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NJ 08854-8020

Minimum Duration of Reactivation at 3 Months of Age

Received 23 April 2001; Accepted 17 May 2001

ABSTRACT: *Briefly exposing subjects to an isolated component of an event after they have forgotten can reactivate their memory of it, leading to renewed retention on an ensuing test. In two experiments with forty-eight 3-month-old infants, we asked what minimum duration of a reactivation treatment could recover their forgotten memory of an operant mobile task and whether the minimum duration was affected by how long the memory was forgotten. In Experiment 1, the minimum duration for reactivating the memory 1 week after forgetting was 120 s—substantially longer than the minimum duration required for reactivation at 6 months after the same relative delay. In Experiment 2, the minimum effective duration for reactivation increased linearly with the time since forgetting, from 7.5 s after 1 day to 180 s after 3 weeks. This study reveals that the duration of an effective memory prime is directly related to age and to memory accessibility.* Dev Psychobiol 40: 23–32, 2002

Keywords: *reactivation; memory; human infants; forgetting; priming duration; retention interral; operant learning*

Memory reactivation is an automatic perceptual identification process that results in the recovery of a previously forgotten memory. The reactivation procedure has been used most often with infant animals and humans, who forget relatively quickly, although it also has been used with adult animals made amnesic by electroconvulsive shock (e.g., Misanin, Miller, & Lewis, 1968) or hypothermia (e.g., Mactutus, Riccio, & Ferek, 1979) and with human amnesics (e.g., Tulving, Schacter, & Stark, 1982). In studies with human adults, the term *priming* is usually used instead of *reactivation*, but the phenomenon is the same—exposing subjects to a fractional portion of a stimulus leads them to respond correctly to it despite the fact that they cannot recognize the stimulus at the time of the exposure (Rovee-Collier, 1997; for review, see Rovee-Collier, Hayne, & Colombo, 2001).

Gordon, Smith, and Katz (1979) were the first to call attention to the importance of the duration of a reactivation treatment. They trained an avoidance response in adult rats and, after the original fear conditioning was forgotten, reexposed them to the conditioned stimulus for either 15 or 75 s as the reactivation treatment. Rats whose reactivation treatment lasted 15 s again produced the avoidance response during the subsequent test, but rats whose reactivation treatment lasted 75 s did not. Gordon et al. hypothesized that both reactivation treatments had initially recovered the forgotten memory, but the continued exposure of the 75-s group to the conditioned stimulus after the memory was again active had led to extinction of the conditioned avoidance response (for review, see Gordon, 1981). This hypothesis was supported by Deweer and Sara (1984), who trained

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Contract grant sponsor: NIMH
Contract grant numbers: MH32307 and K05-00902

DOI 10.1002/dev.10010

independent groups of rats in a maze, allowed them to forget the task, and then exposed them to the contextual cues of the maze as a reactivation treatment. Groups that received either a 30- or a 90-s reactivation treatment performed better during the ensuing retention test than groups that received a shorter (10 s) or a longer (300 s) reactivation treatment.

Subsequently, Arnold and Spear (1993) manipulated the duration of a reactivation treatment with 18-day-old rat pups. They conditioned pups to associate a particular odor with foot shock and, 3 hr after training, exposed the pups to the aversive odor for 30 s (the reactivation treatment). Although these pups subsequently failed to exhibit the trained avoidance response to the odor, new groups whose reactivation treatment lasted 5 or 15 s did. Taken together, the preceding studies not only show that longer reminders may be less effective than briefer ones, but they also suggest that there is a minimum duration of a reactivation treatment that can recover a forgotten memory.

Sweeney (2001) tested this possibility with 6-month-old human infants using an operant task in which infants were trained to kick to move a crib mobile. Typically, 6-month-olds recognize their training mobile for 14 but not 21 days (Hill, Borovsky, & Rovee-Collier, 1988). Once their training memory has been forgotten (i.e., infants no longer respond significantly above their operant level during a long-term retention test), it can be reactivated by briefly exposing them to the original training mobile. When tested 1 day after the reactivation treatment, infants' retention is again as good as it was only 1 day after training. Therefore, Sweeney exposed 6-month-olds to the original mobile 20 days after training for durations ranging from 3.75 to 30 s and tested them 1 day later. She found that reactivation treatments lasting 7.5 s and longer were effective in recovering the forgotten memory, but those shorter than 7.5 s were not.

