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Effects of Priming Duration on Retention over the First $1\frac{1}{2}$ Years of Life

ABSTRACT: *Exposing individuals to an isolated component (a prime) of a prior event alleviates its forgetting. Two experiments with 120 human infants between 3 and 18 months of age determined the minimum duration of a prime that can reactivate a forgotten memory and how long the reactivated memory persists. Infants learned an operant task, forgot it, were exposed to the prime, and later were tested for renewed retention. In Experiment 1, the minimum duration of an effective prime decreased logarithmically with age, but was always longer than the duration of a mere glance. In Experiment 2, the reactivated memory was forgotten twice as fast after a minimum-duration prime as after a full-length one, irrespective of priming delay and infant age. These data reveal that the minimum effective prime duration psychophysically equates the accessibility of forgotten memories. We conclude that priming is perceptually based with effects that are organized on a ratio (log) scale. © 2005 Wiley Periodicals, Inc.* Dev Psychobiol 47: 43–54, 2005.

Keywords: *human infants; reactivation; reminder; accessibility of memory; reactivated memory; forgetting; priming duration; memory development; memory retrieval*

Memories that have been forgotten can be reactivated by briefly exposing subjects to a fractional component of the original event in advance of the long-term retention test. This phenomenon is common to all species and ages (Gordon, 1977, 1981; Mactutus, Riccio, & Ferek, 1979; Rovee-Collier & Hayne, 1987; Spear & Parsons, 1976; Tulving, Schacter, & Stark, 1982). In studies with human adults, the term ‘‘priming’’ is usually used instead of ‘‘reactivation,’’ but the phenomenon is the same (Rovee-Collier, 1997; Rovee-Collier, Hayne, & Colombo, 2001). Amnesic adults, for example, complete word stems (the memory primes) with items from a list they had studied just minutes earlier, even though they cannot recognize the same words or even remember having studied them (Warrington & Weiskrantz, 1970). Similarly, infants cannot recognize the prime at the time it is presented (Rovee-Collier et al., 2001). Because the original event is forgotten at the time the prime is presented, memory reactivation is considered to be an automatic (implicit), perceptual priming process. The present experiments examined the minimum duration of a memory prime that is required to reactivate a forgotten memory at different ages throughout the infancy period and the subsequent persistence of the memory it reactivates.

The priming procedure that we used with human infants was modeled after a priming procedure called ‘‘reactivation’’ that Spear and Parsons (1976) originally developed for use with weanling rat pups. They conditioned fear by pairing a flashing light (conditional stimulus; CS) with a shock in the white compartment of a shuttle box for 30 trials. Twenty-seven days later, after pups had forgotten the conditioning event, they gave pups a single shock (the reactivation stimulus). One day later, they placed pups in the white side of the box, lowered the partition separating the two compartments, and turned on the CS. By crossing into the other compartment, pups could turn off the CS. During the long-term test, trained rats that had received the shock 1 day earlier exhibited excellent retention, but those who had not exhibited none. Another control group that was exposed to the prime

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without prior training also exhibited no retention. The latter control condition ensured that the priming procedure, per se, did not produce new learning. Spear and Parsons hypothesized that exposure to the memory prime facilitated retrieval of the latent or dormant memory by increasing the accessibility of its attributes.

Subsequent fear-conditioning studies with animals have shown that if exposure to the memory prime is so long that the memory is recovered while the prime is still present, then the content of the recovered memory can be modified. Gordon, Smith, and Katz (1979), for example, found that exposing adult rats to the conditioned stimulus (CS+) for 15 s restored their memory of active avoidance, but a 75-s exposure did not. They hypothesized that memory reactivation had begun at the time of exposure to the reactivation stimulus and that once the memory was reactivated, the continued presence of the reactivation stimulus had led to extinction. Similarly, Arnold and Spear (1993) found that exposing 18-day-old rat pups to the CS+ for 5 s or 15 s reactivated their forgotten memory of a learned avoidance response, but exposing them to the CS+ for 30 s did not.

Conversely, studies of perceptual priming with human adults have shown that if exposure to the prime is too brief, then it will be ineffective. For example, Schacter, Cooper, Delaney, Peterson, and Tharan (1991) found that a 1-s exposure was not long enough to produce a perceptual priming effect in human adults, but a 5-s exposure was. Using a different task, Musen (1991) found that adults exhibited a perceptual priming effect whether they were exposed to the prime for 10 s or 1 s. The preceding findings from studies using quite different procedures with animals and humans converge in documenting that the minimum exposure time required to successfully prime a memory representation is seconds at most.

In an initial study of priming duration with human infants, Sweeney and Rovee-Collier (2002) trained 6-month-olds to move a mobile by kicking or a miniature train by lever pressing—tasks they forget after 2 weeks. One week after forgetting, they exposed independent groups to a memory prime (the moving mobile or the moving train, respectively) for durations that decreased logarithmically from 30 s to 3.75 s. One day later, they gave infants a long-term retention test to determine whether the prime had reactivated the memory. Irrespective of task, infants exhibited renewed retention after a 7.5-s prime, but not after a 3.75 s prime. Additionally, 6-month-olds remembered both reactivated memory tasks for only half as long after a 7.5-s prime as they had remembered originally (Hartshorn, Rovee-Collier, Gerhardstein, Bhatt, Wondoloski, et al., 1998) or after a 2-min prime (Hildreth & Rovee-Collier, 2002).

Joh, Sweeney, and Rovee-Collier (2002) asked whether the minimum duration of priming in the mobile task also was 7.5 s at 3 months of age. Their study was motivated by evidence that 3-month-olds who received a full-length prime 1 week after forgetting the task exhibit renewed retention more slowly than 6-month-olds (Boller, Rovee-Collier, Borovsky, O'Connor, & Shyi, 1990; Fagen & Rovee-Collier, 1983; Hildreth & Rovee-Collier, 1999) and forget the reactivated memory more rapidly than 6-month-olds (Galluccio, 2001; Hayne & Rovee-Collier, 1995; Hill, Borovsky, & Rovee-Collier, 1988). Joh et al. found that the minimum duration of an effective memory prime at 3 months was longer: Whereas a 7.5-s prime had alleviated forgetting 1 week after 6-month-olds had forgotten the task (Sweeney & Rovee-Collier, 2002), a 2-min exposure was required to do so 1 week after 3-month-olds had forgotten it; however, a 7.5-s prime was sufficient to reactivate 3-month-olds' memory only 1 day after they had forgotten it, and a 3-min prime was required to reactivate it 2 weeks after they had forgotten it. Their finding that the minimum duration of an effective memory prime at 3 months increased with the time since forgetting suggested that the minimum duration indexed the *accessibility* of the forgotten memory.

The studies with 3- and 6-month-olds raise questions regarding the effect of priming duration on retention for older infants, who take so much longer to forget in the first place, exhibit renewed retention after a full-length prime more rapidly, and forget the reactivated memory more slowly. In the present study, therefore, we extended the study of priming duration and its effects on retention to the entire infancy period. In Experiment 1, we sought to determine the minimum duration of a memory prime that could reactivate the forgotten memory of infants who were trained at different ages between 3 and 18 months. In Experiment 2, we asked how a minimum-duration prime affects the persistence of the memory that it reactivates. Throughout the study, the term ''forgetting'' is operationally defined as a failure to respond significantly above baseline during the long-term retention test (Spear, 1978).

