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Why a Neuromaturational Model of Memory Fails: Exuberant Learning in Early Infancy

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Abstract

The characteristics of memory in infants and adults seem vastly different. The neuromaturational model attributes these differences to an ontogenetic change in the basic memory process, namely, to the hierarchical maturation of two distinct memory systems. The early-maturing (implicit) system is functional during the first third of infancy and supports the gradual learning of perceptual and motor skills; the late-maturing (explicit) system supports representations of contextually specific events, relationships, and associations. An alternative model holds that the basic memory process does not change, but what infants and adults select to encode for learning does. This ontogenetic change in selective attention has been mistaken for an ontogenetic shift in the basic memory process. Over the last 25 years, evidence from transfer studies with developing rats and human infants has revealed that the first third of infancy is actually a period of exuberant learning that ends, not coincidentally, at the same age that the late-maturing memory system presumably emerges. This article reviews data from recent studies of sensory preconditioning, potentiation, associative chains, and transitive inference with human infants that support this conclusion—data for which the neuromaturational model cannot account. Fast mapping is a general learning mechanism that accounts for this evidence.

Keywords

associative chains; extinction; fast mapping; forgetting; implicit memory system; perceptual narrowing; potentiation; selective attention; sensory preconditioning; transitive inference

Introduction

In 1984, three landmark publications appeared, all of which addressed the issue of infants' learning and memory capacity during the first postnatal year. The first publication, by Werker and Tees (1984), described a shift in infants' discrimination of speech sounds after 7 to 9 months of age. Before then, infants can discriminate the speech sounds of all languages, whereas by the end of their first year, infants can discriminate only those phonetic contrasts that are significant in their native language-learning environment. The impact of early listening experience has been replicated many times (e.g., Best, 1990, 1994; Rivera-Gaxiola, Silc-Pereyra, et al., 2005; Werker and Lalonde, 1988) and extended to other domains, including facial processing (Cassia, Kuefner, et al., 2009; Pascalis, 2002), socially-guided vocal learning (Goldstein and Schwade, 2008; Goldstein, Schwade, et al., 2009), and the perception of native/

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nonnative rhythms (Hannon and Trehub, 2005). Scott, Pascalis, et al. (2007) hypothesized that early infancy is a period of perceptual tuning during which, as a result of specific experience, infants learn the features that define the structure of their native environment. Late in their first year, infants undergo perceptual narrowing and no longer discriminate nonnative stimuli.

The second publication, by Schacter and Moscovitch (1984), described the development of an early-maturing and a late-maturing memory system in the first year of life. These systems were based on parallels between learning and memory data from infants younger than 9 to 10 months of age and adult amnesiacs, who behaviorally express the effects of their prior training despite being unaware that it had occurred. Because the neural substrate of infant memory is unknown, the neuromaturational model was developed to correlate the timing of infants' learning and memory abilities with the maturation of the neural structures thought to support those abilities in adults.

According to the neuromaturational model of memory development, a primitive (implicit or nondeclarative) memory system is functional at birth and automatically mediates memories of simple learned procedures and perceptual or motor skills. This system includes different neuroanatomical areas in the medial temporal lobe (MTL) that are not integrated and are variously active during different implicit memory tests (Cohen and Eichenbaum, 1993; Cohen and Squire, 1980). Infants who possess the primitive memory system are thought to be particularly deficient in encoding, with memory traces that are unstable and vulnerable (Bauer, 2008, 2009). The brain structures in the MTL (e.g., the hippocampus and surrounding cortices) that form the adult-like (*explicit or declarative*) memory system mature late in the first year and mediate memories of specific episodes, relational and contextual learning, and associations (Bauer, 2004, 2008; Carver and Bauer, 2001; Eichenbaum, 1999; Nelson, 1997; Richmond and Nelson, 2007; Squire, 1992, 1994).

The third publication, by Spear (1984), proposed that what infants of all species learn and remember at any point in development is determined by the ecological challenges posed by their current niche and the survival value of responding effectively to them. Because their niches change rapidly, what developing organisms select to learn changes as well. Spear argued that the basic memory process is the same for infants and adults; however, what organisms of different ages selectively attend and encode for learning changes ontogenetically. Over the last 25 years, evidence from transfer studies with developing rat pups and human infants has revealed that ontogenetic changes in what infants select to encode for learning have been mistaken for ontogenetic changes in the basic memory process and an ontogenetic shift in memory systems.

In the sections that follow, we review evidence of extraordinarily rapid learning by very young human infants—evidence for which the neuromaturational model of memory development cannot account.

The Period of Exuberant Learning

The first third of infancy is a period of exuberant learning when young infants form associations rapidly, on a single occasion, between simultaneously occurring events. They also treat two, perceptually different stimuli as equivalent if each was previously associated with another common stimulus. Finally, their learning is enhanced in the presence of a more salient stimulus that had previously participated in an association. Spear (1984) viewed infants' rapid and exuberant learning as an adaptive strategy and attributed it to the fact that the younger infant's attention is less selective than the adult's. As a result, young infants notice more about the same event and actually form more intra-event associations (i.e., learn more) than adults.

Spear and colleagues used transfer paradigms to document exuberant learning by developing rat pups. These paradigms included sensory preconditioning, potentiation, and equivalence learning among multiple associations. In the following sections, we review corresponding evidence from human infants on the formation of exuberant associations.

Sensory Preconditioning

Sensory preconditioning (SPC) is behaviorally silent learning in which an association is formed between two neutral, external (“sensory”) stimuli or events in the absence of reinforcement, before formal conditioning (“preconditioning”) occurs. A subsequent training procedure is necessary to provide subjects with an overt means of expressing it.