In studies with 3-month-olds, infants recognize their training mobile for 5 but not 6 days (Butler & Rovee-Collier, 1989; Hayne, 1990). Their training memory also can be reactivated by exposure to the original training mobile (Rovee-Collier, Sullivan, Enright, Lucas, & Fagen, 1980). One week after forgetting, however, 3-month-olds require 24 hr to exhibit renewed retention after the reactivation treatment, whereas 6-month-olds exhibit renewed retention only 1 hr afterward (Boller, Rovee-Collier, Borovsky, O'Connor, & Shyi, 1990; Fagen & Rovee-Collier, 1983; Hildreth & Rovee-Collier, 1999). Because the younger infants take longer than 6-month-olds to renew responding after a reactivation treatment, they also may require a longer minimum exposure to it than the older infants. Whether the duration of an effective reactivation treatment changes with age, however, is unknown. Although a reactivation treatment shorter than 3 min—the duration heretofore used with 3-month-olds—would probably be effective, the minimum duration of an effective reactivation treatment for infants of this age also is unknown. The following experiments were designed to examine these issues.

In Experiment 1, 3-month-olds' duration of exposure to a reactivation stimulus 1 week after forgetting was systemically decreased, and their retention was tested 1 day later until the minimum duration of an effective reactivation treatment was found. The primary research question was whether the minimum duration of an effective reactivation treatment is the same as or longer than was previously found for 6-month-olds after the same relative delay. In Experiment 2, the minimum duration of a reactivation treatment was determined for 3-month-olds after delays ranging from 1 day to 2 weeks after forgetting. Here, the primary research question was whether memories that have been forgotten for longer periods of time require longer reactivation treatments in order to be recovered than memories that have been forgotten for shorter periods.

EXPERIMENT 1: MINIMUM EXPOSURE DURATION AFTER A 1-WEEK DELAY

Sweeney (2001) found that a 7.5-s reactivation treatment was effective in recovering a forgotten memory at 6 months of age 1 week after forgetting, but briefer reactivation treatments were not. In the present experiment, therefore, 3-month-olds were initially exposed to a reactivation stimulus lasting 7.5 s. As at 6 months, the reactivation treatment occurred 1 week after forgetting (2 weeks after training), and infants' retention was tested 1 day later. If the 7.5-s exposure proved to be ineffective in reactivating their forgotten memory, then our strategy was to systematically double the exposure duration until we found the minimum duration for an effective reactivation treatment. If the minimum duration of an effective reactivation treatment increases with age, then 3-month-olds would require a longer reactivation treatment than 6-month-olds (Sweeney, 2001).

Method

Participants. Thirty 3-month-olds (14 boys, 16 girls), recruited from published birth announcements and by word of mouth, were randomly assigned to groups

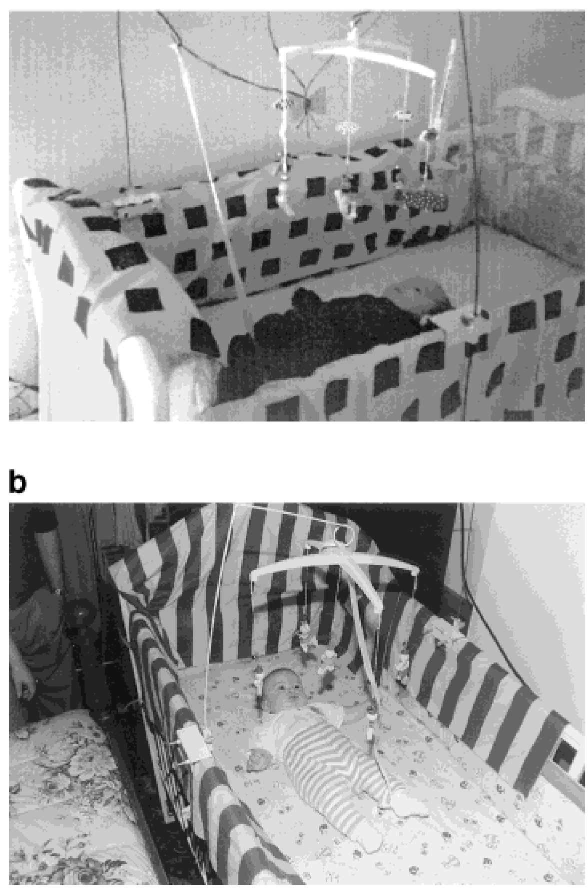
($n = 6$) as they became available for the study. The age of participants on the first day of training ranged from 76 to 111 days ($M = 99.83$ days, $SD = 8.53$). The participants were Asian ($n = 2$), African-American ($n = 2$), Caucasian ($n = 23$), and Hispanic ($n = 3$). Their parents' education ranged from 14 to 16 years ($M = 15.48$ years, $SD = 0.89$), and their mean socio-economic status (Nakao & Treas, 1992), reported by 76.67% of the parents, was 70.79 ($SD = 12.75$). Additional infants were excluded from the study due to crying for 2 consecutive min during any of the three full-length sessions ($n = 6$), a scheduling conflict ($n = 1$), failure to meet the original learning criterion ($n = 3$), and failure to reacquire the task during the motivational control phase after testing ($n = 1$).