EXPERIMENT 1: MINIMUM DURATION OF AN EFFECTIVE PRIME

The first experiment was designed to determine how the minimum duration of an effective memory prime changes over the infancy period. Based on evidence that the minimum duration of an effective prime decreases between 3 and 6 months of age (Joh et al., 2002; Sweeney & Rovee-Collier, 2002), we suspected that it might continue to decrease with age over the infancy period. On the other hand, because infants remember progressively longer as they get older—from 1 to 2 days at 2 months of age to 13 weeks at 18 months of age (Hartshorn, Rovee-Collier, Gerhardstein, Bhatt, Wondoloski, et al., 1998), the training memory also would be progressively older when it was primed, and it seemed improbable that the minimum duration of an effective memory prime would be shorter $3\frac{1}{2}$ months after training (at 18 months) than only 1 day afterward (at 3 months).

Method

Participants. The sample consisted of 48 full-term infants at 9, 12, 15, and 18 months of age who were recruited through published birth announcements, commercial mailing lists, and by word of mouth. Infants were assigned to groups ($n = 6$) as they became available for study.

9-Month-Old Infants. The twelve 9-month-old infants (8 males, 4 females) had a mean age of 279.0 days ($SD = 4.3$) on the first day of training. They were Asian ($n = 1$) and Caucasian ($n = 11$). Parents' mean educational attainment was 15.3 years[1] ($SD = 1.1$), and their mean rank of socioeconomic status (*SEI*[1]; Nakao & Treas, 1992) was 67.75 ($SD = 17.91$).

12-Month-Old Infants. The twelve 12-month-old infants (5 males, 7 females) had a mean age of 372.9 days ($SD = 5.3$) on the first day of training. They were Caucasian ($n = 11$) and of mixed race ($n = 1$). Parents' mean educational attainment was 15.3 years ($SD = 1.1$), and their mean *SEI*, based on occupational information from 83% of the sample, was 71.15 ($SD = 12.53$).

15-Month-Old Infants. The twelve 15-month-olds (7 males, 5 females) had a mean age of 461.6 days ($SD = 3.4$) on the first day of training. They were African American ($n = 1$), Asian ($n = 2$), Caucasian ($n = 8$), and of mixed race ($n = 1$). Parents' mean educational attainment was 15.7 years ($SD = 1.2$), and their mean *SEI*, based on occupational information from 83% of the sample, was 80.06 ($SD = 8.72$).

18-Month-Old Infants. The twelve 18-month-olds (7 males, 5 females) had a mean age of 554.3 days ($SD = 4.6$) on the first day of training. They were African American ($n = 1$), Asian ($n = 4$), Caucasian ($n = 6$), and Hispanic ($n = 1$). Parents' mean educational attainment was 16 years ($SD = 0.0$), and their mean *SEI*, based on occupational information from 92% of the sample, was 65.88 ($SD = 25.09$).

Over all ages, testing was discontinued on additional infants who failed to meet the learning criterion (9 months, $n = 8$; 12 months, $n = 4$; 15 months, $n = 9$; 18 months, $n = 8$) or cried excessively in any of the four sessions (9 months, $n = 1$; 12 months, $n = 2$; 15 months, $n = 9$; 18 months, $n = 4$). Considering the multiple opportunities (sessions) for infants to be lost from the sample, the attrition rate[2] was 35.7%.

Apparatus. Two train sets, counterbalanced within groups, were used. One train set consisted of a blue, aluminum-framed box ($58 \times 58 \times 35$ cm) that was enclosed on three sides by a red curtain with yellow squares. The front window of the box was Plexiglas (58×35 cm). Protruding below it was a blue aluminum lever (30×12.5 cm) which, when pressed, operated a microswitch connected to an interface box and an IBM Thinkpad laptop computer. A Microsoft Power Basic computer program timed the experimental phases, delivered the reinforcer, and registered all microswitch operations that were activated by lever presses in 10-s bins. A white 40-W light bulb in the upper front corners of each box continuously illuminated the interior of the box during all phases.

At the outset of each session, an HO-scale (miniature) train with a black engine and three rail cars (light green, black, and orange) was positioned immediately behind the front window on the circular track (diameter = 47.5 cm). Positioned around the track were a house, Sesame Street characters, and several other small toys and animal figures. The second train set had identical dimensions, but was yellow with a yellow lever. It contained different toys and was enclosed by a blue curtain with pink circles. The train had a black engine and three differently colored rail cars (dark green, brown, and red).

Procedure. All infants were trained, primed, and tested in their homes at a time when they were likely to be playful.

[1]All human studies funded by NIMH are required to report information pertaining to race, ethnicity, and socioeconomic status. Educational attainment, occupational status, and annual income are the major components of socioeconomic status. The index of the parents' mean educational attainment refers to years of formal schooling. It ranges from 6 to 20 years, with 12 years corresponding to a high-school degree, 16 years corresponding to a 4-year college degree, and 20 years corresponding to a doctoral degree. The socioeconomic index (SEI), published by Nakao and Treas (1992), is the recommended source for occupational status. In the SEI, ranks of occupations range from 1 to 100, with higher-paying occupations (e.g., physician and lawyer) being assigned higher ranks.

[2]Because each infant participated in multiple, lengthy sessions, an infant could be lost from the final sample on any of a number of occasions. The older infants who did not reach the learning criterion in this study played with the response lever during the baseline phase, rapidly flipping it up and down. As a result, their baseline rates were so high that it was essentially impossible for them to exceed baseline by 1.5 times (the learning criterion). In fact, when the train moved during the reinforcement phase immediately following the baseline phase, it drew infants' attention away from the lever, and responding by these infants actually decreased. Crying (fussing), the other major source of attrition, usually occurred because according to the mother, the infant was ‘‘cranky’’ that day or wanted to get off her lap before the session was over.

This time varied across infants, but remained relatively constant over sessions for the same infants. The train set was always placed on a table in the same room, and the infant sat in front of it either on the caregiver's lap or in a high chair with the lever chest high.

Infants received two training sessions lasting $5\frac{1}{2}$ min each on 2 consecutive days, were exposed to a memory prime 1 week after they had forgotten the task (2 weeks afterward at 15 and 18 months of age), and were tested for renewed retention 24 hr later. Both training sessions began with a 1-min nonreinforcement period and ended with a 30-s nonreinforcement period. In Session 1, the initial nonreinforcement period was a *baseline phase* when the infant's operant level (the unlearned rate of lever pressing) was measured. In Session 2, the final 30-s nonreinforcement period was the *immediate retention test* when the infant's final level of learning (rate of lever pressing) was measured after zero delay. Interpolated between the two nonreinforcement periods was a 4-min reinforcement period (*acquisition*) during which each lever press was reinforced by train movement. To be included in the final sample, an infant was required to meet a standard learning criterion, defined as lever pressing at least 1.5 times above operant level during 1 min of either acquisition phase.