The SPC paradigm consists of three phases: (1) a *preexposure* phase when subjects are exposed to two paired stimuli (S1, S2), (2) a *training* phase when subjects learn to associate S1 with a source of reinforcement, and (3) a *transfer* test when subjects are tested with the untrained stimulus (S2). If subjects behave during the test as if S2 had been reinforced, then it is concluded that an association was formed between S1 and S2 during the preexposure phase. The standard control group receives the same procedure except that S1 and S2 are preexposed separately (unpaired) in phase 1. This group should not perform the reinforced response during the transfer test with S2.

Spear and colleagues found that the enhanced ability of developing rat pups to form simultaneous associations in the SPC paradigm ends after the first 2 postnatal weeks. Newborns (Cheslock, Varlinskaya, et al., 2003), 8-day-old, and 12-day-old rat pups formed simultaneous associations, but 21-day-olds did not (Chen, Lariviere, et al., 1991).

In the first study of SPC with human infants (Boller, 1997), 6-month-olds were simultaneously preexposed to two distinctive cloth panels (contexts), side by side, for a total of 1 hr daily for 7 consecutive days, while infants in an unpaired control group were preexposed to the two panels equally long but at different times of day (phase 1). One day later, both groups learned to kick to move a mobile in the presence of one of the panels (phase 2), and then both received a 24-hr transfer test with the training mobile in the presence of the other panel (phase 3). At 6 months, infants do not recognize their training mobile in a different context (Borovsky and Rovee-Collier, 1990). Boller, however, found that the paired preexposure group exhibited significant retention in the untrained context, while the unpaired preexposure group exhibited no retention. Apparently, the paired group had associated the two panels in phase 1, and this association had enabled conditioned responding to transfer to the untrained test context.

Barr, Marrott, et al. (2003) followed Boller’s preexposure regimen but assessed SPC using a deferred imitation task. In deferred imitation tasks, infants are merely shown a series of target actions being modeled on S1 (phase 2), and they later receive an opportunity to reproduce them during a transfer test with S2 (phase 3). Unlike traditional SPC procedures, the “training” phase (phase 2) entails neither a motor response nor reinforcement. Their experimental design is presented in Figure 1.

Six-month-olds were simultaneously preexposed to two hand puppets (A and B) for 1 hr daily on 7 consecutive days (phase 1; Figure 2, *left panel*). One day after the last preexposure, a sequence of three target actions (remove the mitten from the puppet’s hand, shake the mitten, replace the mitten) was modeled on puppet A six times for a total of 60 s (phase 2; Figure 2, *center panel*). One day after the demonstration, infants received an imitation transfer test with puppet B (phase 3; Figure 2, *right panel*). An infant’s imitation test score was the total number of target actions (0–3) reproduced within 120 s. The unpaired control group was preexposed to the two puppets for the same amount of time but at different times of day; otherwise, it was treated exactly like the paired group. Finally, an age-matched baseline control group that had

seen neither the puppets nor the demonstration was tested with puppet B. This group provided the baserate (0.133) at which 6-month-olds spontaneously produce the target actions.

As predicted, during the 24-hr transfer test with puppet B, the paired preexposure group had a mean imitation score that was significantly above the baserate, but the unpaired group did not. To assess the specificity of the association, another paired preexposure group was tested with novel puppet C. This group failed to imitate the modeled actions on puppet C, confirming that the association was specific to puppets A and B. The same results were obtained when infants were preexposed to the paired puppets for only 2 days.

Asking how long the puppet A-puppet B association could remain latent before being retrieved, Reynolds and Rovee-Collier (2005) simultaneously preexposed 6-, 9-, and 12-month-olds to puppets A and B for 2 days (phase 1), modeled the target actions on puppet A 1, 2, or 3 weeks later (phase 2), and tested infants with puppet B 1 day afterward (phase 3). We expected older infants to remember the association longer, but such was not the case: Six- and 9-month-olds successfully imitated the actions 2 but not 3 weeks later, but 12-month-olds did not imitate on puppet B after any delay--not even 1 day after the demonstration. The latter result suggested that 12-month-olds did not form the association in the first place. Muentener (2004), using a different deferred imitation task, had also found that 12-month-olds could not acquire a simultaneous association. Recently, Cuevas, Giles, et al. (2009) replicated this result, reporting that 6- and 9-month-olds formed simultaneous associations, but 12- and 15-month-olds did not. At 18 months of age, however, infants' ability to form simultaneous associations reappeared (see Figure 3).

Giles (2010) asked if and how the number and duration of preexposure sessions might affect retention of the association at 6 and 9 months of age. In phase 1, she preexposed infants of both ages to the paired puppets for 1 hr per day on 2 days, for 1 hr on 1 day, or for 1 hr distributed into two 30-min sessions on 1 day. She separated the two sessions by approximately 5 hr in order to necessitate retrieval of the session-1 memory at the outset of session 2¹ and to accommodate infants' daily routines (e.g., feedings, naps). To determine how long infants remembered the puppet A-puppet B association, phase 2 was delayed for 1 to 28 days after phase 1, at which time Giles modeled the target actions on puppet A. In phase 3, 24 hr after phase 2, she gave infants a transfer imitation test with puppet B. The longest phase 1-phase 2 interval after which infants exhibited significant imitation on puppet B defined the upper limit of retention of the association.

