Available online at www.sciencedirect.com
SCIENCE DIRECT®
Learning and Motivation 37 (2006) 1–17
Learning and Motivation
www.elsevier.com/locate/l&m

Nonuniform effects of reinstatement within the time window ☆

Lissa Galluccio, Carolyn Rovee-Collier *

Department of Psychology, Rutgers University, 152 Frelinghuysen Rd., Piscataway, NJ 08854-8020, USA

Received 7 November 2004; received in revised form 7 January 2005
Available online 21 March 2005

Abstract

A time window is a limited period after an event initially occurs in which additional information can be integrated with the memory of that event. It shuts when the memory is forgotten. The time window hypothesis holds that the impact of a manipulation at different points within the time window is nonuniform. In two operant conditioning experiments with 68 3-month-old human infants, we tested the predictive validity of the nonuniformity principle for reinstatement—a partial training trial that forestalls forgetting. After demonstrating that 3-month-olds forget the training task after 5 days (Experiment 1), we presented a reinstatement early (immediately), midway (3 days), or late (5 days) in the time window (Experiment 2). Retention increased exponentially with the reinstatement delay. The surprising magnitude of this result, plus its generality across tasks and species, strongly suggests that the timing of reinstatement differentially affects the outcomes of studies on learning and memory.

Keywords: Reinstatement; Time window; Retention interval; Retention; Forgetting; Human infants; Operant conditioning; Timing; Retrieval difficulty; Temporal contiguity

☆ This research was funded by Grant No. MH32307 from the National Institute of Mental Health to Carolyn Rovee-Collier. We thank Jacob Feldman for statistical advice and assistance with the curve-fitting in Experiment 2.
* Corresponding author. Fax: +1 732 445 2263.
E-mail address: rovee@rci.rutgers.edu (C. Rovee-Collier).

doi:10.1016/j.lmot.2005.01.002

Reinstatement is a reminder procedure in which a brief, partial training trial that is administered during the retention interval maintains access to a memory that would otherwise be forgotten (Campbell & Jaynes, 1966). Its effect does not summate with the effect of original training, but subjects show no retention benefit from reinstatement unless they had previously been trained. In their landmark demonstration of reinstatement, Campbell and Jaynes (1966) classically conditioned fear in weanling rats by administering 30 inescapable shocks on the black side of a shuttle-box while intermittently exposing the pups to the white (no-shock) side. Every week for the next 3 weeks, they gave pups in the reinstatement group a single shock on the black side of the box. When tested 1 month after they were originally trained, pups still exhibited conditioned fear, spending significantly more time on the white side of the box than trained pups that received no interpolated reinstatements (the forgetting control group) or untrained pups that received the same regimen of weekly shocks in the black compartment (the reinstatement control group).

The retention benefit of reinstatement has been replicated many times and is now a staple in studies of animal learning and memory (Campbell & Jaynes, 1969; Campbell & Randall, 1976; Greenfield & Riccio, 1972; Riccio & Haroutunian, 1979; Spear & Parsons, 1976). Recently, we have found that reinstatement forestalls forgetting by human infants in much the same way that Campbell and Jaynes originally described for animal infants (Adler, Wilk, & Rovee-Collier, 2000; Galluccio & Rovee-Collier, 1999; Hartshorn, 2003; Hartshorn & Rovee-Collier, 2003; Rovee-Collier, Hartshorn, & DiRubbo, 1999). In these studies, 2- to 6-month-olds learned to move a mobile by kicking or a toy train by lever-pressing, received one or more brief reinstatements in which responding again moved the mobile or train, and then received a temporally distant retention test. Infants who received a brief reinstatement during the retention interval remembered longer than either trained infants who did not receive a reinstatement before the long-term test (the forgetting control group) or untrained infants who did receive a reinstatement before the test (the reinstatement control group).