In Session 3, 9- and 12-month-olds were exposed to a memory prime during a reactivation treatment that was administered 1 week after same-aged infants last remembered the task, and 15- and 18-month-olds were exposed to the memory prime 2 weeks afterward. Selection of the priming delays in the present study was based on standardized reference forgetting functions that detail the degree of retention of infants between 3 and 18 months from the end of training to the delay at which they exhibit no retention of the operant task (Hartshorn, Rovee-Collier, Gerhardstein, Bhatt, Wondoloski, et al., 1998). These reference curves were based on a composite of data from all studies that had used the same tasks and procedural parameters over the past 25 years and have been repeatedly validated since they were first published (DeFrancisco, 2003; Hartshorn, 2003; Hartshorn, Rovee-Collier, Gerhardstein, Bhatt, Klein, et al., 1998; Hildreth & Hill, 2003; Hildreth & Rovee-Collier, 1999, 2002). Because of the considerable variability around the longest delay at which 18-month-olds last remembered the task (Hartshorn, Rovee-Collier, Gerhardstein, Bhatt, Wondoloski, et al., 1998), we extended the reminder delay for the two older age groups by an additional week to ensure that the task was forgotten at the time of priming.

During the reactivation treatment, infants watched the computer-activated train (the memory prime) move noncontingently. When infants were seated in front of the train set, all immediately looked at the complex array of toys, and the movement of the train plus its accompanying noise elicited infants' attention, ensuring that they witnessed even the briefest prime.

When the specified duration of exposure elapsed, the caregiver removed the infant from in front of the train, and the session was over.

The *long-term retention test* (Session 4) occurred 24 hr later during a 2-min nonreinforcement period that was procedurally identical to the baseline phase and the immediate retention test. At this time, the infant's rate of lever pressing was again measured. Because the lever was deactivated during the test, infants' lever presses reflected solely what knowledge they brought into the session and not new learning or savings at the time of testing. Immediately following the long-term retention test, the response-reinforcement contingency was reintroduced during a *motivational control phase* to ensure that the infants who had performed poorly during the long-term test were not ill, tired, or otherwise unmotivated on that particular day. One 15-month-old and one 18-month-old who did not reacquire the contingency during this phase were not included in the final sample.

Selection of the initial minimum duration of the memory prime to be used with 9-month-olds was based on the finding that a memory prime lasting 7.5 s, but not less, was an effective reminder for 6-month-olds (Sweeney & Rovee-Collier, 2002). At each succeeding age, infants were initially exposed to a memory prime for the briefest duration that had successfully reactivated the forgotten memory of the next-youngest age group. Thereafter, our experimental strategy was to successively halve the duration of priming until infants in a given age group exhibited no retention during the long-term retention test (i.e., their memory was not reactivated). This strategy yielded prime durations of 7.5 s and 3.75 s at 9 months of age (7 weeks after training), 7.5 s and 3.75 s at 12 months of age (9 weeks after training), 3.75 s and 1.5 s[3] at 15 months of age (12 weeks after training), and 3.75 s and 1.5 s[3] at 18 months of age (15 weeks after training).

Retention Measures

Retention was assessed via two individual measures of relative responding that we have used in all previous studies of infant memory (Rovee-Collier, 1996). The primary measure, the baseline ratio (LRT/B), expresses each infant's mean response rate during the long-term retention test (LRT) as a fraction of that same infant's Session 1 baseline rate (B). A mean baseline ratio of 1.00 indicates no retention (the H_0); that is, a group responded during LRT at the same rate as before learning the task. A mean baseline ratio significantly greater than 1.00

[3]We used an exposure duration of 1.5 s because the computer program would not activate the train for 1.88 s.

indicates significant retention; that is, a group significantly exceeded its baseline rate during the LRT.

Although the mean baseline ratio indicates whether a group exhibited retention, it does not indicate the degree of retention. The retention ratio (LRT/IRT), the secondary measure, provides information about the degree of retention by comparing each infant's response rate during the LRT as a fraction of that same infant's rate of responding during the immediate retention test (IRT) at the end of Session 2. If a group's mean retention ratio is not significantly less than 1.00, then this result indicates that its rate of responding during the LRT is essentially the same as its rate of responding immediately after training (H_0: no retention deficit). A mean retention ratio significantly less than 1.00, however, indicates that a group's rate of responding has declined significantly from the end of training to the LRT. If a group's mean baseline rate is significantly greater than 1.00 but its mean retention ratio is significantly less than 1.00, then this result is evidence of partial retention. If a group's mean baseline ratio is not significantly greater than 1.00, then a mean retention ratio significantly less than 1.00 provides convergent evidence that the group demonstrated no retention. Finally, if a group's mean baseline ratio is not significantly greater than 1.00 but its mean retention ratio is not significantly less than 1.00, then the retention ratio is considered meaningless.

Prior to performing all analyses, the baseline and retention ratios of each group were tested for the presence of an outlier (median outliers test; Tukey, 1977), defined as a value falling above the 90th percentile for a given group. When an outlier was found, it was replaced with the next-highest baseline or retention ratio within that group, and 1 *df* was subtracted.

Results and Discussion

To determine whether a given test group exhibited significant retention, one-sample directional *t* tests were used to compare the mean baseline and retention ratios of each test group with the corresponding theoretical population ratios of 1.00 (i.e., no retention and no retention deficit, respectively).

9- and 12-Month-Old Infants. Analyses of the mean baseline ratios indicated that both 9- and 12-month-olds exhibited retention 24 hr after being exposed to a memory prime lasting 7.5 s, but not 3.75 s. Nine-month-olds had a mean baseline ratio significantly greater than 1.00 after a 7.5-s prime, $t(5) = 4.47$, $p < .01$, but not after a 3.75-s prime, $t(5) = 1.02$, n.s. Likewise, 12-month-olds had a mean baseline ratio significantly greater than 1.00 after a 7.5-s prime, $t(5) = 3.30$, $p < .05$, but not after a 3.75-s prime, $t(5) = 1.45$, n.s. (see Figure 1). Analyses of the mean retention ratios indicated that at both ages, little or no forgetting was evident after a 7.5-s prime, 9 months: $t(5) = 1.93$, n.s.; 12 months: $t(5) = 1.72$, n.s. Because the mean retention ratio at 9 months was not significantly less than 1.00 after a 3.75-s prime, $t(5) = 1.38$, n.s., it was considered meaningless (i.e., the primary measure indicated no retention); however, the mean retention ratio at 12 months was significantly less than 1.00 after a 3.75-s prime, $t(5) = 5.75$, $p < .01$, providing convergent evidence that the forgotten memory had not been reactivated.

15- and 18-Month-Old Infants. The baseline ratio analyses indicated that both 15- and 18-month-olds exhibited significant retention after being exposed to a memory prime lasting 3.75 s, 15 months: $t(5) = 2.32$, $p < .05$; 18 months: $t(5) = 2.23$, $p < .05$. Only 18-month-olds, however, exhibited significant retention after being exposed to a prime lasting 1.5 s, $t(5) = 2.01$, $p < .05$; 15-month-olds did not, $t(5) < 1$ (see Figure 1). Despite the fact that infants of both ages exhibited significant retention after being exposed to a 3.75-s prime, their mean retention ratios were significantly less than 1.00, 15 months: $t(5) = 2.57$, $p < .05$; 18 months: $t(5) = 1.93$, $p < .05$. The same result was found for the mean retention ratio of 18-month-olds who were exposed to a 1.5-s prime, $t(5) = 13.53$, $p < .01$, suggesting that the memory was not fully reactivated (DeFrancisco, 2003; Sweeney & Rovee-Collier, 2002). The fact that 15-month-olds' mean retention ratio was significantly less than 1.00 after exposure to a 1.5-s prime, $t(5) = 9.99$, $p < .01$, provided convergent evidence that the memory remained forgotten.