Apparatus. One of two hand-painted, wooden mobiles composed of five highly detailed objects and jingle bells (Nursery Plastics, Models 801 and 809) was used. Mobiles were counterbalanced within groups. Because the mobiles are 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 lined with one of two colorful cloth drapes (red with blue-felt stripes, yellow with green-felt triangles) during all sessions (Figures 1b and 2), counterbalanced within groups. A white satin ribbon, tied to the infant's ankle, was connected to one of the two stands, depending on the phase of the session. During the reactivation treatment, infants were situated in a sling-seat inside the crib. A VHS-C camcorder placed on a tripod near the foot of the crib was used to videotape the sessions for future reliability scoring.

Procedure. All training, reactivation, and test sessions took place in the infant's home crib at a time when the infant was likely to be alert and playful. This time varied across infants, but it remained relatively constant across all sessions for a given infant. Infants received two 15-min training sessions 24 hr apart, a reactivation treatment 13 days later, and a long-term retention test 1 day after that (14 days after training). Independent groups of infants received a reactivation treatment lasting 7.5, 15, 30, 60, or 120 s.

Training (Sessions 1 and 2). Each training session began with a 3-min nonreinforcement phase (the *baseline* phase) during which the mobile was suspended from one stand, and the ankle ribbon was connected to the other. This arrangement allowed the mobile to be in view, but infants could not move it by kicking (Figure 1a). Next followed a 9-min reinforcement phase (the *acquisition* phase) during which the ankle ribbon was attached to the same stand as the mobile. In this arrangement, infants' kicks moved the mobile with an intensity commensurate with their rate and strength (Figure 1b). Finally, each session ended with another 3-min nonreinforcement period that was identical to the baseline phase. In Session 2 during this phase, the number of kicks provided an index of the final level of learning and retention after zero delay (the *immediate retention test* phase). To qualify for the reactivation treatment, infants were required to meet an initial learning criterion by kicking at a rate 1.5 times above their mean baseline rate during 2 of 3 consecutive min of the acquisition phase in either session.

a



b

FIGURE 1 A 3-month-old during a nonreinforcement phase (baseline, all retention tests) (a). The ankle ribbon is attached to the empty suspension hook. A 3-month-old during a reinforcement (acquisition) phase (b). The ankle ribbon and the mobile are attached to the same suspension hook so that kicks move the mobile.

FIGURE 2 A 3-month-old during a reactivation treatment. The ankle ribbon is disconnected from the suspension hook; instead, a second ribbon that is attached to the same hook as the mobile is held by the experimenter, who pulls the ribbon to move the mobile noncontingently.

Reactivation treatment (Session 3). During the reactivation treatment, the infant was placed in a sling-seat inside the crib, which was again lined with the same cloth drapes (Figure 2). One end of the ribbon was attached to the same stand as the mobile; the other end was not connected to the infant's ankle but was held by the experimenter, who pulled it to move the mobile at the same rate that the infant had kicked during the last 3 min of acquisition in Session 2. Timing of the reactivation treatment began when the experimenter hung the mobile from the stand with the ribbon attachment and the infant first looked toward it. As soon as the specified duration expired, the experimenter removed the mobile, the caregiver removed the infant from the sling-seat, and the reactivation treatment was over.

Long-term retention test (Session 4). The long-term retention test (LRT) was administered 2 weeks after the second training session (1 day after the reactivation treatment). It was another 3-min non-reinforcement phase identical to the baseline phase and the immediate retention test during which the infant's kick rate was measured again. Immediately after the LRT, reinforcement was reintroduced as a motivational control procedure to insure that an infant who had responded poorly during the test was not ill, tired, or unmotivated on that particular day. All infants responded appropriately when the contingency was reinstated.

During training and testing, the experimenter stood out of infants' direct line of sight and recorded the number of times per min that they kicked the foot with the ribbon attached. A kick was defined as "any horizontal or vertical movement of the leg that at least partially retraces its original path in a smooth, continuous motion" (Rovee & Rovee, 1969). A second observer, naive to the infants' group assignment, independently recorded the kicks per min of 13 randomly selected infants and 18 sessions throughout the experiment from the videotapes. The Pearson product–moment interobserver reliability coefficient, computed over 279 pairs of joint response counts per minute across both experiments, was 0.98.

Retention Measures

Retention was assessed in terms of two individual measures of relative responding that we have used in all previous mobile studies of infant memory (Rovee-Collier, 1996). The *baseline ratio* compares each infant's kick rate during the LRT with that same infant's baseline rate (BASE): LRT/BASE. A baseline ratio of 1.00 indicates that test performance was not above the pretraining baseline rate (i.e., "no retention"). A mean baseline ratio significantly greater than the theoretical population baseline ratio of 1.00 indicates that a group showed significant retention.

