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The Specificity of Priming Effects over the First Year of Life

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Abstract

Despite its significance for the enduring effect of early experience, the specificity of priming on infants' forgotten memories is unknown. This study determined the impact of cue and context changes on the initial priming and retrieval of the reactivated memory over the first postnatal year. Infants were operantly trained with a distinctive cue in a particular context. After forgetting, they were primed and tested for renewed retention with combinations of old and new cues and contexts. Priming was hyperspecific to the original cue and original context at all but 12 months, when the memory was reactivated in a novel context. At 9–12 months, the reactivated memory generalized to a novel cue or context. At younger ages, the reactivated memory generalized only after a very brief prime. These findings indicate that priming in early infancy is initially conservative, buffering against recovering memories in contexts that might no longer be appropriate.

Keywords

memory; forgetting; reactivation; priming; operant conditioning; human infants; retention; context; development; generalization; specificity; attention-gating model

INTRODUCTION

A memory is a collection of attributes that represent what an individual perceived during encoding (e.g., Estes, 1973; Medin, 1976; Tulving, 1983; Underwood, 1969). These memory attributes include the characteristics of the original event as well as the context in which it occurred. According to the encoding specificity principle, the target memory will be retrieved only if the attributes in the retrieval cue match the attributes in the original memory representation (Tulving & Thomson, 1973). This principle has major implications for the enduring effects of early experiences. For early experiences to affect subsequent behavior, they must be remembered. The longer since an event occurred, however, the more likely the conditions of encoding—real and perceived—will have changed, making it less likely that the event memory will be retrieved. Campbell and Spear (1972) have argued that perceptual changes in rapidly developing organisms are a major source of their rapid forgetting.

After infants' memories have been forgotten, they can be recovered by a reactivation treatment (Spear & Parsons, 1976). At this time, the organism is briefly exposed to an isolated portion of the original training event as a memory prime. According to Spear and Parsons, the reactivation treatment alleviates forgetting by priming the dormant memory and increasing its accessibility to subsequent retrieval cues. Reactivation is an automatic, perceptual identification process that is functionally identical to priming in studies with amnesics (Rovee-Collier, 1997; Rovee-Collier, Hayne, & Colombo, 2001). For both adults and infants, the prime

reactivates a preexisting memory representation at a time when they cannot recognize the target item (Rovee-Collier et al., 2001; Schacter, 1990, 1992; Tulving & Schacter, 1990; Vriezen, Moscovitch, & Bellos, 1995). Apparently, priming increases the accessibility of target memories that are inaccessible but still available (Tulving & Pearlstone, 1966).

The encoding specificity principle has received substantial support in operant and deferred imitation studies with human infants. In operant tasks, fairly small changes in the training cue and/or context impair retention between 2 and 6 months of age (Fagen, Rovee, & Kaplan, 1976; Hayne, Greco, Earley, Griesler, & Rovee-Collier, 1986; Hill, Borovsky, & Rovee-Collier, 1988; Rovee-Collier, Schechter, Shyi, & Shields, 1992). In these tasks, infants learn to activate a particular crib mobile or toy train and are tested with either the original training cue or a novel one in either the same or a different context. In deferred imitation tasks, 24-hr retention is similarly impaired by cue and/or context changes between 6 and 12 months of age (Hayne, Boniface, & Barr, 2000; Learmonth, Lamberth, & Rovee-Collier, 2004). In this task, infants observe a series of actions being modeled on a particular hand puppet, and their ability to imitate those actions is tested after a delay with either the same or a different puppet in either the same or a different context.

In both operant and deferred imitation tasks, the range of stimuli that are effective retrieval cues broadens with age (Barnat, Klein, & Meltzoff, 1996; Hartshorn, Rovee-Collier, Gerhardstein, Bhatt, Klein, et al., 1998; Hayne, Boniface, et al., 2000; Hayne, MacDonald, & Barr, 1997) except after relatively long test delays (Hartshorn, Rovee-Collier, Gerhardstein, Bhatt, Klein, et al., 1998); and changes in the training context produce a similar pattern throughout the first year of life except at 6 months, when the pattern is reversed (Boller, Rovee-Collier, Gulya, & Prete, 1996; Borovsky & Rovee-Collier, 1990; Hartshorn, Rovee-Collier, Gerhardstein, Bhatt, Klein, et al., 1998). Hayne et al. (1997) view the age-related increase in the range of retrieval cues as a hallmark of memory development.

Whether the encoding specificity principle also applies to memories that have been forgotten and then reactivated is unknown, but operant studies with 3- and 6-month-olds suggest that it does. The cues required to reactivate a forgotten memory and subsequently retrieve it at these ages are highly specific to the cue and context that were present during original encoding (Boller & Rovee-Collier, 1994; Borovsky & Rovee-Collier, 1990; Butler & Rovee-Collier, 1989; Hartshorn & Rovee-Collier 1997; Harts-horn, Rovee-Collier, Gerhardstein, Bhatt, Wondoloski, et al., 1998; Hayne, Rovee-Collier, & Borza, 1991; Hayne & Rovee-Collier, 1995; Rovee-Collier, Patterson, & Hayne, 1985). Because young infants forget relatively rapidly, however, the conditions at encoding are unlikely to have changed much by the time of reactivation. Three-month-olds, for example, remember the training event for 5 days, and 6-month-olds remember it for 14 days (Hartshorn, Rovee-Collier, Gerhardstein, Bhatt, Wondoloski, et al., 1998). For older infants, who remember increasingly longer, the circumstances of original encoding are more likely to have changed. Nine-month-olds, for example, remember the training event for 6 weeks, and 12-month-olds remember it for 2 months (Hartshorn, Rovee-Collier, Gerhardstein, Bhatt, Wondoloski, et al., 1998).

The impact of cue and context changes on priming and retrieval of the reactivated memory problem has major implications for the enduring impact of early experiences. If effective memory primes remain as hyperspecific over the first postnatal year as they are at 3 and 6 months of age, then this specificity would guarantee that the original memory would be recovered only if the original conditions of encoding were still intact and would not be recovered in altered circumstances that might prove maladaptive. Once the forgotten memory had been reactivated, however, updating it to include new, contemporaneous information would be possible only if the specificity of the cues that can retrieve the reactivated memory

is less than the specificity of the prime that reactivates the memory in the first place (Galluccio, 2005; Galluccio & Rovee-Collier, 2005).