She found the same retention data at both ages: The 1 day/1 hr preexposure group exhibited significant 24-hr imitation when phases 1 and 2 were separated by 3 days but not longer, whereas the 2-day preexposure group (2 hr total) did so when phases 1 and 2 were separated by 14 but not 21 days. Surprisingly, the 1-day/two-session preexposure group (1 hr total) exhibited significant 24-hr imitation when phases 1 and 2 were separated by 21 but not 28 days (see Figure 4). These results demonstrated that the retention benefit of retrieving a memory at the onset of a second session is huge and outweighs the benefit of longer exposure time. The additional finding that infants remembered the association for 1 week longer when the retrieval occurred on the same day instead of 24 hr later suggests that substantial forgetting takes place

¹We used a retroactive interference paradigm with infants to estimate how long it takes information to transfer from short-term to long-term memory. Our underlying assumption was that exposure to a novel cue can retroactively interfere with recognition of the original training cue only if the original representation still occupies short-term (active) memory; once the original representation is in long-term memory, it buffered against retroactive interference until it is retrieved. At 3 months of age, retroactive interference accompanied exposure delays up to 60 min after training but not longer, suggesting that the original representation remained in primary memory for 60 min (Rossi-George and Rovee-Collier, 1999). At 6 months, retroactive interference accompanied an exposure delay of 0 s but not 10 s (operant train task) or 30 s (puppet imitation task) after training, suggesting that the original representation vacated short-term memory within 10 s (Lee, Gombert, et al., 2008). These data reveal that the duration of short-term memory reaches the adult level (i.e., less than 20 s; Peterson and Peterson, 1959) by 6 months of age.

over 24 hr--a result originally reported by Ebbinghaus (1885/1962). Because there is no measurable behavior in the preexposure phase, however, exactly what infants forget is unknown.

Three-month-olds also associate multiple stimuli they see together without being reinforced for doing so. In a study of correlated attributes, Bhatt and Rovee-Collier (1994, 1996, 1997, 2004) trained 3-month-olds to kick to move a six-block mobile. On all sides of each block were letters or numbers: Three red blocks displayed yellow As, and three green blocks displayed black 2s (training combinations were counterbalanced within groups). Mobile movement was contingent only on kicking; the feature combinations on the mobile blocks were irrelevant. Even so, when infants were tested for operant retention 24 hr later, they treated the training mobile as novel (i.e., responded at operant level) when only a single feature in one set of blocks had been switched with the corresponding feature in the other set, despite the fact that all of the original features were still present on the test mobile.

The feature recombinations on the test mobile (see Figure 5) were a switch in figure color (from yellow As to black As and from black 2s to yellow 2s), a switch in figure shape (from As to 2s and vice versa--but the color of the altered figure on the red block was still yellow, etc.), a switch in block color (from red blocks to green blocks, and vice versa), and a reversal in block color and figure color (from yellow As on red blocks to red As on yellow blocks, etc.). *The only recombination that infants failed to detect-- the figure-ground chromatic reversal--was the only recombination that adults did detect.* The figure-ground chromatic reversal was also the only instance in which the features were recombined *within a block*; all other recombinations were *across blocks*. These data demonstrated that very young infants (1) spontaneously form numerous extraneous associations among the attributes of a multi-element event, (2) select different information to encode in the same multi-element event than adults, and (3) learn more about the same multi-element event than adults.

We have also used the SPC procedure to examine the ability of 3-month-olds to associate two puppets (Campanella and Rovee-Collier, 2005). A paired group was preexposed to puppets A and B for 1 hr on each of 7 days (phase 1), while an unpaired control group was preexposed to puppets A and B at different times of day. Thereafter, the paired and unpaired groups were treated identically. Because 3-month-olds are motorically incapable of performing the target actions on a puppet before 6 months of age, we delayed phases 2 and 3 until then, maintaining the memory of the puppet A-puppet B association by periodically reactivating it six times. During the reactivation treatment, the experimenter merely held puppet A in front of the infant for 30 s. At 6 months, 1 day after the sixth reminder, she modeled the target actions on puppet A for 60 s (phase 2) and tested infants with puppet B--which they had not seen for 3 months--24 hr later (phase 3). The paired group successfully imitated the modeled actions on puppet B, but the unpaired group did not, confirming that the paired group had formed an association between puppets A and B when they were 3 months old.

Asking if 3-month-olds might be able to remember the demonstration in addition to the puppet A-puppet B association for 3 months, we repeated phase 1 and modeled the target actions for 60 s on puppet A (phase 2) 1 day after the last preexposure session. We again delayed phase 3 until infants were 6 months old, maintaining the memory by periodically reactivating it with puppet A, as before. At 6 months, 1 day after the sixth reminder, we tested infants with puppet B (phase 3). Also as before, they imitated the modeled actions on puppet B, even though they had not seen puppet B or the actions for 3 months. These results underscore the rapidity with which very young infants spontaneously form new associations between stimuli or events that simultaneously co-occur and link them with prior associations.

Potentiation

Potentiation refers to the better learning of a weaker (less salient) stimulus when it is presented simultaneously with a stronger (more salient) stimulus than when it is presented alone. The potentiation stimulus is stronger and more salient as a result of having previously acquired associative strength. Presumably, when they co-occur, the two stimuli are associated, and the associative strength of the stronger stimulus transfers to the weaker one. In adults, the same conditions can produce overshadowing instead of potentiation. Overshadowing is the poorer learning of a weaker stimulus that is simultaneously presented with a stronger one and is the result predicted by Rescorla and Wagner (1972). Potentiation in adults has largely been found in odor and taste aversion learning (Domjan, 2003; Lett, 1984; Rusiniak, Hankins, et al., 1979) but has also been reported in autoshaping, maze learning, and context conditioning (Best, Batson, et al., 1990; Graham, Good, et al., 2006; Thomas, Robertson, et al., 1987).