Several years ago, the *time window* construct was introduced to describe the circumstances in which information from two successive events would or would not be integrated (Rovee-Collier, 1995). The biological counterpart of a time window is a *critical period*—a concept originally used by embryologists to describe the limited period of time when a particular organ is undergoing very rapid differentiation and is particularly vulnerable to perturbations (e.g., Spalding, 1873). A perturbation that occurs during a critical period has deleterious effects on the developing organ that are not seen when the perturbation occurs either prior to or after that period. Psychologists borrowed the critical period concept and applied it to the development of socioemotional behavior. Scott (1958; Scott & Marston, 1950; Williams & Scott, 1953), for example, documented a critical period early in canine development during which exposure to another organism is necessary for normal socialization; before or after this period, the same exposure has a small-to-negligible effect. Later, he extended the concept to include critical periods for learning and early experience (Scott, 1962).

Like a critical period, a time window is a limited period within which new information can be integrated with information that is already in memory. The integration will not occur if the same information is encountered either before or after this period; instead, on its the second encounter, the information will be treated as unique—not associated with the initial event. Also as with critical periods, the effect of a particular manipulation within a time window is nonuniform: Information encountered at the end of a time window is hypothesized to have a greater impact on retention than information encountered when the time window first opens. Unlike a critical period, however, a time window is not limited to a particular period of development, and its width is not fixed but expands every time the prior memory is retrieved.

The retention benefit of spacing trials or sessions is well documented across species and ages (Bryan, 1980; Leaton, 1976; Shaughnessy, 1977; Underwood, Kapelak, & Malmi, 1976; Vander Linde, Morrongiello, & Rovee-Collier, 1985). Two early studies of the spacing effect with 3-month-olds illustrate three tenets of the time window construct: (1) the second event must occur before the time window of the initial event closes in order to be integrated with it; (2) each retrieval protracts the prior memory (i.e., expands the time window) longer than the previous one; and (3) retrieving the memory near the end of the time window protracts it longer than retrieving it shortly after the time window first opened. In both studies, infants learned to move a crib mobile by kicking and later were tested for retention during a nonreinforcement phase. Responding significantly above the baseline rate during the long-term test operationally defined retention.

In the first study, experimental groups received a second training session 1, 2, 3, or 4 days after the first, whereas a control group received only the initial training session. All infants received a retention test 8 days after the first training session. During the long-term test, the control group exhibited no retention 8 days later, but the experimental groups exhibited significant retention if their second session followed the first by 1, 2, or 3 but not 4 days. A final experimental group received a 4-day intersession interval and was tested on day 7. This group also exhibited no retention, confirming that long-term retention depended on the interval between sessions 1 and 2 and not between session 2 and the long-term test (Rovee-Collier, Evancio, & Earley, 1995). These data supported the first tenet: the time window for integrating successive training sessions closed after 3 days; when the second session fell outside that period, infants treated the second session as if it were their first, and their long-term retention was no different than if they had been trained for only one session in the first place.

The second study grew out of the first. Infants received three training sessions and a retention test 3 weeks after session 3. Successive sessions occurred on days 0–4–8 (always outside the time window) or on days 0–2–8 (always within the expanding time window and near its end), but the mean intersession interval (4 days) was the same. For a final group, successive training sessions occurred on days 0–1–2 (within the time window and near its beginning). Group 0–2–8 exhibited significant retention on day 29, but groups 0–4–8 and 0–1–2 exhibited none. Although group 0–1–2 exhibited significant retention 7 days after session 3, group 0–4–8 exhibited none (Hartshorn, Wilk, Muller, & Rovee-Collier, 1998). These data supported the second and third tenets: each succeeding session within the time window protracted retention longer than the one before, and the retention benefit was greater when successive sessions occurred at the end of the progressively expanding time window than at its beginning.