The present study was designed to determine if or how the specificity of reactivation of the forgotten memory and its subsequent retrieval changes between 3 and 12 months of age. To this end, data were collected from 9- and 12-month-olds and to fill in the gaps of prior research from 3- and 6-month-olds. The new data were combined with corresponding data previously collected from 3- and 6-month-olds in order to provide a complete picture of the specificity of priming over the first year of life. In Experiment 1, infants were tested with either the original training cue (mobile or train) in a different context or a different cue (mobile or train) in the original training context. In Experiment 2, infants were both primed and tested with either the original training cue in a different context or a different cue in the original training context. In Experiment 3, infants were primed with the original training cue in a different context or a different cue in the original training context. Experiment 4 was procedurally identical to Experiment 2 except that it was performed only with 3- and 6-month-olds, who were exposed to the memory prime for the briefest duration that reactivates the memory 1 week after it was forgotten. The fourth experiment examined the possibility that a minimum duration prime reduces the specificity of the reactivated memory.

GENERAL METHODS

Participants

All infants were healthy and full-term ($N = 138$). They were recruited from published birth announcements, commercial mailing lists, or by word-of-mouth and assigned to groups ($n = 6$) as they became available for study. The demographic characteristics of the participants, combined across experiments, are presented by age. Three-month-olds ($N = 18$) were African-American ($n = 1$), Hispanic ($n = 1$), Caucasian ($n = 15$), and of mixed race ($n = 1$). The parents' mean educational attainment was 14.9 years¹ ($SD = 1.8$) and mean rank of socioeconomic status (SEI¹; Nakao & Treas, 1992) was 58.05 ($SD = 18.84$). Six-month-olds ($N = 48$) participated in both the mobile and train tasks. They were African-American ($n = 1$), Asian ($n = 3$), Hispanic ($n = 5$), Caucasian ($n = 35$), and of mixed race ($n = 4$). The parents' mean educational attainment was 15.8 years ($SD = .8$) and mean SEI was 69.97 ($SD = 16.40$). Testing was discontinued on additional infants (3 months: $n = 9$; 6 months: $n = 6$) in the mobile task who cried excessively in one of the three sessions. Nine-month-olds ($N = 36$) were Asian ($n = 4$), Hispanic ($n = 1$), and Caucasian ($n = 31$). The parents' mean educational attainment was 15.2 years ($SD = 1.7$) and mean SEI was 69.38 ($SD = 18.09$). Twelve-month-olds ($N = 36$) were African-American ($n = 2$), Asian ($n = 5$), Caucasian ($n = 28$), and of mixed race ($n = 1$). The parents' mean educational attainment was 15.7 years ($SD = .7$) and mean SEI was 67.33 ($SD = 15.74$).

Apparatus

All infants were trained, primed, and tested in their homes in either the mobile task (3–6 months) or train task (6–12 months).

Mobile Task—At 3 months, infants lay supine in their cribs and were trained and tested with one of two hand-painted wooden mobiles (Nursery Plastics, Models 801 and 809), counter-

¹All 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 16 years, with 12 years corresponding to a high-school degree and 16 years corresponding to a 4-year college 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) assigned higher ranks.

balanced within groups. Each mobile was composed of five to seven highly detailed objects and jingle bells. Because the mobiles were not commercially available, infants had no prior exposure to them. The mobile was suspended 25–30 cm above the infant's upper abdomen from an aluminum L-shaped stand (BCS Machine Co., South Plainfield, NJ) that was clamped on the crib rail nearest the experimenter. An identical “empty” stand was clamped on the opposite rail. The context was defined by one of two distinctive cloth panels (red with blue stripes or yellow with green circles²), also counterbalanced within groups, which was draped over the end and side rails of the crib. During priming, infants sat in a sling-seat (Baby Bjorn, Model 13) inside the crib to minimize squirming.

At 6 months, infants sat in the sling-seat inside a playpen that the experimenter provided (Graco, Pack'n Play, Model No. 9130-MT). The same mobiles and contexts (draped over three sides of the playpen) were used, but the mobile was suspended slightly above and in front of infants from the end of a flexible metal bar on a floor microphone stand. At both ages, a satin ribbon was strung from the infant's ankle to the mobile suspension hook during reinforcement periods; in this arrangement, kicks moved the mobile with an intensity that was commensurate with their rate and vigor (conjugate reinforcement). During nonreinforcement periods, the ankle ribbon was connected to the empty mobile stand (3 months) or simply disconnected from the suspension hook (6 months); in this arrangement, infants could see the mobile, but kicks could not move it. During the reactivation treatment, the ribbon was attached to the mobile suspension hook but not to the ankle.

Train Task—At 6, 9, and 12 months, infants were trained, primed, and tested with one of two train sets, counterbalanced within groups. One set consisted of an HO-scale (miniature) train in an orange aluminum box (58 cm × 58 cm × 35 cm). The front of the box was Plexiglas (58 cm × 35 cm), and a yellow curtain with fuchsia stripes enclosed the other three sides. A black train engine and three railcars (yellow, green, and red) were positioned directly behind the Plexiglas window on a circular track (47.5 cm diam.). Scattered around the track were various colorful toys. The second train set was purple and had a blue curtain with pink triangles. It consisted of a black engine, three railcars (red, blue, and orange), and different toys. The two train sets were counterbalanced within groups. Below the front window on each set was a Plexiglas lever (30 cm × 12.5 cm). Each discrete lever press activated an optical switch that was connected to an interface box and an IBM Thinkpad-350 laptop computer. A Microsoft Quick Basic computer program timed the experimental phases, delivered the reinforcer, and registered all optical switch operations in 10-s bins. During reinforcement phases, each press activated the train for 1 s (9 and 12 months) or 2 s (6 months). Presses that occurred while the train was already in motion were recorded by the computer but did not affect delivery of the reinforcer. During all phases, two white light bulbs (25 W) continuously illuminated the interior of each box.

The train box was placed on a table, and the infant sat in front of it on the caregiver's lap or in a highchair. A particular room in the infant's home (e.g., the kitchen, dining room, or living room) defined the context.

Procedure

All infants were trained, primed, and tested in their homes during a typical play period. This time varied across infants but was relatively constant over all sessions with the same infant. Because the mobile task is inappropriate for infants older than 6 months, the train task was used with 6-, 9-, and 12-month-olds. The train task is an upward extension of the mobile task because both tasks yield the same forgetting functions after original training (Hartshorn &

²In prior mobile studies, some yellow panels also displayed green triangles or green squares.

Rovee-Collier, 1997) and the same reforgetting functions after priming (Hildreth & Rovee-Collier, 2002) at 6 months. In addition, the latency of responding to a memory prime at 6 months is identical in both tasks (Hildreth & Rovee-Collier, 1999), as are the minimum duration of an effective prime, the rate of forgetting after a minimum duration prime, and the latency of responding to a minimum duration prime (Sweeney & Rovee-Collier, 2002).

Most important for the present study, the mobile and train tasks enter into the same relationships with the reactivation and test context at 6 months of age (Hartshorn & Rovee-Collier, 1997). Thus, even though the contexts in the mobile task (a particular cloth panel covering the sides of the playpen) and the train task (a particular room in the home) differ, infants treat them as functionally equivalent. The procedure consisted of three phases.