Spear and Kucharski (1984) found that potentiation was more prominent in rat pups than in adults. For example, 18- and 60-day-old rats were presented with a footshock paired with lemon odor, orange odor, or a compound of lemon/orange odors (18-day-old rats have not yet been weaned, and their eyes and ears have been open for less than a week, whereas 60-day-old rats are sexually mature young adults). The 18-day-olds exhibited stronger conditioning to an odor when it was presented simultaneously with another odor than when it was presented alone (potentiation). In contrast, 60-day-olds exhibited weaker conditioning to an odor when it was presented simultaneously with another odor than when it was presented alone (overshadowing). Also, when 15-day-olds and adults were conditioned with a footshock in a distinctive location and later learned a classically conditioned odor aversion, the 15-day-olds exhibited less blocking (less impairment) in learning the odor aversion than adults (Caza, 1982, cited in Spear and Kucharski, 1984).

In a study of mediated imitation, we also obtained robust potentiation with 6-month-old human infants. The stronger (potentiation) stimulus was a miniature train that infants had learned to move around a circular track by lever pressing (see Figure 6). After 2 days of operant training, 6-month-olds remember the train task for 2 weeks (Hartshorn and Rovee-Collier, 1997). The weaker (potentiated) stimulus was a hand puppet on which a series of target actions were being modeled. After a 60-s demonstration, 6-month-olds remember the puppet task for only 1 day (Barr, Dowden, et al., 1996). When the actions were modeled *in the presence of the train* immediately after operant training ended (Barr, Vieira, et al., 2001), the puppet task was remembered for as long as the train task--2 weeks--instead of 1 day. The no-association control group, which learned the train task and watched the demonstration in different rooms, continued to remember the puppet demonstration for only 1 day.

Batsell, Trost, et al. (2003) reported that when a taste that had potentiated odor aversion conditioning in rats received additional conditioning, it further strengthened the associated odor aversion. Exploiting the fact that retrieving a memory strengthens it, Barr, Rovee-Collier, et al. (2009) attempted to increase the associative strength of the potentiation stimulus and enhance potentiation through retrieval of its memory at the time of the puppet demonstration. To do so, we merely placed the train on a side table, in infants' view, as a retrieval cue 7 days after operant training and modeled the target actions on the puppet in its presence. We hypothesized that the sight of the train would cue retrieval of the train memory, strengthen it, and further potentiate encoding of the demonstration on the puppet. This is the result we found. Infants apparently associated the puppet demonstration with the retrieved memory of the train task because they subsequently remembered both tasks for 4 weeks.

Because retrieving memories after even longer delays strengthens them more (Bjork, 1988), we attempted to further increase the strength of the train task by doubling the previous retention interval from 7 to 14 days—the longest delay that 6-month-olds remember the train task. As

predicted, retrieving the train memory 14 days after operant training strengthened it even more and potentiated encoding of the puppet demonstration even more: Infants subsequently remembered the train task for 8 weeks instead of 4, and they remembered the puppet task for 6 weeks instead of 4.

The neuromaturational model cannot account for the finding that very young infants remembered the puppet imitation task for at least 6 weeks after a single 60-s demonstration. The model holds that infants are unable to encode and maintain an enduring memory of a one-time demonstration longer than 24 hr until the late-maturing, explicit memory system emerges (Bauer, 2009; Bauer, DeBoer, et al., 2007).

The preceding studies reveal that potentiation is a major mechanism that significantly enhances young infants' encoding and long-term memory of new, potentially predictive relationships in their niche.

Associative Chains and Transitive Inference

Two recent studies demonstrated 6-month-olds' unexpected facility to form a complex sequence of associations. In both, infants formed a series of simultaneous associations that were successively linked over a period of days. The first study, by Cuevas, Rovee-Collier, et al. (2006), was modeled after a Dwyer, Mackintosh, et al. (1998) experiment in which rats formed an indirect association between two stimuli that had never appeared together and that were physically absent at the time the association was formed. In our adaptation, infants were simultaneously preexposed to puppets A and B for 1 hr per day on 2 consecutive days. At this time, infants presumably formed an association between A and B. For the next 2 days, infants learned to kick to move a mobile in a distinctive context. At this time, they presumably formed a mobile-context association. At the end of operant training, we replaced the overhead mobile with puppet A for 2 min (see Figure 7). We predicted that the sight of puppet A would reactivate its associated memory of puppet B and that the context would simultaneously activate its associated memory of the mobile. At this time, then, infants would presumably form an indirect association between the memory of puppet B and the memory of the training mobile.

To determine if the association had been formed, we modeled a series of target actions on puppet B 1 day later and asked how long infants could remember them. If puppet B and the training mobile had not been associated, then infants should defer imitation for only 24 hr (Barr, Dowden, et al., 1996); if they had been associated, however, then infants should defer imitation for 2 weeks (Barr, Vieira, et al., 2001; *see above*). Infants did defer imitation for 2 weeks, but a no-association control group did not. Thus, as in the Dwyer, Mackintosh, et al. (1998), 6-month-olds associated the memories of two absent stimuli that had never appeared together. Also as in that study, the indirect and direct associations were equally effective.