Experiment 1 was designed to determine if and how the minimum duration of an effective memory prime changed

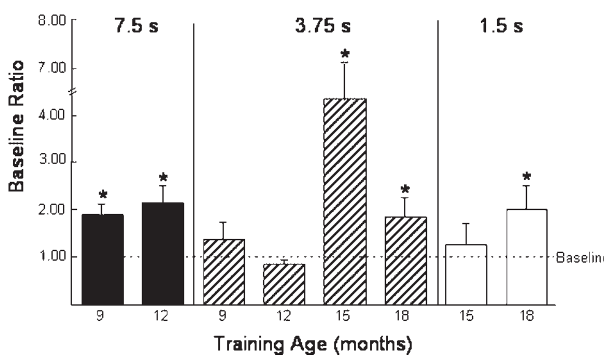

FIGURE 1 Test groups of infants ($n = 6$) who were operantly trained at 9, 12, 15, and 18 months of age and exposed to a memory prime lasting 7.5, 3.75, or 1.5 s. Primes were exposed 1 week (9 and 12 months) or 2 weeks (15 and 18 months) after infants had last remembered the task, and a given age was tested with increasingly briefer primes until it exhibited no retention during the 24-hr test. The dotted line indicates the theoretical population baseline ratio of 1.00 (i.e., no retention). An asterisk indicates significant retention 24 hr after priming (*M* baseline ratio >1.00). Vertical bars indicate +1 *SE*.

with age. Combining the present results with those that had been obtained before revealed that the minimum duration of priming decreases logarithmically from 2 min at 3 months of age (Joh et al., 2002) to 1.5 s at 18 months of age (see Figure 2). The age-related decrease in priming duration is particularly impressive considering that the interval between the last time that infants had remembered the task and the time of priming was held constant (1 week) for infants trained at 3 through 12 months of age and was actually 1 week longer for infants trained at 15 and 18 months of age. Because increasingly older infants initially take increasingly longer to forget the training event, the memory prime was necessarily presented to older infants after an increasingly longer time since training as well. Whereas the prime was exposed only 13 days after training at 3 months of age (when the infants were $3\frac{1}{2}$ months old), for example, it was exposed almost 4 months after training at 18 months of age (when the infants were almost 22 months old). Despite the large difference in the interval between training and priming, the minimum duration of priming actually decreased from 120 s to 1.5 s over this age range. These priming durations fall well within the range of durations that have been used with both animals and human adults (Arnold & Spear, 1993; Deweer & Sara, 1984; Gordon et al., 1979; Musen, 1991; Schacter et al., 1991), indicating that the phenomenon presently observed is neither species nor task specific.

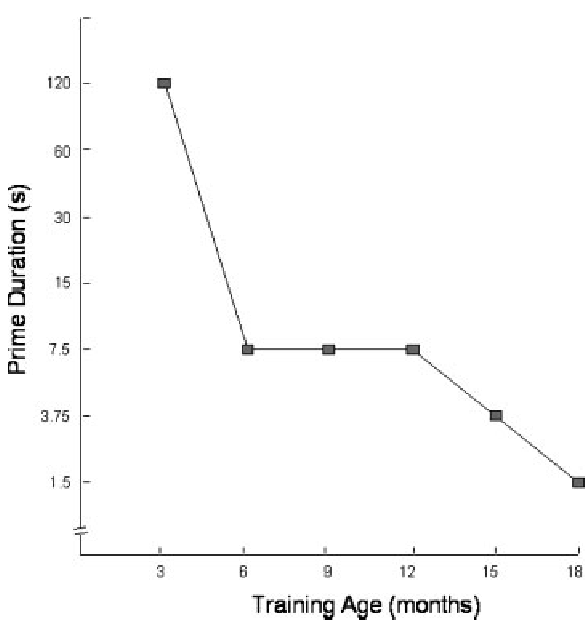

FIGURE 2 Logarithmic decrease with age in the minimum duration of a memory prime required to reactivate a forgotten memory and produce renewed retention 24 hr later. Infants were operantly trained between 3 and 18 months of age, and the prime was exposed either 1 week (9 and 12 months) or 2 weeks (15 and 18 months) after forgetting. Data at 3 months and 6 months were drawn from Joh et al. (2002) and Sweeney and Rovee-Collier (2002), respectively.

The fact that an increasingly briefer prime can reactivate the forgotten memory as infants become increasingly older is consistent with evidence that the speed of information processing increases with age (Barr, Dowden, & Hayne, 1996; Colombo & Mitchell, 1990; Diamond, 1990; Hildreth & Rovee-Collier, 1999). For example, Barr et al. (1996) found that 6-month-olds exhibited significant deferred imitation after a 24-hr delay if they viewed a demonstration of the target actions for 60 s. In contrast, 12-month-olds could imitate the actions 24 hr later if they viewed the demonstration for only 30 s. Likewise, 6-month-olds required a response period of 120 s to imitate the modeled actions, whereas 12-month-olds required a response period of only 90 s to do so. Diamond (1990) found that increasingly older infants required progressively less time to encode a stimulus in a visual paired-comparison task, and Colombo and Mitchell (1990) reported that increasingly older infants spent progressively less time looking at the target, but solved visual discrimination tasks with increasingly greater success.

The age-related decrease in the minimum duration of priming cannot be attributed to a maturational increase in processing speed. Hildreth-Bearce and Rovee-Collier (2004) found that the minimum duration of exposure to an effective memory prime at 3 months was sharply reduced by exposing infants to a full-length prime on a prior occasion. Their results paralleled evidence that the latency of renewed retention after a reactivation treatment, which also reflects the accessibility of the forgotten memory, was dramatically decreased by exposing 3-month-olds to the memory prime once before (Hayne, Gross, Hildreth, & Rovee-Collier, 2000). These findings, together with those of Joh et al. (2002), indicated that the minimum duration of an effective memory prime indexes the accessibility of a forgotten or ‘‘subzero’’ memory. From this, it follows that very brief primes reactivate the forgotten memories of older infants after relatively long delays simply because their memories, even though forgotten, are still relatively more accessible at the time they are primed than the forgotten memories of much younger infants, whose forgetting functions are much steeper. Also contributing to this result may be the greater number of retrieval routes that presumably arise in the course of generalized, age-related retrieval experience.

Finally, is the minimum duration of exposure to an effective prime determined by the age of the memory or by how long it has been forgotten? The findings of Experiment 1 reveal that the answer should be framed in terms of how long the memory has been forgotten, irrespective of its age. For example, because 12-month-olds forget the task after 8 weeks, their memory is four times older when it is forgotten than the memory of 6-month-olds, who forget the task after only 2 weeks; however, at both ages, the memory can be reactivated 1 week after it was forgotten by a prime of the same duration—7.5 s. This result indicates that the accessibility of the forgotten memory, not its age, determines the minimum duration for which a prime must be exposed to reactivate it.