Training Phase (Sessions 1–2)

Infants received two training sessions 24 hr apart. One week after infants last remembered the task, they received a reactivation treatment and, 24 hr later, a long-term retention test. Each training session began with a nonreinforcement period, followed by a reinforcement period and another nonreinforcement period. In session 1, the first nonreinforcement period was the *baseline phase*, in which an infant's operant level was measured. Its duration was 3 min at 3 months, 2 min at 6 months, and 1 min at 9 and 12 months. Next followed the reinforcement phase (*acquisition*), when each kick conjugately moved the mobile, and each lever press moved the train for 2 s at 6 months and 1 s at 9 and 12 months. The acquisition phase lasted 9 min at 3 months, 6 min at 6 months, and 4 min at 9 and 12 months. The final nonreinforcement period lasted 3 min at 3 months, 1 min at 6 months, and 30 s at 9 and 12 months. In session 2, the final nonreinforcement phase served as an *immediate retention test*, when the infant's final level of learning and retention after zero delay were measured.

To advance beyond the training phase, each infant had to meet a learning criterion. At 3 and 6 months, infants had to respond 1.5 times above operant level during 2 of any 3 consecutive min of an acquisition phase; at 9 and 12 months, infants had to respond 1.5 times above operant level during 1 min of an acquisition phase.

Reactivation Treatment or Priming Phase (Session 3)

One week after infants last remembered the task, a reactivation treatment was administered. In the mobile task, the end of the ribbon was not attached to the ankle but was held by the experimenter, who pulled and released it to move the mobile at the same rate that a given infant had kicked to move it during the last 2 (6 months) or 3 (3 months) min of acquisition in session 2 (see Fig. 1a). In the train task, the lever was deactivated, and the train was computer-programmed to move at the rate that the infant had responded during the last 2 min of acquisition in session 2. In this way, the movement of the memory prime was perceptually identical to what each infant had seen at the end of training.

Long-Term Retention Test Phase (Session 4)

The long-term retention test was a nonreinforcement period identical to the baseline phase and the immediate retention test (see Fig. 1b and c). Its duration was 3 min at 3 months and 2 min at 6, 9, and 12 months. Immediately after the long-term retention test, reinforcement was reintroduced during a motivational control phase to ensure that infants who had responded poorly during the test were not tired, sick, or unmotivated on that particular day. This phase lasted 9 min (3 months), 6 min (6 months), or 4 min (9 and 12 months). Infants who failed to respond appropriately to reintroduction of the contingency were excluded from the final sample.

Retention Measure

Retention was assessed via an individual measure of relative responding that has been used in all operant studies of infant memory (for review, see Rovee-Collier, 1996). This measure, the *baseline ratio* (LRT/BASE), expresses each infant's response rate during the long-term retention test (LRT) as a fraction of that same infant's baseline rate (BASE), indexing the extent to which responding during the long-term test exceeds operant level. A mean group baseline ratio that is not significantly greater than a theoretical population baseline ratio of 1.00 signifies no retention (the H_0), whereas a mean group baseline ratio that significantly exceeds 1.00 signifies retention.

Prior to performing all analyses, the baseline 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 (the outer fence) for a given group. If an outlier was found, then it was replaced with the next highest ratio within that group, and one degree of freedom was subtracted.

EXPERIMENT 1: TESTING WITH A DIFFERENT CUE OR CONTEXT

Prior research with both nonhuman animal and human adults and infants found that reactivated memories and newly acquired memories are not always the same (Boller & Rovee-Collier, 1994; Galluccio, 2005; Hitchcock & Rovee-Collier, 1996; Mactutus, Ferek, George, & Riccio, 1982; Mactutus, Riccio, & Ferek, 1979; Miller, Jagielo, & Spear, 1991; Spear, Hamberg, & Bryan, 1980). These findings raise the possibility that the effective retrieval cues for reactivated memories and newly acquired memories might also differ. Three- and 6-month-olds are highly sensitive to changes in the training cue and training context after both original training (Borovsky & Rovee-Collier, 1990; Butler & Rovee-Collier, 1989) and priming (Hartshorn & Rovee-Collier, 1997; Hayne & Rovee-Collier, 1995). With age, infants are increasingly less sensitive to cue and context changes following original training (Hartshorn, Rovee-Collier, Gerhardstein, Bhatt, Klein, et al., 1998), but their sensitivity to the same changes following priming is unknown. Because the range of cues that support memory retrieval in deferred imitation tasks also increases with age (Hayne et al., 1997; Hayne, Gross, Hildreth, & Rovee-Collier, 2000; Learmonth et al., 2004), it seemed possible that the range of cues that could retrieve a reactivated memory in an operant task might increase with age as well.

Experiment 1 examined whether a reactivated memory could be retrieved by a generalized cue or in a generalized context later in the first year of life. To this end, 9- and 12-month-olds were primed with the original training cue in the original training context and were tested 24 hr later with either a different cue in the original training context or the original training cue in a different context. The resulting data were then combined with corresponding data previously collected from 3- and 6-month-olds to provide a complete picture of the effect of cue and context changes on retention of a reactivated memory throughout the first year of life.

Method

Participants—The twelve 9-month-olds (7 girls, 5 boys) had a mean age of 278.1 days ($SD = 8.6$) on the first day of training, and the twelve 12-month-olds (4 girls, 8 boys) had a mean age of 369.0 days ($SD = 6.7$).

Procedure—Infants remember the train task for 42 but not 49 days at 9 months of age and for 56 but not 63 days at 12 months of age. Therefore, infants were primed with the same cue in the same context 48 days (9-month-olds) or 62 days (12-month-olds) after training was over and were tested 24 hr later with the same train in a different context (group Test Context Change) or with a different train in the same context (group Test Cue Change).

Comparison data for age-matched forgetting control groups were provided by Hartshorn, Rovee-Collier, Gerhardstein, Bhatt, Wondoloski, et al. (1998). These groups were tested 49 days (9-month-olds) or 63 days (12-month-olds) after training but received no interpolated reactivation treatment. Age-matched reactivation control groups were not initially trained but were given a 120-s reactivation treatment 24 hr prior to the retention test (from Hildreth & Rovee-Collier, 1999). Age-matched no-change control groups were treated exactly like the experimental groups except that they were trained, primed, and tested with the same cue in the same context (from Hildreth & Rovee-Collier, 1999).

Results and Discussion

Nine-Month-Old Infants—One-way analyses of variance (ANOVAs) over the mean response rates of the two experimental groups during the baseline phase and the immediate retention test indicated that their rates did not differ, both $F(1, 10) < 1$, ruling out the possibility that subsequent group differences in retention were due to differences in baseline or the final level of learning, respectively. One-sample directional t tests were used to compare the mean baseline ratios of each experimental group against the corresponding theoretical population baseline of 1.00. These analyses revealed that 9-month-olds exhibited significant retention whether they were tested with a different train in the original context or with the original train in a different context (see Fig. 2). Group Test Cue Change had a mean baseline ratio significantly above 1.00, $t(5) = 2.12, p < .05$. Similarly, group Test Context Change had a mean baseline ratio significantly above 1.00, $t(5) = 3.85, p < .01$.