The nonuniformity principle has major implications for the effectiveness of reinstatement, which also occurs within the time window. Reinstatement requires retrieval of the prior memory, but it is not a complete training session. Even as a partial training session, however, its effect does not summate with the effects of original training (Galluccio & Rovee-Collier, 1999), and its retention benefit is substantially greater than if subjects were merely overtrained for an equivalent period (Adler et al., 2000). The time window hypothesis predicts that the later a reinstatement is administered within the retention interval, the longer it should protract the prior memory. Although the results of session spacing studies appear to be consistent with this prediction, it is not clear that they actually apply to the reinstatement phenomenon. First, the time window for session spacing closed after 3 days (Rovee-Collier et al., 1995), but 3-month-olds remember the mobile task for approximately 5 days (Hayne, 1990; Galluccio, 2005), and a reinstatement can be administered anytime during that period. Second, the effect of a succeeding training session within the time window cumulated with (was integrated with) the effects of the training session that came before, but the effect of reinstatement does not summate with the effect of prior training (Galluccio & Rovee-Collier, 1999).

The present study was designed to test the validity of the prediction that the later a reinstatement is administered within the time window, the longer it should protract the prior memory. To this end, we operantly trained independent groups of 3-month-olds, presented a brief reinstatement after different delays that spanned their original forgetting function (i.e., at the beginning, middle, or end of the time window), and then assessed the duration of their subsequent retention.

Experiment 1: Confirmation of the Time Window for Memory Retrieval

In the reinstatement procedure, retrieval of the training memory during the retention interval forestalls forgetting. We previously found that independent groups of 3-month-old infants who were operantly trained in the mobile task for 15 min on each of 2 consecutive days exhibited significant retention 5 days but not 6 days later (Galluccio, 2005; Hayne, 1990; Hitchcock & Rovee-Collier, 1996). These studies indicated that, for these parameters of training, the time window for memory retrieval shut after 5 days. Before proceeding to administer a reinstatement at various points within the time window, however, we thought it prudent to confirm within the context of the present study that the time window is still open 5 days after training but is closed thereafter. Therefore, we trained two groups of 3-month-olds and tested them either 5 days (*group 0rn/5*) or 6 days (*group 0rn/6*) after the end of training. In the group labels, "0rn" indicates that a group received no reinstatement and the number after the slash indicates the day since the end of training that retention was tested.

Method

Participants

The final sample contained thirteen 3-month-olds (9 boys, 4 girls) who were recruited from published birth announcements in local newspapers and by word of mouth. Their mean age was 98.2 days ($SD = 10.9$) on the first day of training. Participants were African–American ($n = 1$), Asian ($n = 2$), Hispanic ($n = 1$), and Caucasian ($n = 9$). Parental educational attainment ranged from 14 to 16 years ($M = 15.85$ years, $SD = 0.55$). Ranks of parents' socioeconomic status (Nakao & Treas, 1992)[1] ranged from 61.85 to 92.30 ($M = 75.39$, $SD = 9.87$). Testing was discontinued on an additional infant in *group 0rn/6* who fell asleep during the test session.

Apparatus

Infants were trained with one of two mobiles, counterbalanced within groups. The mobiles were composed of five, highly detailed, painted wooden figures suspended on a white cord from the ends and middle of intersecting cross-bars (Nursery Plastics, Models 801 and 809). During all sessions, the end and sides of the infant's home crib were draped with one of two sets of distinctive cloth liners, counterbalanced within groups. Each set consisted of two 122- × 114-cm broadcloth side panels and a 66- × 122-cm end panel. One liner was constructed of Kelly-green felt squares (5.08 cm^2 separated by 5.08 cm) in a grid pattern on a bright yellow background; the other liner was constructed of blue felt vertical stripes (2.54-cm wide separated by 3.18 cm) on a bright red background.

The mobile was suspended 25–30 cm above the infant's abdomen from a hook at the end of an L-shaped mobile stand that was clamped on one of the crib rails. A second mobile stand was clamped opposite the first such that the ends of the two bars protruded over the crib. One end of a white satin ribbon was secured to the infant's ankle, and the other end was connected to a hook at the end of one of the mobile bars.