Although the mean baseline ratio indicates whether a group exhibited retention, it does not indicate the degree of retention. The *retention ratio* provides information about the degree of retention by comparing each infant's response rate during the LRT with that same infant's final level of learning, or kick rate during the immediate retention test (IRT): LRT/IRT. A retention ratio of 1.00 or greater indicates that an infant's performance did not decline between the immediate and the long-term tests (i.e., "no forgetting"). A mean retention ratio significantly less than the theoretical population retention ratio of 1.00 indicates significant forgetting. Partial retention is indicated if a group's mean baseline ratio is significantly above 1.00 and its mean retention ratio is significantly below 1.00. If a group's mean baseline ratio is not significantly above 1.00, then a mean retention ratio significantly below 1.00 provides convergent evidence that the group showed no retention. Conversely, if a group's mean baseline ratio is not significantly above 1.00, then a mean retention ratio not significantly below 1.00 is meaningless.

Prior to all analyses, the baseline and retention ratios of each group were tested for the presence of an outlier (median outlier test: Tukey, 1977), defined as a value falling above the 90th percentile for a given group, respectively. When an outlier was found, it was replaced with the next highest value in the group, and one degree of freedom was lost. Over both experiments, six outliers were found (three baseline ratios, three retention ratios). None of the corrections affected the significance level of any test in either experiment.

Results and Discussion

Separate one-way analyses of variance (ANOVAs) over the mean kick rates of the five groups during the baseline phase and the IRT yielded no significant differences either before training, $F(4, 25) < 1$, or immediately afterward $F(4,25) = 2.43$, n.s. Therefore, any subsequent differences in retention could not be attributed to initial differences in unlearned activity or the final level of learning.

Although ANOVAs indicate whether the groups differ, they do not answer our primary question of interest—namely, whether any group exhibited significant retention after the reactivation treatment. To answer this question, we used directional *t* tests to compare the mean baseline and retention ratios of each group with the corresponding theoretical population baseline and retention ratios of 1.00 (i.e., "no retention" and "no forgetting," respectively).

These analyses revealed that none of the groups that were given a reactivation treatment shorter than 120 s 13 days after training exhibited significant retention 1 day later (Table 1 and Figure 3). The fact that these groups' mean retention ratios also were significantly below 1.00 was taken as confirmation that they exhibited no retention during the long-term test. In contrast, Group 120 s exhibited significant retention 1 day after the reactivation treatment: Its mean baseline ratio was significantly above 1.00, $t(4) = 3.25$, $p < .025$, and its mean retention ratio was not significantly below 1.00, $t(4) = 1.99$, n.s. (Table 1).

The present results were unequivocal. When the initial reactivation duration of 7.5 s was successively doubled until significant retention was exhibited 1 day later, 3-month-olds required at least a 120-s exposure to a reactivation stimulus in order for their forgotten memory to be retrieved 1 week after it had been forgotten. As expected, a reactivation treatment that lasted less than the 3 min that has been traditionally used with 3-month-olds was indeed effective in recovering a forgotten memory. These data also confirm that the effective minimum duration of a reactivation treatment decreases with age. Six-month-old infants required only a 7.5-s exposure to the reactivation stimulus 1 week after forgetting was complete in order to be successfully reminded (Sweeney, 2001), even though the absolute time between training and reactivation was greater for 6-month-olds (20 days) than for 3-month-olds (13 days). Although younger infants needed more time to process the reactivation stimulus after the same relative delay, whether this process was perceptual or strictly memorial is unknown.

Having determined the minimum effective duration of the reactivation treatment 13 days after training in Experiment 1, Experiment 2 was conducted to determine if the same minimum duration was effective after all retention intervals.

EXPERIMENT 2: THE EFFECTIVE MINIMUM EXPOSURE DURATION AFTER DIFFERENT DELAYS

At 3 months of age, a forgotten memory can be reactivated 6 days (Hayne, 1990), 13 days (Rovee-

Table 1. Mean Baseline Kick Rates (BASE), Immediate Retention Kick Rates (IRT), Retention Ratios (RR), Standard Errors (*SE*), *t* Values, and Degrees of Freedom (*df*) for Five Reactivation Groups of 3-Month-Olds as a Function of the Day-13 Reactivation Treatment Duration ($n = 6$)

Reactivation Group	*M* BASE (*SE*)	*M* IRT (*SE*)	*M* RR (*SE*)	*t*(*df*)[a]
7.5 s	9.00 (2.47)	23.50 (3.49)	0.71 (0.27)	1.06 (5)
15 s	8.60 (3.07)	23.33 (5.33)	0.51 (0.15)	3.22 (4)*
30 s	6.75 (0.96)	16.39 (1.64)	0.70 (0.23)	1.33 (5)
60 s	6.61 (1.62)	13.25 (2.16)	0.43 (0.07)	7.72 (4)**
120 s	6.30 (2.06)	13.95 (1.89)	0.73 (0.14)	1.99 (4)

*$p < .05$. **$p < .01$.
[a]Directional *t* test comparing a *M* RR with a theoretical population RR of 1.00 (i.e., no forgetting).