Twelve-Month-Old Infants—One-way ANOVAs over the mean response rates of the two experimental groups during the baseline phase and the immediate retention test indicated that their response rates also did not differ either before training, $F(1, 10) < 1$, or afterward, $F(1, 10) = 2.75, ns$, again eliminating group differences in baseline or the final level of learning as a basis for subsequent retention differences. One-sample directional t tests comparing the mean baseline ratios against 1.00 revealed that 12-month-old also exhibited significant retention whether they were tested with a different train in the original context or with the original train in a different context (see Fig. 2). Group Test Cue Change had a mean baseline ratio significantly above 1.00, $t(5) = 2.35, p < .05$, and group Test Context Change also had a mean baseline ratio significantly above 1.00, $t(5) = 2.74, p < .05$.

EXPERIMENT 2: PRIMING WITH A DIFFERENT CUE OR CONTEXT

Because memory retrieval is initiated twice in reactivation studies, there are two opportunities for memory retrieval to fail. The first occasion occurs when the prime initiates retrieval of the forgotten memory during the reactivation treatment; the second occasion occurs when cues during the ensuing retention test retrieve the memory that was reactivated. Thus, even if the original cue is present in the original context during the long-term test, retrieval at that time requires that the prime had previously reactivated the memory. At 3 months of age, priming with the original training mobile in a different room was unsuccessful, even though infants were in the same portacrib that was draped with the same cloth panel where they had learned the task (Hayne et al., 1991). At 6 months, priming with the original train in a different room was also unsuccessful (Hartshorn & Rovee-Collier, 1997). In Experiment 1, however, the specificity of cues that could retrieve the reactivated memory had decreased by 9 months of age. It seemed possible, therefore, that the specificity of cues that can reactivate the memory might decrease as well.

Experiment 2 was designed to examine this possibility. Nine- and 12-month-olds were primed with either a different cue in the original training context or with the original training cue in a different context and were tested with the original training cue in the original training context

24 hr later. The resulting data were then combined with corresponding data previously collected from 3- and 6-month-olds.

Method

Participants—The twelve 9-month-olds (6 girls, 6 boys) had a mean age of 278.1 days ($SD = 8.6$) on the first day of training, and the twelve 12-month-olds (4 girls, 8 boys) had a mean age of 375.1 days ($SD = 9.1$).

Procedure—At each age, group React Cue Change was primed with a different train in the same (training) context, and group React Context Change was primed with the same (training) train in a different context either 48 (9-month-olds) or 62 (12-month-olds) days after training was over. They were tested for retention 24 hr later with the original train in the original context.

Results and Discussion

Nine-Month-Olds—One-way ANOVAs over the mean response rates again indicated that the two experimental groups did not differ during either the baseline phase or the immediate retention test, both $F_s(1, 10) < 1$. One-sample directional t tests revealed that 9-month-olds exhibited significant retention when primed with a different cue in the original context but not when primed with the original cue in a different context (see Fig. 3). Group React Cue Change had a mean baseline ratio significantly above 1.00, $t(5) = 2.05$, $p < .05$, but group React Context Change had a mean baseline ratio not significantly above 1.00, $t(4) = 1.35$, ns .

Twelve-Month-Olds—One-way ANOVAs indicated that the mean lever press rates of the two experimental groups did not differ before or after training, both $F_s(1, 10) < 1$. One-sample directional t tests revealed 12-month-olds exhibited significant retention when they were primed with the same (original) train in a different context but not with a different train in the same (original) context (see Fig. 3). Group React Cue Change had a mean baseline ratio that was not significantly above 1.00, $t(5) < 1$, providing evidence that the memory had not been reactivated. In contrast, group React Context Change had a mean baseline ratio significantly above 1.00, $t(4) = 6.23$, $p < .05$, indicating that the memory was reactivated.

The finding that a novel cue was a successful prime at 9 months was unexpected. In the adult priming literature, effective memory primes are notoriously hyperspecific. Even the slightest change in the physical appearance of a studied item significantly reduces the amount of priming (Tulving & Schacter, 1990; for review, see Richardson-Klavehn & Bjork, 1988). In studies with infants, effective memory primes have similarly been hyperspecific to the perceptual properties of the cue. Moreover, if a generalized cue first becomes an effective prime at 9 months, then it should be an effective prime at 12 months too—but it was not. Experiment 3 assessed the reliability of this result.

Finally, the finding that priming with the training cue in a novel context was unsuccessful at all ages except 12 months (see Fig. 3) suggests that the contextual constraints on reactivation loosen by the end of the first year. Experiment 3 also assessed the reliability of this result.

EXPERIMENT 3: A DIFFERENT CUE OR CONTEXT DURING BOTH PRIMING AND TESTING

In Experiment 2, the novel prime differed from both the training cue and the test cue, and either discrepancy could have produced the retrieval failure. In a reactivation study with 3-month-olds, Hayne and Rovee-Collier (1995) had both primed and tested infants with the novel mobile in order to examine the contribution of the discrepancy between the novel prime and the test cue to the retention deficit. Because 3-month-olds had still exhibited no retention, they

concluded that infants' failure to exhibit retention was due to the discrepancy between the novel prime and the training cue. In other words, the novel prime had never reactivated the forgotten memory in the first place. In Experiment 1, 9- and 12-month-olds had generalized to a novel test cue after being priming with the original training cue, but in Experiment 2, 12-month-olds (but not 9-month-olds) had exhibited no retention after priming with a novel cue. If the discrepancy between the training cue and the prime were the critical factor underlying the retention deficit, then the conditions of original encoding would not be reinstated, and the forgotten training memory would not be reactivated in the first place. It is possible, however, that infants would have exhibited retention had they been tested with the same novel stimulus that was used as the prime.

Experiment 3 determined whether the locus of the retention failure associated with priming with a novel cue or in a novel context changes over the first year of life. To this end, 3-, 6-, 9-, and 12-month-olds were trained in the mobile or train task. At each age but 3 months, half of the infants were primed and tested with the training cue in a novel context, and half were primed and tested with a novel cue in the training context. At 3 months, all infants were primed and tested with the training cue in a novel context; corresponding data had previously been collected from identically trained infants who were primed and tested with a novel cue in the training context (Hayne & Rovee-Collier, 1995). Combined, these data provided a complete picture of the locus of the retrieval failure between 3 and 12 months of age.