Procedure

All infants were tested in their homes at a time when they were likely to be awake/alert, as designated by their mother. Although the time of a session varied across infants, it remained relatively constant for a given infant.

Each infant received a 15-min training session on 2 consecutive days and a test session either 5 or 6 days later. The first and last 3 min of each training session were nonreinforcement periods, when the ribbon was attached to the empty hook, and the mobile was suspended from the other one. In this arrangement, the infant could see the mobile, but kicks could not move it. The mean number of kicks during the initial

[1] All human studies funded by NIMH are required to report information pertaining to race, ethnicity, and socioeconomic status. Educational attainment, occupational status, and annual income are the major components of socioeconomic status. The socioeconomic index (SEI), published by Nakao and Treas (1992), is the recommended source for occupational status. In the SEI, ranks of occupations range from 1 to 100, with higher-paying occupations (e.g., physician and lawyer) being assigned higher ranks.

3-min nonreinforcement period of session 1 (*baseline phase*) provided a measure of the infant's pretraining operant level. The mean number of kicks during the final 3-min nonreinforcement period of session 2 (*immediate retention test*) provided a measure of the infant's final level of learning and retention after zero delay. Between these two nonreinforcement periods was a 9-min reinforcement phase (*acquisition*), when the ribbon was attached to the same hook as the mobile. In this arrangement, the infant's kicks activated the mobile in proportion to the rate and intensity of responding (i.e., conjugate reinforcement).

The *long-term retention test* was also a 3-min nonreinforcement period. As a result, test responding reflected only what knowledge the infant brought into the session and not new learning or savings at the time of testing. The mean number of kicks during this period provided the measure of retention. Following the long-term retention test, the contingency was reintroduced during a 9-min motivational control phase. This phase was included to ensure that infants who had performed poorly during the long-term test were not ill, fatigued, or unmotivated on that particular day. None was. All infants responded appropriately to reintroduction of the contingency.

The experimenter, standing out of the infant's direct line of sight, recorded the number of kicks per minute of the foot with the attached ribbon. A kick was defined as a movement of the foot that at least partially retraced its original path in a smooth, continuous motion (Rovee & Rovee, 1969).[2] A second observer, blind with respect to infants' group assignments, independently recorded the kicks per minute of seven infants during 10 randomly selected sessions in both experiments. A Pearson product-moment correlation, computed over 147 pairs of their joint response counts/min, yielded an interobserver reliability coefficient of 0.97.

Retention measures

Retention was assessed by means of two individual measures of relative retention, the *baseline ratio* and the *retention ratio*, that we have used in all previous studies of infant long-term memory (Rovee-Collier, 1996). The baseline ratio (LRT/BASE: kick rate during the long-term retention test/kick rate during the baseline phase) expresses the extent to which an infant's response rate during the long-term retention test (LRT) exceeds that same infant's response rate during the baseline phase (BASE). If the group's mean baseline ratio is significantly greater than 1.00 (H_0: no retention), then it has displayed significant retention.

The degree of retention is indexed by the retention ratio (LRT/IRT: kick rate during the long-term retention test/kick rate during the immediate retention test), which expresses the fraction of an infant's mean response rate during the immediate retention test (IRT) that the infant continues to exhibit during the long-term retention test. (LRT). A retention ratio of 1.00 indicates that an infant's kick rate did not decrease from the immediate to the long-term retention test (H_0: no forgetting).

[2] Repeated attempts to automate this task have been unsuccessful. Infants often kick so hard that they either propel themselves toward the head of the crib or rotate themselves in the crib, obviating the use of microswitches or photocells.

Lower retention ratios indicate greater proportional decrements in responding during the long-term test. The retention ratio measure permits determination of an intermediate degree of retention. Although a group may exhibit significant forgetting (i.e., its mean retention ratio is significantly less than 1.00), forgetting is not considered to be complete unless its mean baseline ratio is not significantly above 1.00.

