of imitation immediately after the demonstration, 24-month-olds remembered six times longer (see Fig. 6).

Additional support for the notion that there are age-related changes in long-term retention has come from studies conducted using the VRM procedure. In a recent attempt to use the VRM procedure to assess age-related changes in long-term retention, Morgan and Hayne (2002) tested 1-, 2-, 3-, and 4-year-olds either immediately after original familiarization or after delays ranging from 1 day to 1 month. Participants of all ages were familiarized with a brightly colored, animated stimulus for a 10-s period. Independent groups of participants of each age were then tested either immediately or after delays ranging from 1 day to 1 month. Although there was no age-related difference in novelty preference scores when participants were tested immediately after familiarization, when tested after a delay, there was a dramatic age-related increase in long-term retention. As shown in Fig. 7, 1-year-olds exhibited retention only when tested immediately after familiarization, 2-year-olds remembered for as long as 1 day, 3-year-olds remembered for as long as 1 week,

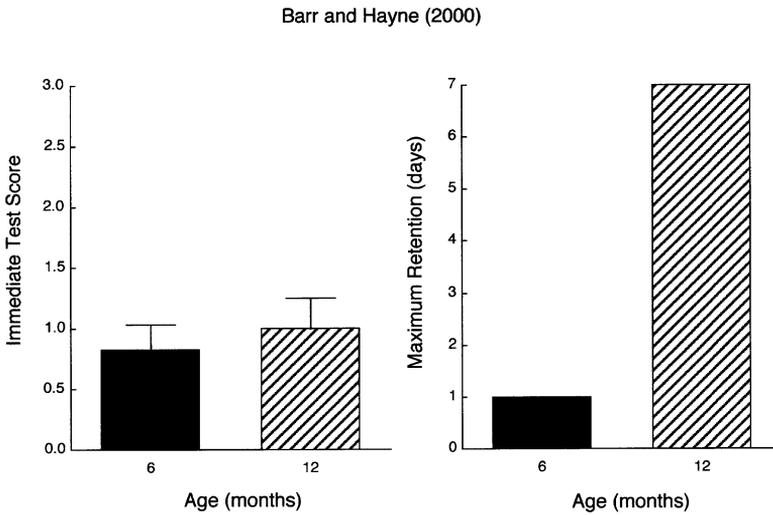


Fig. 5. Imitation scores of 6- and 12-month-old infants tested immediately after the demonstration in the deferred imitation paradigm (left panel). Age-related changes in the duration of retention by 6- and 12-month-olds tested in the deferred imitation paradigm (right panel).



Fig. 6. Imitation scores of 18- and 24-month-old infants tested immediately after the demonstration in the deferred imitation paradigm (left panel). Age-related changes in the duration of retention by 18- and 24-month-olds tested in the deferred imitation paradigm (right panel).

and 4-year-olds remembered for as long as 1 month. These findings confirm findings previously obtained with the mobile conjugate reinforcement, train, and imitation paradigms and suggest that the age-related changes in long-term retention that begin in infancy extend into early childhood (and beyond).

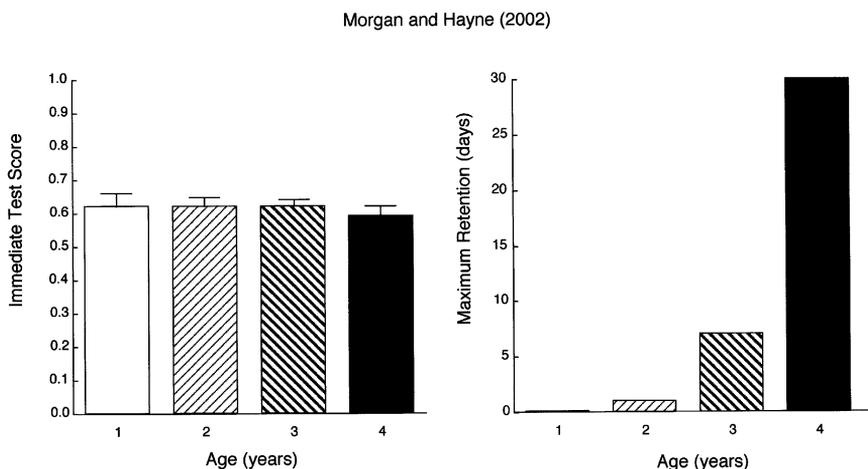


Fig. 7. Novelty preference scores of 1- to 4-year-old children tested immediately after familiarization in the VRM paradigm (left panel). Age-related changes in the duration of retention by 1- to 4-year-old children tested in the VRM paradigm (right panel).