Method

Participants—In the mobile task, there were six 3-month-olds (2 girls, 4 boys) with a mean age of 97.7 days ($SD = 4.8$) and twelve 6-month-olds (5 girls, 7 boys) with a mean age of 173.2 days ($SD = 5.4$). In the train task, there were twelve 6-month-olds (7 girls, 5 boys) with a mean age of 181.6 days ($SD = 8.9$), twelve 9-month-olds (3 girls, 9 boys) with a mean age of 273.2 days ($SD = 7.9$), and twelve 12-month-olds (5 girls, 7 boys) with a mean age of 371.5 days ($SD = 7.3$).

Procedure—All experimental groups were primed and tested 24 hr after priming with a different cue in the original training context or with the original training cue in a different context. At 3–6 months of age, the cue was a particular mobile, and the context was the particular cloth panel draped over the crib or playpen sides; at 6–12 months, the cue was a particular train set, and the context was a particular room in the house. At each age, no-change reactivation control groups were trained, primed, and tested with the original cue in the original context. These groups demonstrated that the reactivation treatment was an effective reminder 1 week after infants had forgotten the task. Their data were drawn from prior studies (3-month-olds: Hayne & Rovee-Collier, 1995; 6-month-olds: Hill et al., 1988 (mobile task); Hartshorn & Rovee-Collier, 1997 (train task); 9- to 12-month-olds: Hartshorn, Rovee-Collier, Gerhardstein, Bhatt, Wondoloski, et al., 1998; Hildreth & Rovee-Collier, 1999) and used for comparison purposes only. The comparison data for groups that were either tested or primed with a different cue or in a different context were from Experiments 1 and 2, respectively.

Results and Discussion

Three-Month-Olds—One-sample directional t tests revealed that group React-Test Context Change, which was both primed and tested with the same (training) mobile in a different context exhibited no retention (see Fig. 4, left panel). Its mean baseline ratio was not significantly above 1.00, $t(5) = 1.67$, ns . Previously, 3-month-olds who were primed and tested with a different mobile in the training context also failed to exhibit retention (Hayne & Rovee-Collier, 1995). These data indicated that 3-month-olds had failed to exhibit retention in Experiments 1 and 2 because the forgotten memory was never reactivated in the first place and not because the conditions of priming and testing differed.

Six-Month-Olds (Mobile Task)—One-way ANOVAs indicated that the mean kick rates of the two experimental groups did not differ either before training or afterward, both $F_s(1, 10) < 1$. One-sample directional t tests revealed that 6-month-olds, like younger infants, exhibited no retention whether they were primed and tested with a different mobile in the training context or with the training mobile in a different context (see Fig. 4, left panel). Groups React-Test Cue Change and React-Test Context Change had mean baseline ratios not significantly above 1.00, both $t_s(5) < 1$.

Six-Month-Olds (Train Task)—One-way ANOVAs indicated that the mean lever press rates of the two experimental groups also did not differ either before training or afterward, both $F_s(1, 10) < 1$. One-sample directional t tests similarly revealed that infants exhibited no retention whether they were both primed and tested with a different train in the original context or with the original train in a different context (see Fig. 4, right panel). Groups React-Test Cue Change and React-Test Context Change had mean baseline ratios not significantly above 1.00, $t(5) < 1$ and $t(4) = 1.38$, *ns*, respectively. These results are identical to those of 6-month-olds in the mobile task and confirm that the locus of retrieval failures at 6 months, as at 3 months, is the discrepancy between the priming and training conditions and not between the priming and test conditions.

Nine-Month-Olds—One-way ANOVAs again indicated that the mean lever press rates of the two experimental groups did not differ before training, $F(1,10) < 1$, or afterward, $F(1, 10) = 1.08$, *ns*). One-sample directional t tests revealed that 9-month-olds exhibited no retention during the long-term test whether they were primed and tested with the same (original) train in a different context or with a different train in the same (training) context (see Fig. 4, right panel). The mean baseline ratio of group React-Test Cue Change was not significantly above 1.00, $t(5) = 1.56$, *ns*, indicating no retention. This result did not replicate the finding in Experiment 2 that 9-month-olds were successfully primed with a different train in the same context (group React Cue Change) and suggests that the prior result was attributable to sampling error. As before, however, the mean baseline ratio of group React-Test Context Change was not significantly above 1.00, $t(5) = 1.38$, *ns*.

Twelve-Month-Olds—One-way ANOVAS indicated the lever press rates of the two experimental groups did not differ either before or after training, both $F_s(1, 10) < 1$. One-sample directional t tests revealed that 12-month-olds exhibited no retention when primed and tested with a different train in the training context, but they did exhibit retention when primed and tested with the original train in a different context (see Fig. 4, right panel). Group React-Test Cue Change had a mean baseline ratio not significantly above 1.00, $t(5) < 1$. Group React-Test Context Change had a mean baseline ratio significantly above 1.00, $t(5) = 2.04$, $p < .05$. These data replicate the finding in Experiment 2 that priming in a novel context did not impair reactivation at 12 months, but priming with a novel focal cue did.

The preceding analyses indicate that priming with a cue that differs from the training cue does not reactivate the memory between 3 and 12 months of age, even when infants are tested with the same cue that served as the prime (see Fig. 4). This finding reveals that the locus of the retrieval failure in Experiment 2 was at priming rather than at testing. Finally, the finding that the Experiment 2 data of 9-month-olds (group React Cue Change) were not replicated in Experiment 3 is consistent with prior evidence from younger and older infants, healthy young and elderly adults, and amnesic adults that priming is hyperspecific to the originally encoded cue (for review, see Rovee-Collier et al., 2001).

Overall, these results reveal that the range of focal cues that can reactivate forgotten memories does not expand over the first year of life, but the range of contexts in which the memory can be reactivated does. By the end of the first year, an exact match between the training and

priming contexts is no longer necessary for either priming a forgotten memory or subsequently retrieving the reactivated memory.

EXPERIMENT 4: TESTING WITH A DIFFERENT CUE OR CONTEXT AFTER A MINIMUM DURATION PRIME

Different kinds of memory attributes are forgotten and retrieved at different rates (Bhatt & Rovee-Collier, 1996; Riccio, Ackil, & Burch-Vernon, 1992; Riccio, Rabinowitz, & Axelrod, 1994; Rovee-Collier & Sullivan, 1980). At 3 months of age, the memory of the training mobile is highly detailed 1 day after training, enabling infants to discriminate a novel test mobile from the training one. Over time, however, as infants progressively forget the specific details of the training mobile, they increasingly generalize to a novel test mobile until they treat the original and novel mobiles equivalently 3–4 days after training (Rovee-Collier & Sullivan, 1980). Later, infants also generalize to a novel test mobile 1 day after priming with the training mobile, but they again discriminate a novel mobile from the training one 3 days after priming (Greco, Rovee-Collier, Hayne, Griesler, & Earley, 1986; Hayne & Rovee-Collier, 1995). These results have been taken as evidence that the latent memory attributes representing the general features of the training mobile (the attributes that infants forgot last) are more accessible—hence are recovered faster by a memory prime—than the latent memory attributes representing its specific details (the attributes that infants forgot first).