Prior to performing all analyses in both experiments, the baseline and retention ratios of each group were tested for outliers (median outliers test: Tukey, 1977). An outlier was defined as a ratio falling above the 90th percentile for a given group. If an outlier was found, it was replaced with the next lowest ratio within that group, and one degree of freedom was lost. Over both experiments, two baseline ratios and one retention ratio were found to be outliers. The resulting corrections did not alter the significance level of any statistical test.

Results and discussion

To determine whether either test group exhibited significant retention, directional one-sample *t* tests were used to compare the mean baseline ratios and mean retention ratios against the corresponding theoretical population ratios of 1.00 (no retention and no forgetting, respectively). These analyses revealed that the 5-day test group (*group 0rn/5*) exhibited significant retention, but the 6-day test group (*group 0rn/6*) did not. The mean baseline ratio of *group 0rn/5* was significantly above 1.00 ($M = 1.97$, $SE = .42$), $t(6) = 2.31$, $p < .05$, but its mean retention ratio was significantly below 1.00 ($M = 0.59$, $SE = .11$), $t(6) = 5.54$, $p < .05$ indicative of some forgetting. In contrast, the mean baseline ratio of *group 0rn/6* was not significantly above 1.00 ($M = 0.81$, $SE = .18$), $t(4) < 1$, and its mean retention ratio was significantly below 1.00 ($M = 0.44$, $SE = .08$), $t(4) = 7.28$, $p < .005$. These results replicated the previous findings that 3-month-olds who are trained in a distinctive context have forgotten the mobile task 6 days after training (Galluccio, 2005; Hayne, 1990; Hitchcock & Rovee-Collier, 1996).

Experiment 2: Reinstatement at Different Points within the Time Window

In Experiment 2, having confirmed that the time window shuts after 5 days, we administered the reinstatement at points that spanned the width of the time window. Specifically, we presented a reinstatement to independent groups of 3-month-olds at the beginning (immediately after training), midpoint (day 3), or end (day 5) of the time window and asked whether its timing would differentially protract retention. Specifically, we predicted that the later in the time window the reinstatement occurred, the longer it would protract infants' subsequent retention.

A second aim of the present study was to compare the slope of the original forgetting function that had been obtained from 3-month-olds (Butler & Rovee-Collier, 1989) with the slopes of the forgetting functions of 3-month-olds whose reinstatement occurred at different points within the time window. Specifically, we predicted that the slope of the forgetting function obtained after a reinstatement on day 5 would be significantly flatter (i.e., its decay rate would be slower) than the slopes of forgetting functions obtained when the reinstatement occurred earlier in the time window.

Method

Participants

Participants were fifty-five 3-month-old infants (26 boys, 29 girls), recruited as before, and randomly assigned to one of nine groups ($n = 6$)[3] as they became available for testing. Their mean age was 93.4 days ($SD = 11.7$) on the first day of training. Participants were African–American ($n = 1$), Asian ($n = 2$), and Caucasian ($n = 52$). Parental educational attainment ranged from 12 to 16 years ($M = 15.74$ years, $SD = 0.88$). Ranks of parents' socioeconomic status (Nakao & Treas, 1992), reported by 92% of the sample, ranged from 29.52 to 92.30 ($M = 67.98$, $SD = 14.91$). Testing was discontinued on additional infants who cried excessively ($n = 3$), became ill ($n = 1$), failed to remain supine ($n = 3$), or failed to meet the learning criterion (responding 1.5 times above the mean baseline rate for 2 of 3 consecutive min during acquisition; $n = 8$). Based on the number of opportunities (sessions) for a given infant to be lost from the sample, the rate of attrition was 5.7%.

Procedure

The procedure was the same as before except that we presented a 3-min reinstatement immediately (0 days), 3 days, or 5 days after training. The reinstatement was procedurally identical to a reinforcement period during training; its duration was timed from an infant's first kick.