Principle 3: Older infants exploit a wider range of retrieval cues

Prior research has shown that memory retrieval by young infants is characterized by Tulving's (1983) Encoding Specificity Hypothesis in extremis. That is, early in development, memory retrieval occurs if and only if the cues present at the time of retrieval are virtually identical to the cues present at the time of original encoding. In the mobile conjugate reinforcement paradigm, for example, 2- to 6-month-olds exhibit no retention whatsoever if they are tested with mobiles that are different to those encountered during original encoding. In fact, 2- and 3-month-olds exhibit no retention when they are tested with a mobile that contains more than one novel component (Hayne et al., 1986).

This high degree of specificity has also been documented in studies using deferred imitation procedures (Hayne et al., 2000a, 1997; Herbert & Hayne, 2000b). For example, 6- and 12-month-olds exhibit no retention when they are tested with objects that differ from those present during the original demonstration. In fact, retrieval is impaired when only the color or the shape of the object is altered (Hayne et al., 1997). This high degree of specificity also extends to changes in contextual cues. In both the mobile conjugate reinforcement (Borovsky & Rovee-Collier, 1990; Butler & Rovee-Collier, 1989) and deferred imitation paradigms (Hayne et al., 2000a), changes in context disrupt retrieval by 2- to 6-month-olds.

Subsequent research with older infants has shown that one hallmark of memory development is an age-related *increase* in the flexibility of memory retrieval. Between the ages of 6- and 30-months, for example, the range of effective retrieval cues for a particular memory gradually broadens, allowing older participants to access their memory representations in a wider range of situations (Barr & Hayne, 2000; Hartsorn et al., 1998b; Hayne et al., 2000a, 1997; Herbert & Hayne, 2000b). In studies of

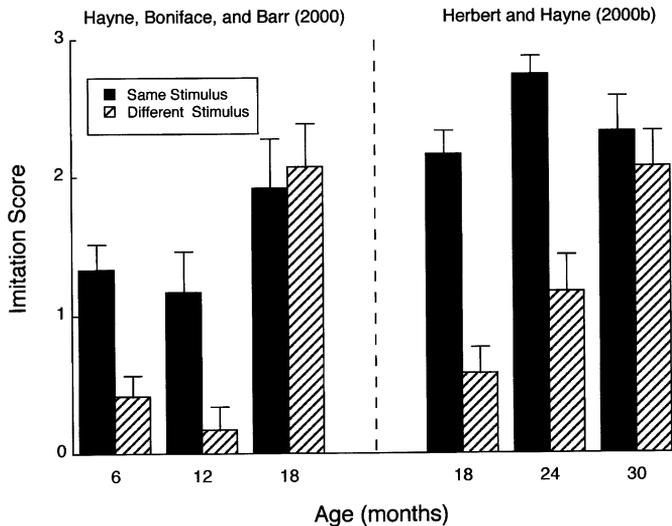


Fig. 8. Imitation scores of 6- to 30-month-old infants who were tested with either the same stimulus that was present during the original demonstration or a different one.

deferred imitation, changes in stimuli between the demonstration and the test preclude memory retrieval by young infants but have no effect on the performance of infants 18-months old and older (Hayne et al., 2000a, 1997). When the task is made more difficult, however, changes in stimuli preclude retrieval by 18-month-olds, impair performance by 24-month-olds, and have no effect on the performance of 30-month-olds (Herbert & Hayne, 2000b; see Fig. 8). Changes in the mobile or train also preclude retrieval by young infants who are tested in operant conditioning paradigms, but these same changes have little or no effect on memory retrieval by 12-month-olds (Hartshorn et al., 1998b, see Fig. 9).

There is also evidence to suggest that changes in contextual cues become less disruptive as a function of age. In studies of deferred imitation, for example, changes in the environmental context preclude memory retrieval by 6-month-olds, but the same changes have no effect on memory retrieval by infants who are 12-months old and older (Barnat, Klein, & Meltzoff, 1996; Hanna & Meltzoff, 1993; Hayne et al., 2000a; Klein & Meltzoff, 1999, see Fig. 10). A similar age-related change in the effect of novel contextual cues has also been shown for infants tested in the train paradigm (Hartshorn et al., 1998b).