In the second study, Townsend, Cuevas, et al. (2010) asked whether 6-month-olds could associate multiple pairs of hand puppets (see Figure 8) within and across days and, if so, how they represented this knowledge. The experimental design is presented in Figure 9. We followed the basic procedure of Barr, Marrott, et al. (2003) but preexposed infants to a different puppet pair (instead of the same pair) on consecutive days in phase 1. In phase 2, the target actions were modeled on either puppet C or puppet A; and in phase 3, groups received a transfer test of deferred imitation with either puppet A (group Paired C/A) or puppet C (group Paired A/C), respectively. An unpaired control group (Unpaired C/A) was preexposed to puppets A and B equally long but separately on day 1; thereafter, it received the same procedure as group Paired C/A. Even though puppets A and C had never appeared together, both paired preexposure groups imitated the modeled actions on the untrained test puppet, but the unpaired control group did not.

During the imitation test, however, the mean RT (latency to touch the puppet) of the Paired A/C group was twice as long as the mean RTs of the Paired C/A group and the Paired D/A group from Experiment 2, even though the distance between the demonstration and test puppets was the same or shorter, respectively (see Figure 10). The significantly longer RT of the Paired A/C group must have reflected the longer time needed to retrieve the representation of the chain from long-term memory. The Paired A/C group, whose retrieval cue was puppet C, was required to retrieve the chain backwards ($C \rightarrow B \rightarrow A$), in the opposite order from which it acquired, whereas groups Paired C/A and Paired D/A, whose retrieval cue was puppet A, retrieved the chain in the same order they had learned it ($A \rightarrow B \rightarrow C$; $A \rightarrow B \rightarrow C \rightarrow D$, respectively).

Extinguishing the A-B association was as effective in disrupting deferred imitation in phase 3 as preventing the A-B association from being formed in the first place. Exposing infants to puppet B-alone on day 2--*before* the actions were modeled on puppet B (phase 2)--extinguished the A-B association that was formed on day 1 and disrupted imitation during the transfer test with puppet A. Similarly, exposing infants to puppet B-alone on day 2--*after* infants were preexposed to puppets B and C but *before* the actions were modeled on puppet C (phase 2)--extinguished the B-C association (and possibly the A-B association) and also disrupted imitation during the transfer test with puppet A. Taken together, these results provided convergent evidence that infants represented the sequence of two puppet pairs as a linear associative chain in which puppet B was the central link.

In Experiment 2, the associative chain was lengthened to include two more puppet pairs (see Figure 11). When infants were preexposed to a third puppet pair (C+D) on day 4 (phase 1), and the actions were modeled on puppet D (phase 2), infants who were tested with puppet A imitated them (phase 3), but a generalization group that was tested with novel puppet E did not, confirming that the infants had not responded categorically to puppet A as a result of having been exposed to multiple puppet exemplars. When infants were preexposed to a fourth puppet pair (D+E) on day 5 (phase 1), and the actions were modeled on puppet E (phase 2), infants also imitated them on puppet A (phase 3).

In a critical test of transitive inference (TI), we assessed 6-month-olds' knowledge of the ordinal relationship between two non-adjacent puppets that did not anchor either end of the associative chain (see Brannon, Cantion, et al., 2006). We again successfully preexposed infants to four puppet pairs (phase 1) but demonstrated the target actions on puppet D (phase 2) and tested infants with puppet B (phase 3). Infants successively imitated the actions on puppet B, even though neither end anchor (puppet E or A) had been present during the demonstration and test. This result confirmed that infants had exhibited TI, contrary to the assumption of the neuromaturational model that transitivity requires a mature explicit memory system (Smith, Hopkins, et al., 2006).

Pruning Excessive Associations

A major drawback to infants' exuberant learning is that infants learn too many associations, many of which are potentially inappropriate, useless, or irrelevant. The problem then becomes how to prune the large number of excessive associations. Spear, Kraemer, et al. (1988) likened this problem to the overproduction and selective pruning of excessive synapses during brain development and proposed that an adaptive infantile disposition for exuberant learning would likely be accompanied by age-specific mechanisms for selectively pruning the multitude of irrelevant associations that infants would form. The two mechanisms that they identified were (1) more rapid forgetting at younger ages, and (2) more rapid extinction at younger ages.

Rapid Forgetting

There is no dispute that infants forget more rapidly than adults. In most species, including rats (Campbell and Campbell, 1962), monkeys, (Green, 1962), humans (Hartshorn, Rovee-Collier, et al., 1998), puppies (Fox, 1971), mice (Nagy, 1979), chicks (Peters and Isaacson, 1963), and frogs (Miller and Berk, 1977), younger animals forget faster than older animals as the retention interval increases, even though their retention is equivalent after the shortest test delays. Their more rapid forgetting is widely described as a memory deficit and has been attributed to sparser or weaker encoding (Bauer, 2008; Jones and Herbert, 2006), an inability to maintain memories in storage (Carver, Bauer, et al., 2003), or a retrieval deficit (Campbell and Spear, 1972; Liston and Kagan, 2002). Nelson (1993) also argued that infants cannot remember events over the long term until they are able to rehearse them by talking about them. Finally, the neuromaturational model holds that infants lack the brain mechanisms requisite for long-term memory until the explicit memory system is functionally mature (Carver and Bauer, 2001).

The ubiquity of rapid forgetting by the young of so many species, however, suggests that *rapid forgetting is not a memory deficit but is an evolutionarily-selected survival-related strategy* that facilitates young infants' adaptation to their rapidly changing niche and enables them to shed the excessive number of recent, rapidly formed associations that are potentially useless, irrelevant, or inappropriate.