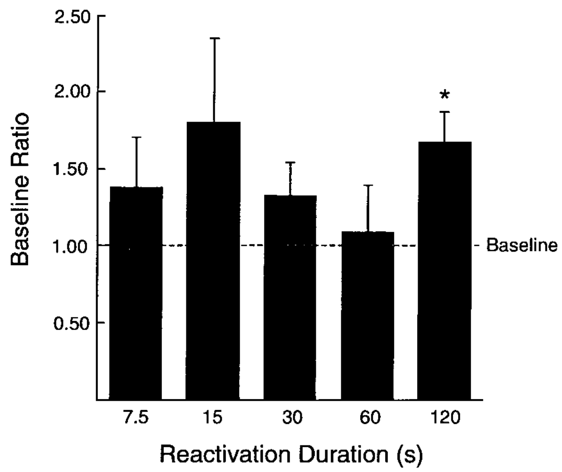


FIGURE 3 Mean baseline ratios (+1 *SE*) of infants as a function of the reactivation treatment duration (Experiment 1). The dashed line indicates baseline test performance ("no retention"); the asterisk denotes significant retention (mean baseline ratio significantly greater than 1.00).

Collier et al., 1980), 20 days (Hayne, 1990), or 27 days (Rovee-Collier et al., 1980) after training if infants are exposed to a 3-min reminder. Experiment 1 determined that 120 s is the minimum duration of exposure to a reminder that is necessary to reactivate 3-month-olds' memory 1 week after forgetting. In Experiment 2, we asked if the minimum effective exposure time is affected by when the reactivation treatment occurs in relation to when the memory was forgotten. Is the same exposure duration effective after even longer delays? Or must infants be exposed to a longer reminder when their memory has been forgotten longer? Also, is a shorter exposure duration effective after a shorter delay?

To answer these questions, we gave independent groups of 3-month-olds a brief reactivation treatment after different delays since the memory was forgotten (recall that infants of this age exhibit retention 5 but not 6 days after training) and tested them for evidence of renewed retention 1 day later. If a 120-s exposure was not effective, then we did not plan to test any additional groups because a 180-s exposure is effective in reactivating a forgotten memory 20 and 27 days after training at 3 months (Hayne, 1990; Rovee-Collier et al., 1980).

Method

Participants. Eighteen 3-month-old infants (8 girls, 10 boys), recruited as in Experiment 1, were randomly assigned to reactivation groups ($n = 6$) as they became available for study. The participants ranged in age from 72 to 113 days on the first day of training ($M = 96.72$ days, $SD = 11.86$). They were Asian ($n = 1$), African-American ($n = 1$), Caucasian ($n = 13$), and Hispanic ($n = 3$). Their parents' education ranged from 14 to 16 years ($M = 15.65$ years, $SD = 0.79$), and their mean socioeconomic status (Nakao & Treas, 1992), reported by 83.33% of the parents, was 74.99 ($SD = 12.04$). Testing was discontinued on additional infants due to a scheduling conflict ($n = 2$), rolling over during any of the four sessions ($n = 2$), an excessively high baseline rate ($n = 1$), and crying for 2 consecutive min during any of the three full-length sessions ($n = 3$).

Apparatus and Procedure. The apparatus and procedure were the same as in Experiment 1 except for the duration of the reactivation treatments and the retention intervals. Infants received a reactivation treatment on either Day 6 or 20 and were tested 1 day later. After the 20-day delay, the starting reactivation treatment duration was the same duration that had been effective after 13 days (120 s). After the 6-day delay, the starting duration was 7.5 s. If the 7.5-s exposure duration was effective in restoring retention 1 day later, then we planned to halve the exposure duration until an ineffective reactivation exposure duration was found. If the 7.5-s exposure-duration was ineffective, however, then we planned to double it until an effective one was found, as in Experiment 1. This strategy yielded one exposure-duration group who received a reactivation treatment after 20 days (120 s) and two exposure-duration groups who received a reactivation treatment after 6 days (7.5 s, 3.75 s). Because it was impossible to follow this regimen exactly for the 3.75-s reminder, its actual exposure duration more nearly approximated 4 s. Data for Group 120 s from Experiment 1 were included in the present data analyses as well.