Because a control group in a prior study that had received a 3-min reinstatement immediately after training had exhibited no retention 7 days later (Adler et al., 2000), we began testing the immediate reinstatement group 6 days after training (*group rn0/6*). Next, we successively tested independent groups that received a reinstatement on either day 3 or day 5 until we determined their maximum duration of retention. Our strategy was to begin testing each succeeding group after a delay longer than the maximum delay at which the preceding reinstatement-timing group had exhibited retention. Thereafter, we increased or decreased the test delay in steps of 2–3 days depending on whether or not, respectively, a group remembered after the preceding test delay. This strategy, known as the staircase-method in psychophysics, yielded eight groups that were tested 7, 10, 11, 13, 16, 21, 25, or 28 days after training (*group rn3/7*, *group rn3/10*, *group rn3/11*, *group rn3/13*, *group rn5/16*, *group rn5/21*, *group rn5/25*, or *group rn5/28*, respectively). In the group labels, the number immediately before the slash indicates the day since the end of training when the reinstatement (rn) was administered, and the number immediately after the slash indicates the day since the end of training when long-term retention was tested.

[3] An extra infant was tested in *group rn3/13* ($n = 7$).

Finally, the two test groups from Experiment 1 that received no reinstatement (*group 0rn/5*, *group 0rn/6*) served as forgetting control groups in Experiment 2. Recall that "0rn" indicates that a group received no reinstatement.

Results and discussion

Preliminary one-way analyses of variance (ANOVAs) were performed over the mean kick rates of the nine reinstatement groups and two forgetting control groups during the baseline phase and the immediate retention test. These analyses confirmed that the groups did not differ either before training, $F(10, 57) < 1$, $MSe = 14.26$, or immediately afterward, $F(10, 57) < 1$, $MSe = 104.63$, thereby ruling out the possibility that differences in responding during the long-term retention test could be due to group differences in either unlearned activity or the final level of learning, respectively.

The main analyses confirmed that administering a reinstatement at the end of the time window protracted retention longer than administering it either at the beginning or in the middle of the time window (see Fig. 1). Infants whose reinstatement immediately followed training (i.e., at the beginning of the time window) and were tested 6 days later had a mean baseline ratio that was significantly above 1.00 ($M = 1.84$, $SE = .32$), $t(5) = 2.66$, $p < .05$, and a mean retention ratio that was not significantly less than 1.00 ($M = 0.72$, $SE = .14$), $t(5) = 1.91$, *ns*, indicative of retention.