When infants are trained, primed, and tested in a distinctive context, however, they never generalize to a novel test mobile after either training or priming (Butler & Rovee-Collier, 1989; Shields & Rovee-Collier, 1992). These results have been taken as evidence that the context and the focal cue are processed serially, which also reflects the order in which the context and cue are encountered: The context encountered first, and the cue embedded in it. As a result, contextual cues prime (precue) the forgotten attributes that represent the specific details of the cue so that infants continue to discriminate between new and old mobiles instead of generalizing to them after relatively long test delays. This finding led to the attention-gating model.

At older ages, the forgotten memory is recovered so rapidly that the rates at which different types of memory attributes are reactivated cannot be documented with available methods. Recent research, however, has found that the duration of a memory prime might differentially affect the type of memory attributes that it reactivates. At 6 months of age, a memory prime lasting 7.5 s (the minimum duration of an effective prime 1 week after forgetting) recovered the forgotten training memory more slowly than a standard (2-min) prime (Sweeney & Rovee-Collier, 2002). Also, infants between 3 and 12 months of age remembered a memory reactivated by a minimum duration prime for only half as long as they remembered a memory reactivated by a standard prime, suggesting that a minimum duration prime is weaker (Hsu, Rovee-Collier, Hill, Grodkiewicz, & Joh, 2005; Sweeney & Rovee-Collier, 2002). Given that a standard prime recovers memory attributes representing general features before it recovers memory attributes representing specific details at 3 months of age (Greco et al., 1986; Hayne & Rovee-Collier, 1995), it seemed possible that a minimum duration prime might reactivate only the general features represented in the original training memory. If so, then infants given a minimum duration prime would generalize to a different test cue or to a different test context 24 hr later.

Experiment 4 tested this possibility with 3- and 6-month-olds. Nine- and 12-month-olds were not included in this experiment because they had generalized to different test stimuli 24 hr after a standard prime in Experiment 1.

Method

Participants—Infants were recruited as before and assigned to groups ($n = 6$) as they became available for study. The twelve 3-month-olds (3 girls, 9 boys) had a mean age of 97.5 days ($SD = 6.2$) on the first day of training. The twelve 6-month-olds (7 girls, 5 boys) in the mobile task had a mean age of 178.2 days ($SD = 8.1$), and the twelve 6-month-olds (7 girls, 5 boys) in the train task had a mean age of 190.8 days ($SD = 6.5$) on the first day of training.

Apparatus and Procedure—The apparatus and procedure were the same as in Experiment 1 except that the memory prime at each age lasted for the minimum duration that was effective in recovering the training memory 1 week after it had been forgotten. At 3 months, the minimum duration prime lasted 120 s (Joh, Sweeney, & Rovee-Collier, 2002); at 6 months, it lasted 7.5 s (Sweeney & Rovee-Collier, 2002). Independent groups of 3- and 6-month-olds were tested 24 hr after priming with either a different cue in the training context or with the training cue in a different context.

Control data previously collected from no-change minimum duration prime groups, cue-change standard prime groups, and context-change standard prime groups at 3 and 6 months were included for comparison purposes. At 3 months, the no-change minimum duration prime group was tested 24 hr later with the original mobile in the original context (from Joh et al., 2002). This group documented that a 120-s prime reactivated the forgotten memory of the mobile task. At 6 months, the no-change minimum duration prime groups were tested 24 hr later with the original mobile or the original train in the original context (from Sweeney & Rovee-Collier, 2002). These groups documented that a 7.5-s prime reactivated the forgotten memory of the mobile and train tasks. At 3 months, the cue-change prime group (from Hayne & Rovee-Collier, 1995) received a standard prime lasting 180 s and was tested 24 hr later with a different mobile in the original context. This group documented that 3-month-olds do not generalize to a different mobile 24 hr after a standard prime. The 6-month-old cue-change prime group received a standard prime lasting 120 s and was tested 24 hr later with a different cue in the original context (from Hartshorn & Rovee-Collier, 1997). These groups documented that 6-month-olds do not generalize to a different mobile 24 hr after a standard prime; they do, however, generalize to a different train 24 hr after priming.

The 3-month-old context-change prime group was treated the same as the 180-s cue-change prime group except that infants were tested with the original mobile in a different context (from Hayne & Rovee-Collier, 1995). This group ensured that 3-month-olds do not generalize responding in a different context 24 hr after a standard prime. The 6-month-old context-change prime groups were treated the same as the 120-s cue-change prime groups except that infants were tested with the original mobile or train in a different context (from Borovsky & Rovee-Collier, 1990; Hartshorn & Rovee-Collier, 1997). These groups ensured that 6-month-olds do not generalize responding in a different context 24 hr after a standard prime in the mobile and train tasks.

Results and Discussion

Three-Month-Old Infants—One-way ANOVAs indicated that the mean response rates of the two experimental groups did not differ either before or after training, both $F_s(1, 10) < 1$. One-sample directional t tests revealed that 3-month-olds who were given a minimum duration prime exhibited significant retention 24 hr later when tested with a different mobile in the original context but not when tested with the original mobile in a different context (see Fig. 5, left panel). Group Min React-Test Cue Change had a mean baseline ratio significantly greater than 1.00, $t(5) = 2.15$, $p < .05$, indicating generalization to a novel cue. In contrast, the mean baseline ratio of group Min React-Test Context Change was not above 1.00, $t(4) < 1$, indicating that infants could not recognize the training mobile in a novel retrieval context. Three-month-

olds' generalization to a novel mobile supports the conclusion that a minimum duration prime reactivates only the general features of the cue that are represented in the training memory.

Six-Month-Old Infants (Mobile Task)—One-way ANOVAS again indicated that the response rates of the two experimental groups did not differ either before training, $F(1, 10) = 2.48$, *ns*, or afterward, $F(1, 10) = 1.28$, *ns*. One-sample directional *t* tests revealed that group Min React-Test Cue Change failed to generalize to a novel mobile in the original context, $t(5) < 1$, performing like 6-month-olds given a standard mobile prime. In contrast, group Min React-Test Context Change had a mean baseline ratio significantly above 1.00, $t(5) = 2.19$, $p < .05$, indicating that 6-month-olds given a minimum duration prime recognized the original mobile in a novel context (see Fig. 5, left panel).