Delays longer than 3 weeks after training were not used in Experiment 2 because previous studies have shown that a 3-min (180-s) reactivation treatment also recovers the forgotten memory after 4 weeks (Hayne, 1990; Hayne & Findlay, 1995; Rovee-Collier et al., 1980), which is the upper limit of reactivation at this age (Greco, Rovee-Collier, Hayne, Griesler, & Earley, 1986; Hartshorn, Wilk, Muller, & Rovee-Collier, 1998).

Results and Discussion

Separate one-way ANOVAs performed over the mean kicks/min of the four reactivation groups during the baseline and immediate retention test phases revealed that the groups did not significantly differ either before or after training, $Fs(3, 20) < 1$. As a result, any subsequent group differences in long-term retention could not reflect differences in either unlearned activity or the final level of learning, respectively. Identical one-way ANOVAs indicated that the mean baseline ratios of the four groups were significantly different, $F(3, 20) = 3.46$, $p < .05$, but their mean retention ratios were not, $F(3, 20) = 1.76$, n.s. (Table 2).

Because the group who received a 3.75-s reminder 6 days after training exhibited no retention 1 day later, it effectively served as a forgetting control group and confirmed that the memory was forgotten by the time of the long-term test. In succeeding analyses, therefore, this group will be termed the *forgetting control group*. To assess whether the mean baseline ratios of Groups 7.5 s/Day 6, 120 s/Day 13, and 120 s/Day 20 were significantly higher than that of the forgetting control group, Dunnett's *t* tests ($p < .05$) were used. This test controls for Type I errors across multiple comparisons with a control group (Dunnett, 1955). The mean baseline ratios of both Group 120 s/Day 13, $t(5) = 2.35$, $p < .05$, and Group 7.5 s/Day 6, $t(5) = 2.78$, $p < .05$, were significantly higher than that of the forgetting control group, whereas the mean baseline ratio of Group 120 s/Day 20 was not, $t(5) < 1$. The fact that infants in the forgetting control group did not kick significantly above the baseline rate confirmed that the performance of Groups 120 s/Day 13 and 7.5 s/Day 6 was due to infants' memory of the training mobile.

Directional *t* tests were again used to compare each group's mean baseline and mean retention ratios with the corresponding theoretical ratio of 1.00. The baseline ratio analysis revealed that a reactivation treatment lasting 120 s did not recover the forgotten memory of the mobile 20 days after training, although it had recovered the memory when given 1 week earlier (Figure 4). Group 120 s/Day 20 had a mean baseline ratio not significantly above 1.00, $t(5) < 1$, and a mean retention ratio significantly below 1.00, $t(5) = 3.27$, $p < .01$. By comparison, Group 180 s/Day 20 (Hayne, 1990) had a mean baseline ratio that was significantly above 1.00 and a mean retention ratio that was not significantly less than 1.00 (Table 2).

In contrast, the reactivation treatment administered on Day 6 (only 1 day after forgetting) was effective even though a reminder of the same duration had not reactivated the forgotten memory when given 1 week later in Experiment 1. Group 7.5 s/Day 6 had a mean baseline ratio that was significantly above 1.00, $t(4) = 2.18$, $p < .05$, although its mean retention ratio was significantly below 1.00, $t(5) = 3.00$, $p < .01$. The latter result suggests that the memory might not have been fully recovered by the time of the long-term test even though retention was significant. This result is not particularly surprising: Even after a 3-min reactivation treatment on Day 13, the memory is not fully recovered until 3 days after reminding, although retention is significant 1 day later (Fagen & Rovee-Collier, 1983). On the other hand, Group 3.75 s/Day 6 had a mean baseline ratio that was not significantly different from 1.00, $t(5) < 1$, and a mean retention ratio that was significantly below 1.00, $t(5) = 11.22$, $p < .0001$, exhibiting no evidence of retention without an effective reactivation treatment on Day 6. As indicated earlier, this group served as the control for forgetting.

These analyses indicate that the minimum effective duration of a reactivation treatment is affected by when that treatment occurs in relation to when the memory was forgotten. Increasingly longer retention intervals require increasingly longer exposure to a reactivation stimulus if the reminder is to be effective. When the memory of the mobile task had been forgotten for only 1 day, a 7.5-s exposure to the

Table 2. Mean Baseline Kick Rates (BASE), Immediate Retention Kick Rates (IRT), Retention Ratios (RR), Standard Errors (*SE*), *t* Values, and Degrees of Freedom (*df*) for Five Reactivation Groups of 3-Month-Olds as a Function of Reactivation Treatment Duration and Delay ($n = 6$).