The forgetting of a new association is forestalled and its retention is prolonged when a member of the association (or a cue linked to it) is reencountered and retrieves the memory. Moreover, its retention is prolonged more when the interval between encoding and retrieval is longer (Bjork, 1988). The retention benefit of retrieving the memory after a long interval, however, is greatest for younger infants. Retrieving the memory at the end of the forgetting function, for example, prolongs retention by 136% at 6 months, 67% at 9 months, 62% at 12 months, but by only 40% at 15 months (Hsu and Rovee-Collier, 2009). Even after the association has been forgotten, its memory can still be recovered (reactivated) should an individual reencounter exactly the same cues that were present at the time of original encoding; however, the interval after which this is possible has an upper limit (see Figure 12).

The neuromaturational model cannot account for these data. Among other things, the model holds that the brains of young infants are insufficiently mature to encode, maintain, and/or retrieve long-term memories before the end of the first year.

Rapid Extinction

Infant rats extinguish more rapidly than adults (Kucharski and Spear, 1985; Spear, 1979a, 1979b). Their rapid extinction is ensured by the fact that they do not exhibit the partial reinforcement extinction effect before 11 to 13 days of life (Chen and Amsel, 1980). Corresponding studies with human infants are lacking, as are studies of extinction with infants more generally. In a recent series of systematic studies with 3-month-olds, we found that extinction is rapid and enduring, with little or no spontaneous recovery.

In these studies, infants learned to move an overhead crib mobile by kicking via a ribbon strung from one ankle to a flexible mobile stand that was clamped on one side rail. During baseline, extinction, and the long-term retention test (nonreinforcement periods), the ankle ribbon was connected to an identical "empty" stand on the opposite rail, so that the mobile remained in full view, but kicks did not move it. Infants' rate of spontaneous kicking (operant level) was obtained during a preliminary, 3-min baseline phase on day 1. Next, during a 9-min acquisition phase (9 min), kicks moved the mobile with an intensity that corresponded to their rate and magnitude ("mobile conjugate reinforcement"). On day 2, infants received a 6-min acquisition phase followed immediately by a 9-min extinction period. After delays ranging from 1 to 5

days, a period that spanned their entire forgetting function, independent groups received a 3-min long-term retention test.

Three-month-olds did not reduce conditioned responding during the 9-min extinction manipulation. Surprisingly, however, all infants exhibited an extinction effect 1 day later, responding at baseline during the long-term test, and continued to respond at baseline for the next 5 days. These results revealed that infants had actually acquired the extinction contingency during the 9-min extinction phase immediately after operant training but were unable to express it when they were behaviorally aroused. In contrast, no-extinction control groups exhibited significant retention of conditioned responding over the same delays (Shafer and Rovee-Collier, 2007). In a follow-up study, when the extinction phase was delayed for 24 hr, infants exhibited spontaneous recovery after 1 day but not longer.

Extinction studies with adults have yielded different results: (1) adults—but not 3-month-olds—reduce conditioned responding during the actual extinction manipulation; (2) adults—but not 3-month-olds—exhibit spontaneous recovery 1 day after immediate extinction, but 3-month-olds do not; and (3) adults exhibit no spontaneous recovery 1 day after delayed extinction (Huff, Hernandez, et al., 2009), but 3-month-olds do. Whether the extinction paradigms used with adults and infants are analogous, however, is debatable. Most recent extinction studies with adults have used a classically conditioned fear paradigm that mimics the paradigm used with adult rats (e.g., Phelps, Delgado, et al., 2004), whereas most extinction studies with infants have used appetitive classical or operant conditioning paradigms (e.g., Allesandri, Sullivan, et al., 1990; Blass, Ganchrow, et al., 1984).

There are other procedural differences as well. Adults typically receive partial reinforcement to slow the extinction of conditioned fear (e.g., LaBar, Gatenby, et al., 1998), but very young infants do not exhibit a partial reinforcement effect during extinction (Chen and Amsel, 1980). Adults are usually tested for spontaneous recovery within a few days of extinction, whereas infants are often tested over their entire forgetting function. (Testing human and nonhuman adults over a comparable period is impractical because they take so long to forget.) Finally, adults receive verbal instructions, but prelinguistic infants do not.

Rapid extinction by young infants is not limited to conditioning tasks. A transfer test of deferred imitation in phase 3 of the SPC paradigm revealed that preexposing 6-month-olds to puppet B-alone completely eliminated the A-B association that was formed 1 day earlier when infants were exposed to paired puppets A and B (*see above*, Townsend, Cuevas, et al., 2010).

The preceding experiments document that the associations formed by very young human infants extinguish rapidly, just like those formed by infant rats (Kucharski and Spear, 1985; Shafer, 2009; Shafer and Rovee-Collier, 2007), and support Spear's (1984) original proposition that rapid extinction, like rapid forgetting, is an evolutionarily selected strategy by which very young organisms eliminate excessive exuberant associations that are useless (nonpredictive) or inappropriate.

The End of the Period of Exuberant Learning

The facility with which rat pups form exuberant associations between simultaneously presented stimuli disappears during their third postnatal week (Spear and Kucharski, 1984). Chen, Lariviere, et al. (1991) documented that the effective SPC preexposure regimen shifts developmentally over this period: Eight-day-olds associated two odors that were preexposed simultaneously but not sequentially, 12-day-olds associated two odors that were preexposed either simultaneously or sequentially, and 21-day-olds associated two odors that were preexposed sequentially but not simultaneously.