Six-Month-Old Infants (Train Task)—One-way ANOVAS indicated that the mean response rates of the two experimental groups did not differ before training, $F(1, 10) = 2.53$, *ns*, but they did immediately afterward, $F(1, 10) = 6.20$, $p < .04$. Because both groups exhibited significant retention during the long-term test, this difference was inconsequential. One-sample directional *t* tests indicated that group Min React-Test Cue Change generalized to a novel train in the original context, $t(4) = 2.40$, $p < .05$, but this result was expected because 6-month-olds given a standard prime also generalized to a novel train in the original context (Hartshorn & Rovee-Collier, 1997). Thus, in both the mobile and train tasks, 6-month-olds responded to a novel test cue after a minimum duration (7.5-s) prime in exactly the same way that they had responded to it after a standard (120-s) prime.

Infants in group Min React-Test Context Change recognized the original train in a novel context, $t(4) = 3.07$, $p < .025$ (see Fig. 5, right panel), just as they had in the mobile task. Given that memory retrieval at 6 months of age is context-specific after a standard prime in the mobile and train tasks, these results foreshadow the finding that 9- and 12-month-old infants recognize the original cue in a novel context after a standard prime. Finally, these findings confirm that methodological differences associated with defining the context as a distinctive colored-and-patterned curtain over the playpen sides in the mobile task or as a particular room in the home in the train task did not differentially influence the results in the present study.

GENERAL DISCUSSION

The enduring effect of early experience has been a subject of debate for more than a half-century (Stevenson, Hess, & Rheingold, 1967). Hildreth and Hill (2003) found that a forgotten memory could be recovered by the original training cue in the original training context after a delay four times longer than it was initially remembered throughout the first year of life. Thus, 3-month-olds initially remember an event for slightly less than a week, and its forgotten memory can still be recovered a month afterward, whereas 12-month-olds initially remember an event for 2 months, and its forgotten memory can still be recovered 8 months later. The more time that has elapsed since the memory of the event was encoded, however, the greater is the likelihood that the circumstances of original encoding will have changed. On the one hand, effective cues for the reactivation and/or retrieval of an early memory are less likely to be encountered after long delays would buffer the memory against reactivation and retrieval in inappropriate circumstances. On the other hand, the reactivation and retrieval of the early memory would also be less likely in changed circumstances that might be useful. The present study asked how such changes affect memory recovery over the first year of life. The results showed that priming throughout the first year of life is highly conservative, but after the original memory has been successfully reactivated, the constraints on its expression progressively loosen with age.

To summarize these findings, first, the original memory cannot be reactivated by any stimulus other than the original training cue between 3 and 12 months of age. This result extends evidence from healthy and amnesic adults that effective primes are highly veridical to the cue that was represented in (or associated with) the original memory throughout the life span. Second, the original memory cannot be reactivated by an otherwise effective prime in any context other than the original one in which it was encoded until 12 months of age. Third, following reactivation by the original cue in the original context, the reactivated memory becomes increasingly less context-specific over the first year of life. At 3 months of age, a reactivated memory does not generalize to a novel context after a minimum duration prime but does generalize to a novel cue if the context is unchanged. By 6 months of age, infants generalize across contexts after a minimum duration prime (Experiment 4). By 9 months of age, a reactivated memory generalizes to novel test cues and contexts after a standard prime, thereby providing an opportunity for the training memory to be updated (Experiment 1). Finally, at 12 months of age, the forgotten memory can also be reactivated by a standard prime in a novel context (Experiments 2 and 3).

The finding that memory retrieval becomes progressively less context-dependent after 6 months of age is seen as a functional adaptation to the onset of locomotion³ (scooting, crawling, walking), which makes the focal cue less likely to be uniquely associated with one place. This interpretation is based on findings from 3- and 6-month-olds that context-dependent retention is overridden when infants are trained in two or more contexts (Amabile & Rovee-Collier, 1991; Rovee-Collier & DuFault, 1991) as well as when they merely encounter the original cue in a different context shortly after training (Boller & Rovee-Collier, 1992; Boller et al., 1996; Rossi-George & Rovee-Collier, 1999). Thereafter, infants respond to the training cue in contexts they had not encountered before, and the training cue can prime the forgotten memory in novel contexts. Given that older infants are increasingly likely to be somewhere other than where an event was originally encoded, it is not surprising that the focal cue is an effective prime by 12 months of age regardless of its context.

The present study provides additional evidence that the cue and the context have different functions.⁴ The function of the training context is to prime or activate the memory attributes representing the training cue. The contextual priming function was previously demonstrated in operant studies in which the context alone was an effective prime for the forgotten training memory of 3-month-olds (Hayne & Findlay, 1995; Rovee-Collier, Griesler, & Earley, 1985).

The same contextual priming effect occurs after shorter retention intervals. When 3-month-old infants were tested with a novel mobile in a distinctive training context 3–5 days later, for example, they did not generalize to it, but they did generalize to a novel mobile after these same delays when trained and tested in the familiar context of their home cribs without a distinctive context (Rovee-Collier & Sullivan, 1980). These data suggest that the context primes or reactivates the memory attributes representing the specific details of the cue that have been forgotten but those representing its general features are still active. Once the memory attributes that represent the original specific details have been recovered, the infants are again able to discriminate a novel test mobile from the training one and respond selectively. Contextual priming of the forgotten attributes of the cue implicates a more general serial retrieval mechanism in which contextual information (i.e., where an event occurs) is processed first.

³Borovsky and Rovee-Collier (1990) interpreted 6-month-olds' heightened sensitivity to context after short delays as an anticipatory functional adaptation to the emergence of independent locomotion.

⁴Infants treat the cue and context as separable entities and not as a configuration. If infants encoded the cue and context as a configuration, then they would not exhibit retention when either element (the cue only or the context only) is changed. However, they respond differentially to such changes during training, priming, and testing (Butler & Rovee-Collier, 1989; Hayne & Rovee-Collier, 1995; Shields & Rovee-Collier, 1992).

Attention-Gating Model of Memory Retrieval

The attention-gating model of memory retrieval is a hierarchically organized model of memory retrieval in which the context is the first attention gate, and the cue is the last one (Butler & Rovee-Collier, 1989). Retrieval is the endpoint of a series of automatic, attention-driven perceptual identification processes. The retrieval process is initiated when the organism's attention is automatically drawn to an element of the most remote or distal context that strikes a perceptual match with a corresponding attribute of the context that is represented in memory. A contextual match opens the first attention gate, thereby initiating the serial retrieval process by allowing attention to flow automatically to the next more-proximal (less remote) level of context. If attention is drawn to an element at this second level of context that strikes a perceptual match with a corresponding attribute that is represented in the same memory, then a second attention gate opens, allowing attention to flow to the next more-proximal level of context, and the process continues in this manner until attention ultimately flows to the focal cue. If elements in the physically present cue strike a perceptual match with the corresponding memory attributes that represent it, then the memory is retrieved. Whether retrieval is direct (overt) or indirect (covert) depends on whether a unique response to the cue is available to the subject and whether there is an occasion to express it. At each level of the hierarchy, if there is not a match between the attended stimulus and corresponding attributes in the memory representation, however, then the next attention gate will not open, and the retrieval process will terminate.