Principle 4: Forgotten memories can be retrieved through the presentation of a reminder

In 1966, Campbell and Jaynes revolutionized our thinking about forgetting during the infancy period. They showed that, despite rapid forgetting, infantile memories could be retained over significant periods of development. In their hallmark study, 25-day-old weanling rat pups were trained in a traditional Pavlovian

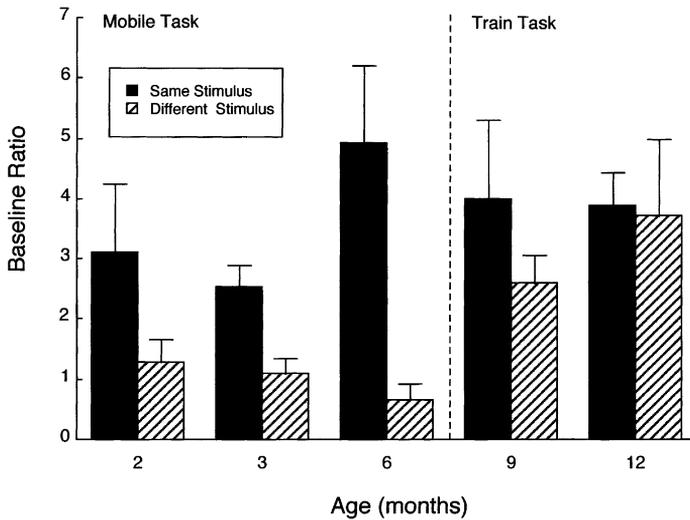


Fig. 9. Baseline ratios of 2- to 12-month-old infants who were tested with either the same stimulus that was present during original acquisition or a different one.

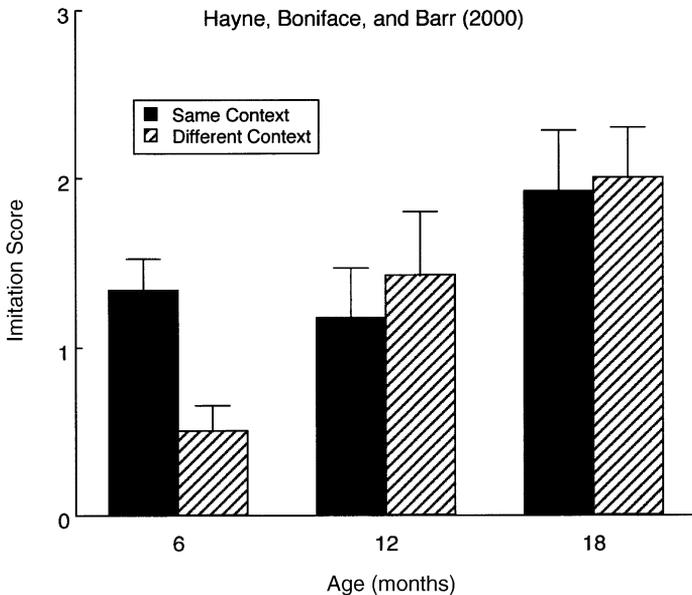


Fig. 10. Imitation scores of 6- to 18-month-old infants who were tested in either the same context in which the demonstration occurred or in a different one.

fear-conditioning paradigm in which shocks were presented on the black side of a black/white shuttle box. Pups were placed on the white side of the apparatus for an equivalent period of time, but they were never shocked there. During the reten-

tion interval, subjects in the experimental group were returned to the apparatus for weekly reminder treatments. During the reminder treatment, each rat pup was placed on the black side for a 2-min period and was given a single shock; the pup was then placed on the white side of the apparatus for the same amount of time, but was given no shocks. This reminder procedure was repeated weekly during the 28-day retention interval.

The retention test occurred 7 days after the final reminder or 28 days after the conclusion of training. To ensure that forgetting did occur over the 28-day retention interval, one control group received identical training but no interpolated reminder treatments. To assess the effects of the reminder treatments per se, a second control group received the reminder treatments without prior training. Campbell and Jaynes reported that, in the absence of the reminder treatments, forgetting was complete after the 28-day retention interval. Furthermore, in the absence of prior training, the interpolated reminder treatments were insufficient to yield retention. Only the group that was both trained and reminded exhibited retention after the 28-day delay.