EXPERIMENT 2: FORGETTING THE REACTIVATED MEMORY

Having determined the minimum duration of exposure to an effective memory prime during the infancy period, we next asked how exposing infants to such a brief prime affects the persistence of the memory it reactivates. Hildreth and Rovee-Collier (2002) reported that infants who are operantly trained between 3 and 12 months of age forget the reactivated memory and the original memory at approximately the same rate; however, Sweeney and Rovee-Collier (2002) found that 6-month-olds forgot the reactivated memory twice as fast as the original one after a minimum-duration prime. Experiment 2 was designed to determine whether exposing infants to a minimum-duration prime produces a similar effect at other ages.

Method

Participants. The total sample consisted of 72 healthy, full-term infants at 3, 9, 12, 15, and 18 months of age who were recruited as before and assigned to groups ($n = 6$) as they became available for study.

3-Month-Old Infants. The twenty-four 3-month-olds (11 males, 13 females) had a mean age of 95.1 days ($SD = 7.1$) on the first day of training. They were Asian ($n = 4$), Caucasian ($n = 19$), and Hispanic ($n = 1$). Parents' mean educational attainment was 15.3 years ($SD = 1.1$), and their mean *SEI*, based on occupational information from 87.5% of the sample, was 64.33 ($SD = 19.96$).

9-Month-Old Infants. The twelve 9-month-olds (7 males, 5 females) had a mean age of 277.9 days ($SD = 8.6$) on the first day of training. They were African-American ($n = 2$), Asian ($n = 1$), and Caucasian ($n = 9$). Parents' mean educational attainment was 15.8 years ($SD = 0.6$), and their mean *SEI* was 71.37 ($SD = 14.04$).

12-Month-Old Infants. The twelve 12-month-old infants (6 males, 6 females) had a mean age of 373.7 days ($SD = 8.7$) on the first day of training. They were Asian ($n = 1$) and Caucasian ($n = 11$). Parents' mean educational attainment was 15.7 years ($SD = 0.8$), and their mean *SEI*, based on occupational information from 75% of the sample, was 68.23 ($SD = 17.04$).

15-Month-Old Infants. The twelve 15-month-olds (10 males, 2 females) had a mean age of 467.0 days ($SD = 4.1$) on the first day of training. They were Asian ($n = 1$), Caucasian ($n = 10$), and of mixed race ($n = 1$). Parents' mean educational attainment was 15.2 years ($SD = 1.6$), and their mean *SEI*, based on occupational information from 87.5% of the sample, was 75.34 ($SD = 21.09$).

18-Month-Old Infants. The twelve 18-month-olds (6 males, 6 females) had a mean age of 557.6 days ($SD = 4.0$) on the first day of training. They were Asian ($n = 3$), Caucasian ($n = 8$), and of mixed race ($n = 1$). Parents' mean educational attainment was 15.8 years ($SD = 0.6$), and their mean *SEI*, based on occupational information from 58.3% of the sample, was 65.15 ($SD = 25.19$).

Over all ages, testing was discontinued on additional infants who failed to meet the learning criterion (3 months, $n = 3$; 9 months, $n = 4$; 12 months, $n = 5$; 15 months, $n = 4$; 18 months, $n = 6$) or cried excessively in any of the four sessions (3 months, $n = 4$; 9 months, $n = 2$; 12 months, $n = 1$; 18 months, $n = 4$). Considering the multiple opportunities (sessions) for infants to be lost from the sample, the attrition rate[2] was 20.8%.

Apparatus. The apparatus used with 9- to 18-month-old infants was the same as in Experiment 1. The 3-month-olds were trained, reminded, and tested in their home cribs at a time they were likely to be playful. The apparatus consisted of one of two hand-painted wooden mobiles, counterbalanced within groups, that were composed of five highly detailed objects and jingle bells (Nursery Plastics, Inc., Models 801 and 809). Because the mobiles were not commercially available, infants had no prior exposure to them.

During each session, the mobile was hung from an aluminum L-shaped stand (BCS Machine Co., South Plainfield, NJ) that was clamped to the crib rail nearest the experimenter. An identical "empty" stand was clamped to the opposite rail. The end and side panels of the crib were covered with one of two colorful cloth drapes (red with blue felt stripes, yellow with green felt triangles), also counterbalanced within groups. A white satin ribbon was tied to the infant's ankle and connected to one of the two mobile stands, depending on the phase of the session. During the reactivation treatment, infants were situated in a sling-seat inside the crib.

Procedure. As in Experiment 1, all infants received two operant training sessions separated by 24 hr, a reactivation treatment, and an LRT after a specified delay. During the reactivation treatment, the prime was exposed for the minimum duration that had been effective in recovering the forgotten memory in Experiment 1 at 9, 12, 15, and 18 months of age. At 3 months, the prime was exposed for the minimum duration that had successfully reactivated the forgotten memory either 1 week after forgetting (120 s) or 1 day afterward (7.5 s) (Joh et al., 2002).

Between 3 and 12 months of age, a memory that is reactivated by a full-length (2 min at 6–12 months; 3 min at 3 months) prime persists for the same duration as the original memory (Hildreth & Rovee-Collier, 2002), but at 6 months of age, the reactivated memory persists for only half as long after a minimum-duration prime as after the full-length prime (Sweeney & Rovee-Collier, 2002). In Experiment 2, therefore, we began testing 3-, 9-, 12-, 15-, and 18-month-olds given a minimum-duration prime after a delay half as long as same-age infants originally remember the task (Hartshorn, Rovee-Collier, Gerhardstein, Bhatt, Wondoloski, et al., 1998; Hsu, 2004). Depending on whether infants of a given age exhibited evidence that they remembered the reactivated memory after the initial test delay, our experimental strategy was to either progressively increase the test delay until infants of a given age finally failed to exhibit retention or progressively decrease the test delay until infants of a given age finally did exhibit retention, respectively. This strategy yielded two independent test groups at each age except 3 months, when four groups were tested because a minimum-duration memory prime was exposed after two different delays.

At 3 months, the memory prime was exposed for 120 s approximately 1 week after forgetting or for 7.5 s 1 day after forgetting. In each instance, independent groups were tested either 3 or 2 days after priming. At 9 months, the prime was exposed for 7.5 s 1 week after forgetting, and testing occurred either 5 or 3 weeks afterward; at 12 months, the prime also was exposed for 7.5 s 1 week after forgetting, and testing occurred either 6 or 4 weeks afterward; at 15 months, the prime was exposed for 3.75 s 2 weeks after forgetting, and testing occurred either 4 or 6[4] weeks afterward; at 18 months, the prime also was exposed for 3.75 s[5] 2 weeks after forgetting, and testing occurred either 9 or 7 weeks afterward.

Results and Discussion

One-sample directional t tests were again used to compare the mean baseline and retention ratios of each test group with the corresponding theoretical baseline and retention ratios of 1.00 (i.e., no retention and no retention deficit, respectively).