Butler and Rovee-Collier (1989) originally developed the attention-gating model of memory retrieval to explain why 3-month-olds did not recognize the original mobile in a novel context 3 or 5 days after training but did recognize it in the distinctive training context after the same delays. The same result was found throughout the first year of life when operantly trained infants were tested after a relatively long retention interval: Testing with the original cue in the distinctive training context facilitates recognition after a relatively long retention interval, but testing in a novel context does not (Hartshorn, Rovee-Collier, Gerhardstein, Bhatt, Klein, et al., 1998).

According to the attention-gating model, although testing in the original context facilitates recognition, testing in a novel context does not actively impair it. Rather, the lack of a contextual match simply terminates the retrieval process. Contextual facilitation of retrieval is particularly well illustrated in a study with densely amnesic Korsakoff patients, who cannot recognize what they had studied just minutes earlier. When the amnesic patients studied material in a unique and highly distinctive room, they could remember it for as long as 48 hr if they were tested in the same distinctive context (Winocur & Kinsbourne, 1978). These data indicated that contextual priming did not entail conscious awareness—an interpretation that is consistent with evidence that lesions and other brain damage does not affect priming (for review, see Kandel & Squire, 1999).

Maturation or Priming Experience?

In numerous instances, facilitated memory processing with increasing age over the first year of life that were initially thought to be maturational were later found to be experiential. Such instances are not specific to conditioning studies—they have occurred in deferred imitation studies as well (e.g., Barr, Rovee-Collier, & Campanella, 2005; Bullman, Atkins, & Rovee-Collier, 2008; Campanella & Rovee-Collier, 2005). Although the maximum duration of retention increases linearly from 3 to 18 months of age (Hartshorn, Rovee-Collier, Gerhardstein, Bhatt, Wondoloski, et al., 1998), for example, prior priming doubles the duration of retention at 3 months, so that it is equivalent to that of 6-month-olds who were primed only once (Hayne, 1990). Similarly, the speed of recovering a forgotten memory increases logarithmically after priming over the first year of life (Hildreth & Rovee-Collier, 1999), but

it is recovered as rapidly after two primes at 3 months as after one prime at 6 months (Hayne, Gross, et al., 2000). Also, the minimum duration of an effective prime decreases sharply between 3 and 12 months of age (Hsu et al., 2005), but after a prior prime at 3 months, the minimum duration of an effective second prime is the same as that of 12-month-olds who have been primed only once (Bearce & Rovee-Collier, 2006).

Finally, Hitchcock and Rovee-Collier (1996) reactivated the forgotten memory of 3-month-olds twice, and either the cue or the context was novel only during the second prime. Nonetheless, the second prime successfully recovered the memory when the context (but not the cue) was novel—just as an initial prime recovered the memory at 12 months when the context was novel in the present study. After a longer delay, priming with either a novel cue or context during the third prime recovered the memory. The findings of the present study, considered jointly with those of Hitchcock and Rovee-Collier, provide another example of the effect of prior experience on memory retrieval. Evidence that the specificity of priming can be eliminated by prior priming experience at 3 months of age sounds a cautionary note for maturational interpretations of memory development over the first year of life.

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FIGURE 1.

(a) A 3-month-old during a reactivation treatment and (b) a long-term retention test (a nonreinforcement phase) in the mobile task. (c) A 9-month-old during a long-term retention test (a nonreinforcement phase) in the train task.

FIGURE 2.

Mean baseline ratios of independent groups of 3-, 6-, 9-, and 12-month-olds as a function of test group and task in Experiment 1. Infants were tested with a different cue in the same context or the same cue in a different context 24 hr after a reactivation treatment. Left panel: Groups trained, primed, and tested in the mobile task. Right panel: Groups trained, primed, and tested in the train task. Data for all 3-month-olds and for 6-month-olds in group Test Context Change in the mobile task were from Hayne and Rovee-Collier (1995) and Borovsky and Rovee-Collier (1990), respectively. The data for 6-month-olds in group Test Cue Change in the mobile task and for both groups of 6-month-olds in the train task were from Hartshorn and Rovee-Collier (1997). The dotted line indicates the theoretical baseline ratio of 1.00 (i.e., no retention). The asterisks indicate significant retention (M baseline ratio > 1.00). Vertical bars indicate $+1SE$.

FIGURE 3.

Mean baseline ratios of independent groups of 3-, 6-, 9-, and 12-month-olds as a function of test group and task in Experiment 2. Infants were primed with a different cue in the same context or the same cue in a different context and tested 24 hr later with the original cue in the original context. Left panel: Groups trained, primed, and tested in the mobile task. Right panel: Groups trained, primed, and tested in the train task. Data for all 3-month-olds and for all 6-month-olds in the mobile task were from Hayne et al. (1991). The data for 6-month-olds in the train task were from Hartshorn and Rovee-Collier (1997). The dotted line indicates the theoretical baseline ratio of 1.00 (i.e., no retention). The asterisks indicate significant retention (M baseline ratio > 1.00). Vertical bars indicate $+1SE$.

FIGURE 4.

Mean baseline ratios of independent groups of infants as a function of age and task in Experiment 3. All infants were given a reactivation treatment with a different cue in the same context and were tested 24 hr later with the different cue in the same context or were given a reactivation treatment with the same cue in a different context and tested 24 hr later with the same cue in the different context. Left panel: Groups trained, primed, and tested in the mobile task. Right panel: Groups trained, primed, and tested in the train task. Data for group React and Test Cue Change at 3 months are from Hayne and Rovee-Collier (1995). The dotted line indicates the theoretical baseline ratio of 1.00 (i.e., no retention). The asterisk indicates significant retention (M baseline ratio >1.00). Vertical bars indicate $+1SE$.

FIGURE 5.

Mean baseline ratios of independent groups of 3- and 6-month-olds as a function of test group and task in Experiment 4. Infants were given a reactivation treatment of the minimum effective duration and were tested 24 hr later with a different cue in the same context or the same cue in a different context. Responding at the baseline level indicates that a group discriminated that either the test cue or the test context was different. If the minimum duration prime were to reactivate only the general features of the original cue or context that were represented in the training memory, then a group would respond significantly above baseline during the 24-hr test (i.e., generalization). Left panel: Groups trained, primed, and tested in the mobile task. Right panel: Groups trained, primed, and tested in the train task. Data for the minimum duration no-change test groups at 3 and 6 months were from Joh et al. (2002) and Sweeney and Rovee-Collier (2002), respectively. The dotted line indicates the theoretical baseline ratio of 1.00 (i.e., no retention). The asterisk indicates significant retention (M baseline ratio > 1.00). Vertical bars indicate $+1SE$.