In the original Campbell and Jaynes (1966) experiment, the reminder was presented weekly during the retention interval. Subsequent research, however, also indicated that a single reminder presented at the end of the retention interval also improves long-term retention. In 1976, for example, Spear and Parsons used a training procedure similar to that used by Campbell and Jaynes but rather than administering multiple reminder treatments throughout the retention interval, administered a single treatment 24 h prior to the long-term test. This single treatment yielded retention identical to that observed following multiple reminder treatments distributed throughout the retention interval.

In the seminal demonstration of the reminder phenomenon with human infants, Rovee-Collier and her colleagues found that, despite substantial forgetting, 3-month-old infants exhibited excellent retention if they were exposed to a single reminder treatment 24 h prior to the long-term test (Rovee-Collier et al., 1980). In that experiment, 3-month-old infants were trained in the mobile conjugate reinforcement paradigm. Infants in the experimental group received a 3-min exposure to the training mobile that was moved noncontingently by the experimenter 24 h prior to the long-term test, which occurred 14 days after the conclusion of training. To ensure that forgetting occurred over the 14-day retention interval in the absence of reminding, one control group received identical training but no interpolated reminder treatment. To assess the effect of the reminder per se, a second control group received the reminder treatment without prior training.

In the absence of the reminder treatment, there was substantial forgetting after the 14-day retention interval. Furthermore, in the absence of prior training, the reminder treatment was insufficient to yield retention. In contrast, the experimental group that was both trained and reminded exhibited excellent retention after the 14-day delay. In fact, the performance of this group was identical to that typically seen 24 h after the conclusion of training. Furthermore, the rate of forgetting following the reminder treatment was identical to that following original training.

Subsequent research with human infants has shown that the reminder phenomenon is extremely pervasive. Reminder effects have not only been documented in

numerous studies using the mobile conjugate reinforcement paradigm, but they have also been obtained in studies using the train (Hartshorn & Rovee-Collier, 1997), imitation (Decampo & Hudson, 2003; Hayne et al., 2003; Hudson & Sheffield, 1998; Sheffield & Hudson, 1994), and VRM paradigms (Cornell, 1979). Within these tasks, a wide range of reminder treatments have been shown to alleviate forgetting including exposure to the original training context (Hayne & Findlay, 1995; Rovee-Collier, Griesler, & Earley, 1985, 1985) and videos or photographs of the original event (Decampo & Hudson, 2003; Hudson & Sheffield, 1999).

The original studies of reminding with human infants involved single reminder treatments similar to those used by Spear and Parsons (1976). Subsequent research has shown that repeated reminder treatments prolong retention (Hartshorn, 2003; Hayne, 1990); speed retrieval (Hayne et al., 2000b), and increase the range of effective retrieval cues (Hitchcock & Rovee-Collier, 1996) relative to that seen following a single reminder treatment. In fact, Hartshorn (2003) has shown that repeated retrieval throughout the retention interval can maintain a memory over a 1½-year period. That is, infants who were initially trained at 6-months of age exhibited excellent retention when they were tested at the age of 2 years if they were periodically reminded during the delay between original acquisition and the test.

Although reminder treatments have been shown to alleviate forgetting by both infants and toddlers, five age-related changes in the effect of reminder treatments have been documented over the first two years of life. First, the retention interval after which a single reminder treatment will alleviate forgetting increases as a function of age (cf. Greco et al., 1986; Hildreth & Rovee-Collier, 2002). For example, when trained to the same criterion in operant conditioning paradigms, 2-month-olds can be reminded after a retention interval of 18 days while 12-month-olds can be reminded after a retention interval of 9 weeks. Second, once the memory has been retrieved through reminding, the duration of subsequent retention also increases as a function of age. For example, 6-month-olds exhibit retention for 2 weeks following an effective reminder treatment, while 12-month-olds exhibit retention for a period of 12 weeks (Hildreth & Rovee-Collier, 2002).

Third, the minimum duration of an effective reminder decreases as a function of age (cf. Joh, Sweeney, & Rovee-Collier, 2002; Sweeney & Rovee-Collier, 2001). When the total retention interval is held constant, for example, 6-month-olds exhibit retention following exposure to a 7.5 s reminder treatment, while 3-month-olds require a 180 s exposure to the same reminder. Fourth, the speed with which the target memory is recovered increases as a function of age (cf. Boller, Rovee-Collier, Borovsky, O'Connor, & Shyi, 1990; Fagen & Rovee-Collier, 1983; Hildreth & Rovee-Collier, 1999). For example, when trained in the operant train paradigm, 6-month-olds exhibit retention for the first time when they are tested 60 min after exposure to the reminder; 12-month-olds, on the other hand, gain access to the memory almost immediately (Hildreth & Rovee-Collier, 1999).