3-Month-Old Infants. Infants who were exposed to the memory prime for 120 s on Day 13 had a mean baseline ratio that did not significantly exceed 1.00 either 3 or 2 days later, Day 16: $t(5) = 1.51$, n.s.; Day 15: $t(5) < 1$ (see Figure 3). Their mean retention ratios were significantly less than 1.00 after both test delays, Day 16: $t(5) = 11.14$, $p < .01$; Day 15: $t(5) = 8.80$, $p < .01$, providing convergent evidence of no retention. Likewise, 3-month-olds who were exposed to the memory prime for 7.5 s on Day 6 had mean baseline ratios that did not significantly exceed 1.00 either 3 or 2 days later, Day 9: $t(5) < 1$; Day 8: $t(5) = 1.45$, n.s., and mean retention ratios that were significantly less than 1.00 after both delays, Day 9: $t(5) = 15.24$, $p < .01$; Day 8: $t(5) = 3.20$, $p < .01$, again providing convergent evidence of no retention. We previously found that 3-month-olds remember the mobile task for 5 days after the end of original training (Galluccio, 2001; Hayne, 1990; Joh et al., 2002); however, when exposed to a full-length (3-min) memory prime on Day 13, they remember the reactivated memory for only 3 days (Hayne & Rovee-Collier, 1995; Rovee-Collier, Enright, Lucas, Fagen, & Gekoski, 1981).

9-Month-Old Infants. Analyses of the mean baseline ratios indicated that 9-month-olds who were exposed to the memory prime for 7.5 s exhibited no retention when

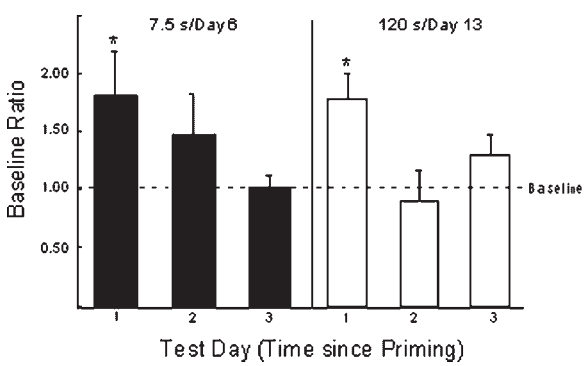

FIGURE 3 Retention of the reactivated memory following exposure to two different minimum-duration primes after two different delays at 3 months of age. Left panel: Retention of infants exposed to a 7.5-s memory prime 6 days after training (1 day after forgetting) and tested 3 or 2 days later. Right panel: Retention of infants exposed to a 120-s memory prime 13 days after training ($\approx$1 week after forgetting) and tested 3 or 2 days later. The dotted line indicates the theoretical population baseline ratio of 1.00 (i.e., no retention). An asterisk indicates significant retention 24 hr after priming (M baseline ratio $>$1.00). Vertical bars indicate $+1$ SE. The 24-hr data points were drawn from Joh et al. (2002).

[4]Because infants trained at 15 months and exposed to a 10-s memory prime 2 weeks after forgetting had previously exhibited no retention 7 weeks later (Hsu, 2004), we did not test infants who were exposed to a 3.75-s prime after a delay longer than 6 weeks.

[5]Half of the infants trained at 18 months exhibited robust retention after a 1.5-s prime, even though it was not presented until nearly 4 months after training, but the remaining half exhibited none. Thus, although the 18-month group as a whole exhibited significant retention, we thought it unwise to assess their rate of forgetting after a 1.5-s prime.

tested 5 weeks later, $t(5) < 1$, but they did when tested 3 weeks later, $t(5) = 4.03$, $p < .01$; however, at both test points, infants' mean retention ratios were significantly less than 1.00, 5 weeks: $t(5) = 4.48$, $p < .01$; 3 weeks: $t(5) = 3.48$, $p < .01$. The retention ratio analyses provided convergent evidence of no retention 5 weeks after priming and evidence of partial retention 3 weeks afterward. Hartshorn, Rovee-Collier, Gerhardstein, Bhatt, Wondoloski, et al. (1998) found that 9-month-olds exhibit retention of the original memory 6 weeks after training.

12-Month-Old Infants. Analyses of the mean baseline ratios indicated that 12-month-olds exhibited no retention when tested 6 weeks after a 7.5-s exposure to the prime, $t(5) < 1$, but they did when tested 4 weeks afterward, $t(5) = 2.16$, $p < .05$. As at 9 months, infants' mean retention ratios were significantly less than 1.00 at both test points, 6 weeks: $t(5) = 6.22$, $p < .01$; 4 weeks: $t(5) = 3.60$, $p < .01$, again providing convergent evidence of no retention 6 weeks after priming and evidence of partial retention 4 weeks afterward. Hartshorn, Rovee-Collier, Gerhardstein, Bhatt, Wondoloski, et al. (1998) found that 12-month-olds exhibit retention of the original memory 8 weeks after training.

15-Month-Old Infants. The baseline ratio analyses indicated that 15-month-olds exhibited marginally significant retention 4 weeks after priming and significant retention 6 weeks[4] afterward, 4 weeks: $t(5) = 1.84$, $p = .06$; 6 weeks: $t(5) = 3.04$, $p < .05$. Both mean retention ratios were significantly less than 1.00, 4 weeks: $t(5) = 3.79$, $p < .01$; 6 weeks: $t(4) = 5.70$, $p < .01$, indicating that infants exhibited only partial retention after both test delays. Hartshorn, Rovee-Collier, Gerhardstein, Bhatt, Wondoloski, et al. (1998) found that 15-month-olds originally remembered for 10 weeks after training.

18-Month-Old Infants. The baseline ratio analyses revealed that 18-month-olds exhibited no retention 9 weeks after being exposed to a 3.5-s prime, $t(4) < 1$, but they did exhibit significant retention 7 weeks afterward, $t(5) = 2.40$, $p < .05$. Again, both test groups had mean retention ratios significantly less than 1.00, 9 weeks: $t(4) = 4.03$, $p < .01$; 7 weeks: $t(5) = 4.95$, $p < .05$. Hartshorn, Rovee-Collier, Gerhardstein, Bhatt, Wondoloski, et al. (1998) found that 18-month-olds originally remembered for 13 weeks after training.

In Experiment 2, when infants of all ages were exposed to a memory prime for the minimum amount of time necessary to yield significant retention 1 day later, infants remembered the reactivated memory for only half as long as when same-age infants were exposed to a full-length prime (Hildreth & Rovee-Collier, 2002; Hsu, 2004) (see Figure 4). Moreover, when retention was exhibited, it was only partial, suggesting that the minimum-duration prime had not reactivated the full complement of forgotten memory attributes (DeFrancisco, 2003; Sweeney & Rovee-Collier, 2002). These data are consistent with the prior conclusion that memory reactivation is not an all-or-none phenomenon (Sweeney & Rovee-Collier, 2002). If it were, then the persistence of the reactivated memory at a given age would be the same irrespective of how long it was primed. That is, the memory would either be recovered fully or it would not be recovered at all.