Reactivation Group	*M* BASE (*SE*)	*M* IRT (*SE*)	*M* RR (*SE*)	*t*(*df*)[b]
3.75 s/Day 6	9.97 (2.51)	22.50 (4.15)	0.34 (0.06)	11.23 (5)**
7.5 s/Day 6	4.61 (1.12)	16.05 (3.72)	0.58 (0.14)	3.01 (5)**
120 s/Day 13[b]	6.30 (2.06)	13.95 (1.89)	0.73 (0.14)	1.99 (4)
120 s/Day 20	6.28 (1.32)	11.83 (2.60)	0.61 (0.12)	3.27 (5)**
180 s/Day 20[c]	10.60 (0.56)	25.33 (2.15)	0.85 (0.08)	1.98 (4)

*$p < .05$. **$p < .01$.
[a]Directional *t* test comparing a *M* RR with a theoretical population RR of 1.00 (i.e., no forgetting).
[b]Data from Experiment 1. [c]Data from Hayne, 1990.

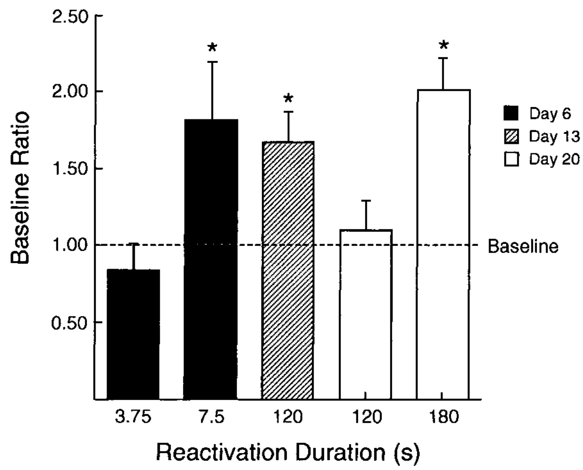


FIGURE 4 Mean baseline ratios (+1 *SE*) of infants as a function of reactivation treatment duration and time since training (Experiment 2). The dashed line indicates baseline test performance ("no retention"); asterisks denote significant retention (mean baseline ratio significantly greater than 1.00). Data for Group 180 s/Day 20, drawn from Hayne (1990), are presented for comparison purposes.

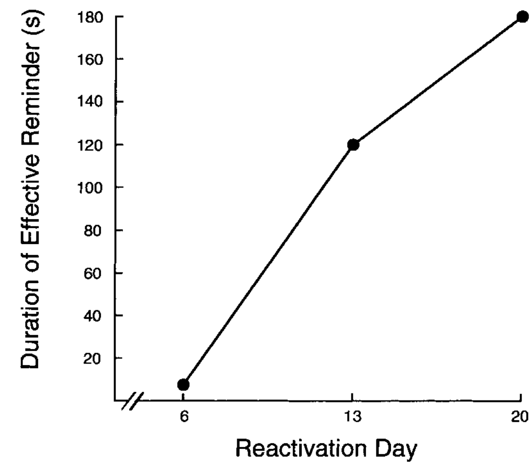


FIGURE 5 A composite showing the minimum effective duration of a reactivation treatment as a function of the time since training (Reactivation Day 6, 13, or 20). These times correspond to 1, 8, or 15 days since the memory was forgotten.

reactivation stimulus was sufficient to recover it. However, when the memory had been forgotten for 1 week, a 120-s exposure was required, and by 2 weeks after forgetting, a 180-s exposure was necessary to alleviate forgetting (Figure 5).

GENERAL DISCUSSION

The present study demonstrates the critical importance of the duration of a reactivation treatment in alleviating forgetting. How long a stimulus must be present before it is an effective retrieval cue varies with both the age of the infant and when the memory was forgotten. The younger the infant and the longer the memory has been forgotten, the longer the reminder needs to be. A briefer exposure to a reminder is not sufficient to reactivate the forgotten memory.

The finding that infants of different ages need different minimum exposures to a stimulus for it to reactivate a forgotten memory was not entirely unexpected, but the magnitude of the difference was. Six-month-old infants (Sweeney, 2001) require a much shorter minimum exposure duration after the same relative time since forgetting. In fact, 3-month-olds needed a reactivation treatment 16 times longer than 6-month-olds 1 week after forgetting. The basis for this result is unknown. Previously, Boller et al. (1990) found another temporal disparity between these two ages approaching the same order of magnitude. In that study, 6-month-olds required only 1 hr to evidence renewed retention after a reactivation treatment, but 3-month-olds required 24 hr to do so. Further, the magnitude of retention following reactivation peaked after 4 hr at 6 months of age, but it did not peak for 3 days at 3 months of age. Because the speed of reactivation was subsequently found to increase linearly with age (Hildreth & Rovee-Collier, 1999), it is tempting to attribute timing differences to maturational changes within the nervous system. Recently, however, Hayne, Gross, Hildreth, and Rovee-Collier (2000) reported that giving 3-month-olds two reactivation treatments increased the speed of reactivation from 24 hr to 1 hr or less, thus eliminating a maturation-based account. Because maturational changes cannot account for age differences in the speed of reactivation, they probably cannot explain the age difference in the minimum effective duration of a reactivation treatment either—at least, they are unlikely to be the sole account.