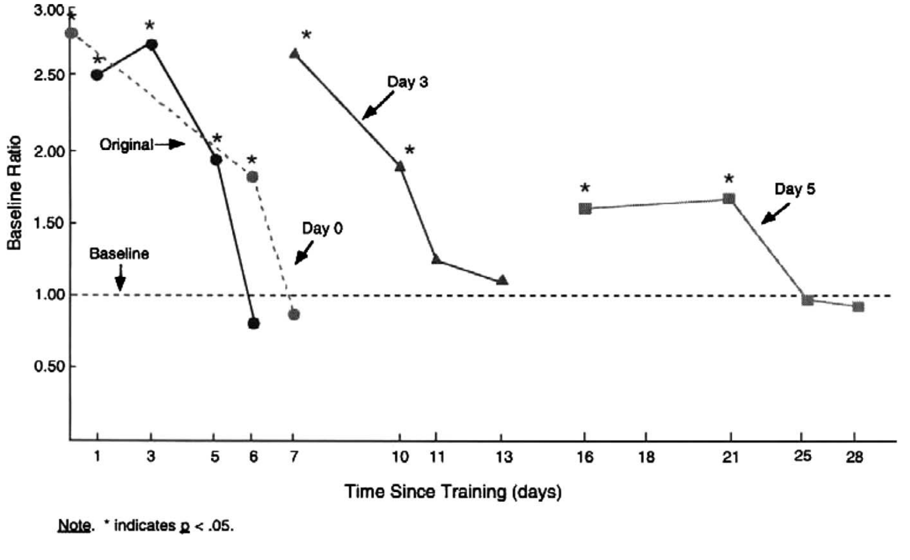

Fig. 1. Mean baseline ratios of the independent groups of 3-month-old infants whose retention was tested after increasing delays since training (the simple forgetting function: *circles*, *solid lines*) and after receiving a reinstatement on day 0 (*circles/dashed lines*), day 3 (*triangles/solid lines*), and day 5 (*squares/solid lines*). The first point on the day-0 function is the retention of *group rn0/6* at the end of training, immediately before the reinstatement was administered. An asterisk indicates that a group exhibited significant retention (*M* baseline ratio significantly >1.00).

In the Adler et al. (2000) study, infants who received a 3-min reinstatement immediately after training had exhibited no retention 7 days later. Thus, presenting the reinstatement immediately after training produced a small retention benefit, protracting retention 1 day longer than that of infants given no reinstatement in Experiment 1.

In contrast, infants whose reinstatement was presented on day 3 exhibited significant retention both 7 days and 10 days after training but not 11 or 13 days afterward. The mean baseline ratios of infants tested after 7 days ($M = 2.72$, $SE = .60$) and 10 days ($M = 1.90$, $SE = .28$) were significantly greater than 1.00, $t(5) = 2.86$, $p < .05$ and $t(5) = 3.19$, $p < .05$, respectively, but the mean baseline ratios of infants tested after 11 days ($M = 1.23$, $SE = .14$) and 13 days ($M = 1.15$, $SE = .18$) were not, $t(5) = 1.70$, *ns*, and $t(6) < 1$, respectively. Like *group rn0/6* (the immediate reinstatement group), which had been tested after the shortest delay, *group rn3/7*, which was tested after the next shortest delay, exhibited no forgetting: Its mean retention ratio was not significantly less than 1.00 ($M = 0.88$, $SE = .12$), $t(4) < 1$. The remaining mean retention ratios of the preceding groups, however, were significantly less than 1.00 (*rn3/10*: $M = 0.75$, $SE = .04$, $t(4) = 5.79$, $p < .01$; *rn3/11*: $M = 0.73$, $SE = .09$, $t(4) = 2.83$, $p < .05$; *rn3/13*: $M = 0.57$, $SE = .08$, $t(4) = 5.25$, $p < .05$), indicating that significant forgetting had taken place since the end of training (see Table 1).

Finally, infants whose reinstatement was presented 5 days after training exhibited significant retention both 16 and 21 days after training but not 25 or 28 days afterward. The mean baseline ratios of infants tested after 16 days ($M = 1.62$, $SE = .27$) and 21 days ($M = 1.68$, $SE = .24$) were significantly greater than 1.00, $t(5) = 2.30$,

Table 1
Mean baseline ratios (BR) and retention ratios (RR), standard errors (±1 SE), *t* values, and degrees of freedom (*df*) of 3-month-olds in 2 no-reinstatement groups (Experiment 1) and 9 reinstatement groups (Experiment 2)

	Baseline ratios		Retention ratios	
	M (*SE*)	*t* (*df*)[a]	*M* (*SE*)	*t* (*df*)[b]
Experiment 1				
0rn/5	1.97 (0.42)	2.31 (6)*	0.59 (0.11)	3.81 (6)*
0rn/6	0.81 (0.18)	−1.05 (4)	0.44 (0.08)	7.28 (4)**
Experiment 2				
rn0/6	1.84 (0.32)	2.66 (5)*	0.72 (0.14)	1.91 (5)
rn3/7	2.72 (0.60)	2.86 (5)*	0.88 (0.12)	0.90 (4)
rn3/10	1.90 (0.28)	3.19 (5)*	0.75 (0.04)	5.79 (4)**
rn3/11	1.23 (0.14)	1.70 (5)	0.73 (0.09)	2.83 (5)*
rn3/13	1.15 (0.18)	0.85 (5)	0.57 (0.08)	5.25 (4)*
rn5/16	1.62 (0.27)	2.30 (5)*	0.62 (0.15)	2.61 (5)*
rn5/21	1.68 (0.24)	2.88 (5)*	0.61 (0.12)	3.26 (5)*
rn5/25	0.74 (0.08)	0.18 (6)	0.32 (0.05)	14.66 (5)***
rn5/28	0.94 (0.08)	−0.77 (5)	0.30 (0.07)	10.69 (5)***