Finally, the range of effective reminder treatments also increases as a function of age. Prior work with 2- to 6-month-olds trained in the mobile conjugate reinforcement paradigms has shown that, in order to be effective, a reminder must match the stimuli present at the time of original encoding almost exactly (for review, see

Rovee-Collier & Hayne, 1987). Changes in either the proximal stimuli (e.g., the mobile; Rovee-Collier, Patterson, & Hayne, 1985) or in the environmental context (Borovsky & Rovee-Collier, 1990; Butler & Rovee-Collier, 1989; Hayne, Rovee-Collier, & Borza, 1991) at the time of the reminder decrease or preclude its effectiveness in alleviating forgetting. Studies conducted using the operant train paradigm have confirmed that, for 6-month-olds, a reminder must be highly specific to the conditions of original training, but that 12-month-olds can be successfully reminded in a novel environmental context (DeFrancisco, 2003).

Taken together, data collected using reminder treatments clearly show that the long-term accessibility of early memories increases throughout the infancy period.

Implications for childhood amnesia

What are the implications of empirical research on infant memory development for the phenomenon of childhood amnesia? The data described thus far rule out any explanation of childhood amnesia that relies upon a qualitative shift from one memory system to another. The finding that even 6-month-olds exhibit memory skills that meet the definition of declarative or explicit memory casts doubt on the notion that childhood amnesia results from infants' inability to encode information in a declarative or explicit format. Furthermore, empirical research on infant memory has shown that changes in encoding, retention, and retrieval occur gradually as a function of age. These data rule out any explanation for childhood amnesia that relies on an abrupt, stage-like transition in memory processing.

I concur with Spear (1979) that a clear explanation of childhood amnesia is contingent upon careful examination of memory development per se. The data available thus far highlight three memory-related achievements that may help children scramble over the childhood amnesia barrier during their second or third year of life. First, the speed with which infants encode information increases as a function of age. Thus, under the same encoding conditions, older infants undoubtedly establish richer memory representations than those of their younger counterparts (Rovee-Collier, Earley, & Stafford, 1989). Age-related differences in the speed of encoding may also influence memory retrieval. That is, infants' ability to detect adequate retrieval cues clearly increases as a function of age as does their ability to strike a match between a retrieval cue and a target memory attribute. One or both of these factors would increase the efficiency of memory retrieval and enhance the probability that it would occur in the first place (Hayne et al., 2000b).

Second, the retention interval over which infants' memories remain accessible to retrieval increases dramatically as a function of age. Although the absolute duration of retention in simple forgetting procedures varies across memory tasks, within the same task, infant retention has been shown to improve by a factor of 6 (Herbert & Hayne, 2000a) to 91 (Hartshorn et al., 1998a) over the first two years of life. This development alone could potentially account for childhood amnesia. If forgetting occurs within days or weeks during early infancy, it is hardly surprising that those memories are unavailable when we try to access them after retention intervals of

years (or decades)! Over the course of development, however, the forgetting function gradually flattens, increasing the accessibility of a given memory even after very long delays. Furthermore, even after forgetting has occurred, data collected using reminder procedures has shown that the accessibility of the representation varies dramatically as a function of age. Older infants retrieve their memories more quickly, over longer delays, and once retrieved, maintain them for longer periods of time. Any or all of these changes could have dramatic effects on the long-term retention of any given memory representation.

Third, the flexibility of memory retrieval also increases as a function of age during the infancy period. That is, memory retrieval by young infants is highly specific to the conditions of original encoding. Changes in either the proximal or contextual cues disrupt or preclude retrieval of the target memory. The high degree of specificity of the cues required to initiate memory retrieval by these young infants suggests that it may be difficult, if not impossible, for early memories to be retrieved by cues (or in contexts) that were not a part of the original experience. As such, our early memories probably go unretrieved and unexpressed even during infancy, and are eventually lost through disuse.