Cuevas (2009) documented a parallel developmental shift in the effective preexposure regimen with 6-, 9-, and 12-month-old human infants—ages that correspond to the ages of the infant rats tested by Chen, Lariviere, et al. (1991). Six-month-olds associated two puppets that were preexposed simultaneously but not sequentially; 9-month-olds associated two puppets that were preexposed either simultaneously or sequentially; and 12-month-olds associated two puppets that were preexposed sequentially but not simultaneously. Thus, the facility with which human infants form exuberant associations between simultaneously presented stimuli similarly disappears after 9 months of age. Cuevas also found that increasing or decreasing the number of trials in the sequential preexposure condition affected SPC only at the transitional age of 9 months, when more trials increased the interstimulus interval at which infants formed a sequential association, and fewer trials eliminated their ability to form a sequential association altogether.

The preceding data reveal that the period of exuberant learning by human infants ends after 9 months—the same age at which the early period of experience-based perceptual tuning gives way to perceptual narrowing (Scott, Pascalis, et al., 2007) and the explicit memory system presumably supplants the implicit memory system (Bauer, DeBoer, et al., 2007; Carver and Bauer, 2001; Carver, Bauer, et al., 2003; Nelson, 1995, 1997; Richmond and Nelson, 2007). *The common age at which these three transitions occur is not a coincidence.* All transitions describe the same phenomenon—a developmental change in what young infants learn and remember. Both the period of exuberant learning (Rovee-Collier and Cuevas, 2009; Spear, 1984) and the early period of perceptual tuning (Werker and Tees, 1984) are concerned with how immature, rapidly developing organisms “flesh in” the skeletal structure of their native environment with the survival-related relationships they learn while adapting to each of a succession of rapidly changing ecological niches. Because their niches change more rapidly when they are younger, more immature infants must learn those critical relationships more rapidly. The timing of the transition for both periods has been empirically determined. In contrast, the neuroanatomical underpinnings of the implicit memory system have never been studied directly with young human infants (Bauer, 2008).² As a result, the timing of the transition to the explicit memory system has been inferred from the appearance of behaviors that have been linked to different neuroanatomical structures of the explicit memory system in adults.

The failure of the implicit memory system to account for the period of exuberant learning is not surprising: *The operating characteristics of the implicit memory system were defined by the learning and memory performance of amnesic adults who had already undergone the period of exuberant learning as infants* (Bauer, 2004, 2008; Bauer, DeBoer, et al., 2007; Schacter and Moscovitch, 1984). No one denies that developmental changes in the neural mechanisms that support learning and memory are important, but as Spear (1984) observed, “an ontogenetic change in the neurophysiological mechanisms responsible for *all* [our emphasis] learning and memory seems unlikely” (p. 326).

Fast Mapping: A General Learning Mechanism?

If a neuromaturational model does not account for the exuberant learning of very young infants, what does? A general learning mechanism is likely to be responsible for infants’ rapid acquisition. One candidate mechanism is *fast mapping*, which Carey and Bartlett (1978) introduced to describe the cognitive process by which 24-month-olds learned a new word during a single, brief exposure to the information. Since then, fast mapping the meaning,

²Electrophysiological correlates of imitation were obtained in a multi-session study with 9- and 10-month-olds, but the use of multiple retrievals after individual delays that varied widely at every point of the study rendered the data uninterpretable (Bauer, Wiebe, et al., 2003).

function, relations, and properties of words to objects has been broadly invoked to explain the rapidity with which children in their second year gain vocabulary (Markson and Bloom, 1997). Infants as young as 13 months also learned novel word-object labels rapidly when they were trained in a socially interactive context and performed an activity that required associating the label with the object instead of just looking at or touching it (Woodward, Markman, et al., 1994). Using a simpler and less supportive habituation/looking time paradigm with 8-, 12-, and 14-month-olds, however, Werker, Cohen, et al. (1998) found that only the 14-month-olds rapidly learned novel word-object labels in one session. They concluded that the threshold for the appearance of fast mapping is 14 months of age.

During the period of exuberant learning, however, 6-month-olds rapidly associate labels with salient familiar individuals in their environment (Tincoff and Jusczyk, 1999), and even 6-week-olds learn the distinctive facial expression (facial label) associated with a particular adult in one session, reproducing it upon encountering that adult 24 hr later (Meltzoff and Moore, 1994). These data reveal that fast mapping also occurs very early in life. Although fast mapping has been described as a device that is specialized for word learning, Bloom and Markson (2001) argued that it is not unique to word learning but is a *general learning mechanism*. The evidence presented in this article strongly supports their position.

A fast mapping general learning mechanism would also promote a veritable explosion in the growth of the early knowledge base during the period of exuberant learning if, in addition to linking two simultaneous and perceptually present stimuli, it were to link the activated memory representation of one association to a contemporaneously attended physical stimulus or event or to the memory representation of another association that was simultaneously activated or “brought to mind.” The present evidence suggests that it does: Fast mapping readily accounts for the effortless learning of correlated attributes (Bhatt and Rovee-Collier, 1994, 1996) and SPC (Campanella and Rovee-Collier, 2005) at 3 months and for the rapid potentiation of deferred imitation (Barr, Rovee-Collier, et al., 2009; Barr, Vieira, et al., 2001), the rapid association of stimuli *in absentia* (Cuevas, Rovee-Collier, et al., 2006), and the rapid learning of associative chains and TI at 6 months (Townsend, Cuevas, et al., 2010).

Conclusion

The neuromaturational model of memory development holds that the basic memory process changes ontogenetically, controlled by two different neuroanatomical memory systems that mature at different rates. An alternative, ecological model holds that the basic memory process does not change ontogenetically, but what immature infants and adults select to encode for learning does. *This ontogenetic change in selective attention has been mistaken for an ontogenetic shift in the basic memory process itself.* Empirical evidence supporting this conclusion has been obtained from numerous and diverse studies with very young human infants over the last 15 years. This evidence clearly documents that a period of rapid and exuberant learning occurs in early infancy—a period that cannot be accommodated by the neuromaturational model of memory development.