The finding that a memory that has been forgotten longer requires a longer reactivation treatment to be recovered (Figure 5) is theoretically important. Before now, once a memory was no longer expressed, there was no way of determining just how inaccessible it might be. Determining the minimum duration of exposure to a stimulus that can successfully reactivate it, however, provides a direct measure of the inaccessibility of the memory. An alternative account, that the minimum duration of exposure simply might have reflected slower perceptual processing by infants who were younger at the time of reactivation [i.e., by infants whose reactivation treatment occurred only

6 days after training (1 day after forgetting)], as compared with those whose reactivation treatment was 20 days after training (15 days after forgetting), can be rejected. Some 3-month-olds in the 20-day reactivation group, who presently exhibited no retention after a 120-s reactivation treatment, were actually younger than some infants in the 6-day group, who required only a 7.5-s reactivation treatment. Moreover, even 2-month-olds require only a 180-s reactivation treatment 20 days after training (Rovee-Collier, Hartshorn, & DiRubbo, 1999).

From a functional perspective, the finding that the minimum duration of a successful reminder increases with the time since forgetting makes adaptive sense, particularly for very young infants who have poor inhibitory control (Diamond, 1990a, 1990b). One likely consequence of poor inhibitory control is a tendency to selectively attend to stimuli that are salient but irrelevant. In selective-attention tasks, elderly adults, who also lack an effective inhibitory system, can subsequently recall more distractor letters than young adults despite being instructed to suppress attention to them during the study period (Hasher, Stoltzfus, Sacks, & Rypma, 1991). From this perspective, the minimum exposure duration increases the probability that only information which is most relevant is processed. That is, if a more sustained exposure to a stimulus is necessary for it to reactivate a forgotten memory, then the many stimuli over which infants' eyes pass only fleetingly will not reactivate the multitude of potentially irrelevant memories that would flood their consciousness and that they would be unable to suppress. Instead, any stimulus that infants might attend for less than the minimum duration would not serve as an effective reactivation cue (see Harnishfeger, 1995, for a discussion of changes in the inhibitory system as a function of age).

Moreover, because stimuli that have not been encountered for a relatively long time must be attended longer to cue reactivation, stimuli that have lost their significance in the interim will be even less likely to cue reactivation after a long delay. The latter possibility would seem most likely to occur for the very young, who are undergoing rapid developmental changes. Even so, a prior memory that can still potentially guide behavior will be reactivated as long as its retrieval cue is sufficiently attended. Thus, for example, infants in Experiment 2 behaved as if they had never seen the original training mobile when given a 3.75-s reactivation treatment 6 days after training. When that duration was doubled, however, they subsequently recognized the original mobile again. Likewise, infants behaved as if they had never seen the original mobile when it was presented for 1 min after 2 weeks, but again, they did subsequently recognized it again when that duration was doubled.

The present results raise other theoretically important questions, some of which pertain to the underlying issue of whether the reactivation process is all-or-none. Would, for example, the upper limit of reactivation be lowered if the reactivation treatment were briefer? Would the persistence of memories reactivated by a cue of the minimum duration be reduced? And, would a briefer reactivation treatment affect the rate at which the forgotten memory is recovered in the first place? Fagen and Rovee-Collier (1983) found that 13 days after training (1 week after forgetting—the interval used in Experiment 1), 3-month-olds' memory of the mobile task was not fully recovered for 3 days, even after they were given a 180-s reactivation treatment. Would a memory recovered by a shorter reactivation treatment follow this same pattern? Or would that forgotten memory ever be fully recovered? Finally, recall that a memory that had been reactivated once before was recovered more rapidly than a memory that had not previously been reactivated (Hayne et al., 2000). Would the minimum duration that is required for an effective reactivation treatment also be shorter if a memory had been reactivated before? In short, although the present study has answered some important questions, it has generated a number of others.

NOTES

This research was conducted as a Henry Rutgers Scholars Thesis by the first author under the direction of the third. It was funded by a Henry Rutgers Scholars Research Fellowship (A. J.) and by Grants MH32307 and K05-00902 from the National Institute of Mental Health (C. R. C.). We are grateful to Lissa Galluccio for coding the videotapes for interobserver reliability and Rachel Barr for statistical assistance. An earlier version of this article was presented to the Northeastern Mini-Conference on Infant Studies, January 2001, Lowell, MA.

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