As a function of both maturation and experience, older infants gradually exploit more or different retrieval cues allowing them to access their memories in a wider range of situations. As memory retrieval becomes increasingly more flexible during late infancy and early childhood, individual memories are more likely to be retrieved, and their repeated retrieval will ultimately prolong subsequent retention (Hayne, 1990; Hartshorn, 2003; Hudson, 1990).

What about language?

Before concluding, I would like to address the potential contribution that language development might make to childhood amnesia. It may be no coincidence, for example, that the period of childhood amnesia is marked by limited verbal skill. Furthermore, even as children begin to acquire language during late infancy and early childhood, their ability to use it in the service of memory is remarkably limited (Simcock & Hayne, 2002). Historically, language development has been central to a number of theories of childhood amnesia (e.g., Allport, 1937; Schachtel, 1947) and it continues to be the focus of theories that emphasize the importance of conversation in children's memory development (Hayne et al., 2003; Hudson, 1990; Nelson, 1993; Reese, 2002). In fact, if you ask parents of young children why they think we can't remember our infancy and early childhood, the vast majority will provide explanations that are based on the lack of language during infancy.

Despite the intuitive appeal of a theory that is based exclusively on language acquisition, such a theory ignores a large body of data collected with nonhuman animals. On the one hand, some investigators have argued that the phenomenon of childhood amnesia is unique to humans. For these investigators, explanations of childhood amnesia that are uniquely human will not cause intellectual grief. On the other hand, however, some investigators (including me) are struck by the

similarity between memory processing in humans and memory processing by nonhuman animals. In fact, the rapid forgetting that is commonly exhibited by altricial animals bears a striking resemblance to the rapid forgetting exhibited by human infants (Bachevalier, 1990; Bachevalier & Mishkin, 1984; Campbell & Spear, 1972; Spear, 1979). Given this, explanations of childhood amnesia that are uniquely human pose a bit of a conundrum.

One way to resolve this issue without ignoring language completely may be to consider its role in the context of a more general theory of childhood amnesia that focuses on age-related changes in basic memory mechanisms. I would argue that childhood amnesia can be explained by age-related changes in the same encoding, retention, and retrieval mechanisms that characterize memory processing across the lifespan. From this perspective, language serves two important functions. First, children's ability to encode information in a linguistic format increases both the quality and durability of a given representation. Second, children's ability to exploit language-based retrieval cues increases the range of situations in which they can successfully retrieve a particular memory. Considered in this way, language serves as a memory attribute or as a retrieval cue just like any other stimulus. This account of childhood amnesia incorporates the role of language, and yet is not unique to humans.

I suspect that a similar argument could also be made for other uniquely human achievements including children's emerging sense of self and theory of mind. These cognitive skills may contribute to the decline of childhood amnesia insofar as they too influence the encoding, retention, and retrieval of past experiences. In my view, the key to unlocking the mystery of childhood amnesia still lies in understanding the way in which these higher order cognitive processes influence basic memory phenomenon.

Where do we go from here?

In 1972, Campbell and Spear published a landmark paper entitled *Ontogeny of Memory*. In that paper, they reviewed the extant literature on the psychobiology of memory development. The goal of their review was twofold: First, they generated testable hypotheses regarding the mechanisms responsible for the development of long-term retention. Second, they attempted to stimulate research on the relative contributions of neurological and behavioral variables in memory development. Their review was based largely on research with animals, owing to a lack of empirical research with human infants.

Since the publication of their review, over 7000 empirical papers on memory development have been published. Our understanding of age-related changes in human memory, particularly those that occur during the infancy period, has expanded tremendously. We have now moved beyond simple questions about whether or not infants can remember to highly sophisticated questions about the conditions under which remembering is likely to occur. A few brave souls have also begun to test infants following retention intervals that encapsulate significant periods of

development (e.g., Hartshorn, 2003; Hartshorn & Rovee-Collier, 2003). Future research of this kind will help us to understand the fate of our early memories and to establish the conditions under which our early experiences are likely to be reflected in subsequent behavior. Although evidence for verbal recall of preverbal memories is extremely limited at the present time (Simcock & Hayne, 2002), the possibility remains that some preverbal memories may break the language barrier and become accessible to verbal report. Establishing the conditions under which this might occur is an important avenue for future research.

Perhaps the most exciting challenge for the 21st century will be to establish the critical link between age-related changes in memory performance and maturation of the human central nervous system. This challenge was originally issued by Campbell and Spear in 1972—30 years down the track, we are finally in a position to accept it.

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