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SPC Experimental Design of Barr, Marrott, et al. (2003)

TEST GROUP	PHASE 1 EXPOSE Days 1-7	PHASE 2 DEMO Day 8	PHASE 3 TEST Day 9
Paired	S1+S2	S1	S2 ✓
Unpaired	S1/S2	S1	S2
(Generalization) Paired	S1+S2	S1	S3
Baseline Control	----	----	S2

Figure 1.

The experimental design of a simultaneous sensory preconditioning study with 6-month-olds; significant deferred imitation on the untrained stimulus in phase 3 was the measure of association formation in phase 1. A check indicates that a test group exhibited significant deferred imitation.

Figure 2.

A 6-month-old infant in the sensory preconditioning (SPC) procedure. *Left panel, phase 1:* The paired preexposure to puppet A and puppet B. *Center panel, phase 2:* Demonstration of the target actions on puppet A. *Right panel, phase 3:* The deferred imitation test with puppet B.

Figure 3.

Mean imitation scores of simultaneous preexposure groups as a function of age. The *dashed line* indicates the base rate of infants' spontaneous production of the target actions. Asterisks mark groups with imitation scores significantly above the test score of the base rate. The data reveal that only the youngest (6- and 9-month-old) and oldest (18-month-old) infants could form a simultaneous association. Error bars represent +1 *SE*.

Figure 4.

Mean imitation scores of independent test groups of 6-month-olds as a function of the time that the puppet A-B association, presumably formed in phase 1, remained latent before being activated in phase 2, when the target actions were modeled on puppet A. Phase 3 (the transfer test with puppet B) followed 24 hr later. If the association was not activated in phase 2, then imitation could not transfer to the untrained test puppet in phase 3. The *dashed line* indicates the baserate of infants' spontaneous production of the target actions. Asterisks indicate that a group's mean imitation score significantly exceeded the baserate. Error bars represent $+1 SE$.

Figure 5.

Left column: The two sets of feature combinations (black As on 3 red blocks and yellow 2s on 3 green blocks) on 3-month-olds' 6-block training mobile. *Right column:* The two sets of feature recombinations on the 6-block test mobile of independent test groups; *from top to bottom:* (1) a switch in figure colors, (2) a switch in figure forms, (3) a switch in block colors, or (3) a reversal in the block color and figure color (Bhatt and Rovee-Collier, 1994).

Figure 6. The experimental arrangement used with 6- to 24-month-old infants in the operant train task, shown here with a 6-month-old. Each discrete lever press moved the train for 1 s (2 s at 6 months).

Figure 7.

A 6-month-old infant during a 2-min exposure to puppet A in the mobile training context. During the 2-min exposure, the memory representations of puppet B and the mobile--neither of which was physically present--were associated. Previously, the infant was simultaneously exposed to puppets A and B and then was operantly trained with the mobile in the distinctive context.

Figure 8.

The pool of six puppets used in deferred imitation studies with 3- to 12-month-old infants. During a 24-hr deferred imitation test, infants younger than 18 months do not spontaneously generalize between any of these puppets, despite a common color or form. *Left to right:* pink mouse, grey rabbit, black-and-white cow, yellow duck, pink rabbit, grey mouse.

EXPERIMENT 1 DESIGN
(Letters Designate Puppets)

TEST GROUP (Demo/Test Puppet)	PHASE 1 EXPOSE Day 1	PHASE 1 EXPOSE Day 2	PHASE 2 DEMO Day 3	PHASE 3 TEST Day 4
Paired C/A Paired A/C	A+B A+B	B+C B+C	C A	A √ C √
Unpaired C/A	A (am), B (pm)	B+C	C	A
(Ext B) B/A (Ext B) C/A	A+B A+B	B B+C, B (pm)	B C	A A

Figure 9.

The experimental design for the three phases of Experiment 1 as a function of test group. A check indicates that a test group exhibited significant deferred imitation, even though the training (demonstration) puppet and the test puppet (the retrieval cue) were not directly linked.

Figure 10.

Mean reaction time (s) to touch the test puppet before initiating the modeled actions. The asterisk indicates that the mean reaction time of group A/C was significantly longer than the mean reaction times of groups C/A and D/A (from Experiment 2). Error bars represent +1 *SE*.

EXPERIMENT 2 DESIGN
(Letters Designate Puppets)

TEST GROUP (Demo/Test Puppet)	PHASE 1 EXPOSE Day 1	PHASE 1 EXPOSE Day 2	PHASE 1 EXPOSE Day 3	PHASE 1 EXPOSE Day 4	PHASE 2 DEMO Day 4 or 5	PHASE 3 TEST Day 5 or 6
D/A E/A	A+B A+B	B+C B+C	C+D C+D	---- D+E	D E	A √ A √
(Gen) D/E	A+B	B+C	C+D	----	D	E
(TI) D/B	A+B	B+C	C+D	D+E	D	B √

Figure 11.

The experimental design for the three phases of Experiment 2 as a function of test group. A check indicates that a test group exhibited significant deferred imitation.

Figure 12.

The maximum retention (weeks) of the original memory (*solid lines*) or reactivated memory (*dashed lines*) for infants trained between 6 and 12 months of age. All groups but one were trained for two sessions that were 24 hr apart except, in one instance, session 2 occurred after the longest possible retrieval delay (*max delay*). The memory was reactivated within 1 week of forgetting (*min react delay*) or after the longest possible reactivation delay (*max react delay*).