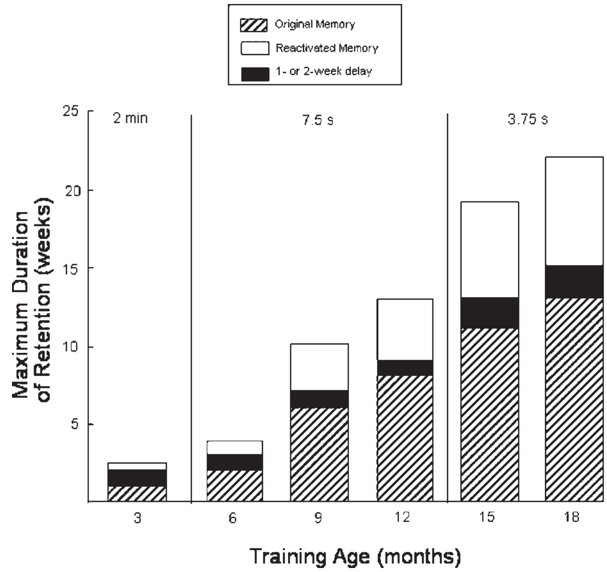

FIGURE 4 The total accessibility of a training memory that was reactivated by a minimum-duration prime. The height of each column indicates the total period of time, in weeks, that infants who were operantly trained between 3 and 18 months of age and later were exposed to a minimum-duration prime remembered the training memory. Depicted in each column are the duration of the original memory (stripes) and the 1- or 2-week period between forgetting and priming (black). The height of the white bar in each column depicts the persistence of the memory that was reactivated by the minimum-duration prime. Note that the height of the white column is half the height of the striped portion in the column at each age. These data reveal that an increasingly briefer prime extended the absolute duration of retention increasingly longer with age, but the relative duration for which a minimum-duration prime extended retention was constant over age. The duration of the original memory of infants trained between 3 and 18 months of age is from Hartshorn, Rovee-Collier, Gerhardstein, Bhatt, Wondoloski, et al. (1998).

GENERAL DISCUSSION

Two major empirical findings emerged from the present study. First, the minimum duration of exposure to a prime that is sufficient to recover the forgotten memory 24 hr later decreases logarithmically over the infancy period, from 2 min for infants trained at 3 months to 1.5 s for infants trained at 18 months (Experiment 1). Even at its briefest, however, the prime had to last longer than is required for an individual to merely glance at a stimulus, which takes 1 s (Hartshorn & Rovee-Collier, 1997; Volosin & Rovee, 1976) to be effective. In retrospect, this constraint ensures that in the course of everyday life, each sweep of the gaze across the busy landscape will not automatically trigger a flood of latent memories; rather, a forgotten memory will be reactivated only if the infant's gaze alights and briefly rests on a potential retrieval cue. Second, a memory that is reactivated by a minimum-duration prime is considerably less enduring than a memory reactivated by a full-length prime (Experiment 2).

These empirical findings lead to two major insights. *First, the minimum effective exposure duration psychophysically (subjectively) equates primes across ages as well as over delays within a given age in terms of the relative accessibility of the forgotten memory.* Even though the minimum duration of exposure to an effective memory prime decreased logarithmically over the infancy period, the memory that it reactivated was subsequently forgotten at the same relative rate despite vast differences in the absolute duration of primes, in the intervals that elapsed between forgetting and priming, in the duration of original retention, and in infant age. Across ages, for example, the relative persistence of the memory reactivated by a minimum-duration prime was the same at 3 and 18 months of age, even though the prime durations were at or near opposite prime extremes and the training memory had been forgotten for vastly different periods—on the order of months—at the two ages. Likewise, within a given age, presenting a 7.5-s prime only 1 day after 3-month-olds last remembered the task yielded exactly the same relative persistence of the reactivated memory as presenting a 120-s prime 1 week afterward (see Figure 3).

Second, the consistent finding that a variety of different priming manipulations at a variety of different ages affect infant retention on a ratio (log) scale rather than an interval scale reveals that this characteristic is a fundamental property of priming during early development. This insight is consistent with the conclusion that reactivation is an automatic, perceptual priming process (Rovee-Collier et al., 2001). A log function is evidence that the underlying process is perceptual.

In the current study, for example, we found that the minimum effective priming duration decreased logarithmically between 3 and 18 months of age and that the persistence of the memory it reactivates was reduced by a constant fraction of one half. In previous research, we found that the speed with which retention is renewed after a full-length prime increased logarithmically between 3 and 12 months of age (Hildreth & Rovee-Collier, 1999), as did the persistence of the memory reactivated by a full-length prime between 3 and 12 months (Hildreth & Rovee-Collier, 2002). Additionally, we found that although the *absolute* upper limit of reactivation (i.e., the longest point since the end of training at which a forgotten memory can be successfully reactivated) increased linearly from 3 to 12 months, the *relative* upper limit of reactivation was a constant 4:1 ratio of the original duration of infants' retention (Hildreth & Hill, 2003). Most recently, we found that the duration for which a reinstatement reminder extends 3-month-olds' retention increased on a ratio scale as a function of when it was presented: Presenting the reinstatement 3 days after training (i.e., the midpoint of the forgetting function) doubled retention, but presenting it 5 days afterward (i.e., the end of the forgetting function) quadrupled it (Galluccio & Rovee-Collier, 2005).

Finally, we note that even though infants remember only half again as long as after a minimum-duration prime as they had remembered originally and after a full-length prime (Hildreth & Rovee-Collier, 2002), the absolute period of time for which the reactivated memory is available to guide behavior is still quite considerable. Whereas the reactivated memory remained accessible for only 1 additional day at 3 months of age, it remained accessible for almost a week at 6 months of age, for almost a month at 9 and 12 months of age, for $1\frac{1}{2}$ months at 15 months of age, and for almost 2 months at 18 months of age (see Figure 4, white columns). When the duration of the reactivated memory is added to the duration of the original memory (see Figure 4, striped columns) plus the interval between the last point at which infants exhibited retention and subsequent priming (see Figure 4, black columns), even a minimum-duration prime ensures that the memory of an original event will remain available to guide behavior for periods of 5 months or more at the oldest age.

NOTES

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REFERENCES

Arnold, H. M., & Spear, N. E. (1993). Order and duration of stimuli are important determinants of reactivation. Animal Learning & Behavior, 21, 391–398.

Barr, R., Dowden, A., & Hayne, H. (1996). Developmental changes in deferred imitation by 6- to 24-month-old infants. Infant Behavior and Development, 19, 159–170.

Boller, K., Rovee-Collier, C., Borovsky, D., O'Connor, J., & Shyi, G. C.-W. (1990). Developmental changes in the time-dependent nature of memory retrieval. Developmental Psychology, 26, 770–779.

Colombo, J., & Mitchell, D. W. (1990). Individual differences in early visual attention: Fixation time and information processing. In J. Colombo & J. W. Fagen (Eds.), Individual differences in infancy (pp.193–227). Hillsdale, NJ: Erlbaum.

DeFrancisco, B. S. (2003). The effects of cue and context changes on reactivation in the first year of life. Unpublished doctoral dissertation, Rutgers University, New Brunswick, NJ.

Deweer, B., & Sara, J. S. (1984). Background stimuli as a reminder after spontaneous forgetting: Role of duration of cuing and cuing-test interval. Animal Learning & Behavior, 12, 238–247.

Diamond, A. (1990). Rate of maturation of the hippocampus and the developmental progression of children's performance on the delayed non-matching to sample and visual paired comparison tasks. In A. Diamond (Ed.), The development and neural bases of higher cognitive functions (Vol. 608, pp. 394–426). Annals of the New York Academy of Sciences. New York: New York Academy of Sciences.

Fagen, J. W., & Rovee-Collier, C. (1983, December 23). Memory retrieval: A time-locked process in infancy. Science, 222, 1349–1351.

Galluccio, L. (2001, May). Distorting infants' reactivated memories: Passive- vs. active-exposure effects. Unpublished doctoral dissertation, Rutgers University, New Brunswick, NJ.

Galluccio, L., & Rovee-Collier, C. (2005). Nonuniform effects of reinstatement within the time window. Learning and Motivation.

Gordon, W. C. (1977). Susceptibility of a reactivated memory to the effects of strychnine: A time-dependent phenomenon. Physiology & Behavior, 18, 95–99.

Gordon, W. C. (1981). Mechanisms of cue-induced retention enhancement. In N. E. Spear & R. R. Miller (Eds.), Information processing in animals: Memory mechanisms (pp. 319–339). Hillsdale, NJ: Erlbaum.

Gordon, W. C., Smith, G., & Katz, D. (1979). Dual effects of response blocking following avoidance learning. Behavioural Research & Therapy, 17, 79–83.

Hartshorn, K. (2003). Reinstatement maintains a memory in human infants for $1\frac{1}{2}$ years. Developmental Psychobiology, 42, 269–282.

Hartshorn, K., & Rovee-Collier, C. (1997). Infant learning and long-term memory at 6 months: A confirming analysis. Developmental Psychobiology, 30, 151–170.

Hartshorn, K., Rovee-Collier, C., Gerhardstein, P., Bhatt, R. S., Klein, P. J., Aaron, F., Wondoloski, T. L., & Wurtzel, N. (1998). Developmental changes in the specificity of memory over the first year of life. Developmental Psychobiology, 33, 61–78.

Hartshorn, K., Rovee-Collier, C., Gerhardstein, P., Bhatt, R. S., Wondoloski, T. L., Klein, P. J., Gilch, J., Wurtzel, N., & Campos-de-Carvalho, M. (1998). The ontogeny of long-term memory over the first year-and-a-half of life. Developmental Psychobiology, 32, 69–89.

Hayne, H. (1990). The effect of multiple reminders on long-term retention in human infants. Developmental Psychobiology, 23, 453–477.

Hayne, H., Gross, J., Hildreth, K., & Rovee-Collier, C. (2000). Repeated reminders increase the speed of memory retrieval by 3-month-old infants. Developmental Science, 3, 312–318.

Hayne, H., & Rovee-Collier, C. (1995). The organization of reactivated memory in infancy. Child Development, 66, 893–906.

Hildreth, K., & Hill, D. (2003). Retrieval difficulty and retention of reactivated memories over the first year of life. Developmental Psychobiology, 43, 216–229.

Hildreth, K., & Rovee-Collier, C. (1999). Decreases in the response latency to priming over the first year of life. Developmental Psychobiology, 35, 276–289.

Hildreth, K., & Rovee-Collier, C. (2002). Forgetting functions of reactivated memories over the first year of life. Developmental Psychobiology, 41, 277–288.

Hildreth-Bearce, K., & Rovee-Collier, C. (2004, May). Prior reminding reduces the time needed for future reminding at 3 months. Paper presented at the meeting of the International Conference on Infant Studies, Chicago.

Hill, W., Borovsky, D., & Rovee-Collier, C. (1988). Continuities in infant memory development over the first half-year. Developmental Psychobiology, 21, 43–62.

Hsu, V. C. (2004, May). The effects of memory reactivation on retention at 15 and 18 months. Unpublished master's thesis, Rutgers University, New Brunswick, NJ.

Joh, A., Sweeney, B., & Rovee-Collier, C. (2002). Minimum duration of reactivation at 3 months of age. Developmental Psychobiology, 40, 23–32.

Mactutus, C. F., Riccio, D. C., & Ferek, J. M. (1979, June 22). Retrograde amnesia for old (reactivated) memory: Some anomalous characteristics. Science, 204, 1319–1320.

Musen, G. (1991). Effect of verbal labeling and exposure duration on implicit memory for visual patterns. Journal of Experimental Psychology: Learning, Memory, and Cognition, 17, 954–962.

Nakao, K., & Treas, J. (1992). The 1989 Socioeconomic Index of Occupations: Construction from the 1989 Occupational Prestige Scores (General Social Survey Methodological Reports No. 74). Chicago: NORC.

Rovee-Collier, C. (1996). Measuring infant memory: A critical commentary. Developmental Review, 16, 301–310.

Rovee-Collier, C. (1997). Dissociations in infant memory: Rethinking the development of implicit and explicit memory. Psychological Review, 104, 467–498.

Rovee-Collier, C., Enright, M. K., Lucas, D., Fagen, J. W., & Gekoski, M. J. (1981). The forgetting of newly acquired and reactivated memories of 3-month-old infants. Infant Behavior and Development, 4, 317–331.

Rovee-Collier, C., & Hayne, H. (1987). Reactivation of infant memory: Implications for cognitive development. In H. W. Reese (Ed.), Advances in child development and behavior (Vol. 20, pp. 185–238). New York: Academic Press.

Rovee-Collier, C., Hayne, H., & Colombo, M. (2001). The development of implicit and explicit memory. Amsterdam/ Philadelphia: John Benjamins.

Schacter, D. L., Cooper, L. A., Delaney, S. M., Peterson, M. A., & Tharan, M. (1991). Implicit memory for possible and impossible objects: Constraints on the construction of structural descriptions. Journal of Experimental Psychology: Learning, Memory, and Cognition, 17, 3–19.

Spear, N. E. (1978). The processing of memories: Forgetting and retention. Hillsdale, NJ: Erlbaum.

Spear, N. E., & Parsons, P. J. (1976). Analysis of a reactivation treatment: Ontogenetic determinants of alleviated forgetting. In D. L. Medin, W. A. Roberts, & R. T. Davis (Eds.), Processes of animal memory (pp. 135–165). Hillsdale, NJ: Erlbaum.

Sweeney, B., & Rovee-Collier, C. (2002). The minimum duration of reactivation at 6 months: Latency of retrieval and reforgetting. Infant Behavior and Development, 24, 259–280.

Tukey, J. W. (1977). Exploratory data analysis. Reading, MA: Addison-Wesley.

Tulving, E., Schacter, D. L., & Stark, H. A. (1982). Priming effects in word-fragment completion are independent of recognition memory. Journal of Experimental Psychology: Learning, Memory, and Cognition, 8, 336–342.

Volosin, D., & Rovee, C. (1976, April). Simultaneous habituation of multiple visual stimuli using a free-operant procedure. Paper presented at the meeting of the Eastern Psychological Association, New York.

Warrington, E. K., & Weiskrantz, L. (1970). Amnesic syndrome: Consolidation or retrieval? Nature, 228, 629–630.