[a] Directional *t* test comparing the *M* BR with a theoretical population BR of 1.00 (i.e., no retention).
[b] Directional *t* test comparing the *M* RR with a theoretical population RR of 1.00 (i.e., no forgetting).
* $p < .05$.
** $p < .01$.
*** $p < .0005$.

$p < .05$ and $t(5) = 2.89$, $p < .05$, respectively, but the mean baseline ratios of infants tested after 25 days ($M = 0.74$, $SE = .08$) and 28 days ($M = 0.94$, $SE = .08$) were not, $t(4) < 1$ and $t(5) < 1$, respectively. Identical analyses of the corresponding retention ratios indicated that all of these groups had mean retention ratios that were significantly less than 1.00 (*rn5/16*: $M = 0.62$, $SE = .15$, $t(5) = 2.61$, $p < .05$; *rn5/21*: $M = 0.61$, $SE = .12$, $t(5) = 3.26$, $p < .05$; *rn5/25*: $M = 0.32$, $SE = .05$, $t(5) = 14.66$, $p < .0005$; *rn5/28*: $M = 0.30$, $SE = .07$, $t(5) = 10.69$, $p < .0005$), indicating that all exhibited significant forgetting by the time of testing (see Table 1).

Infants whose reinstatement was presented 3 days after training still exhibited retention 10 days after training. Relative to the 1-day retention gain that was afforded by presenting the reinstatement immediately after training, the additional gain afforded by presenting the reinstatement in the middle of the time window was considerable. Because 3-month-olds had remembered the mobile task for only 5 days without an interpolated reinstatement in Experiment 1, the day-3 reinstatement in Experiment 2 effectively *doubled* the duration of their retention. However, when the reinstatement was presented on day 5, at the end of the time window, it more than *quadrupled* the duration of infants' retention, extending it to 21 days after training. These findings confirm that the impact of reinstatement is not uniform within the time window; rather, the later in the time window the reinstatement occurs, the greater is its impact on retention.

In the subsequent analyses, we focused on differences in the characteristics of the forgetting functions after differently timed reinstatements. Specifically, we asked if the decay rates of the original forgetting function (no reinstatement), the forgetting function after a day-3 reinstatement, and the forgetting function after a day-5 reinstatement differed statistically. (The forgetting function of the immediate reinstatement group was not included in these analyses because it was based on only two points—performance on day 6 and performance on day 7.)

Each of the forgetting functions was modeled separately using a linear regression analysis in which the natural log of the baseline ratio for each reinstatement condition (none, day 3, day 5) was the dependent variable, and the test day (time since training) was the independent variable. Prior to all analyses, we transformed infants' baseline ratios, which had a theoretical mean of 1.00, into natural logs with a corresponding mean of zero.[4] This transformation did not change the shape of the forgetting functions, but values below baseline became negative, and values above baseline became positive. These analyses indicated that a linear model provided a significant fit for each of the three forgetting functions: *original forgetting function*, $F(1, 23) = 12.38$, $p < .01$; *day-3 function*, $F(1, 23) = 11.39$, $p < .01$; *day-5 function*, $F(1, 22) = 7.32$, $p < .05$ (see Fig. 2).

Next, we compared the slopes of each linear function with one another (original forgetting vs. day 3, day 3 vs. day 5, original forgetting vs. day 5) by means of Student

[4] This transformation was necessitated by the fact that it is conceptually inaccurate to think of a forgetting function as decreasing indefinitely, as a line does. A line would predict that a group's mean baseline ratio would eventually drop below zero.

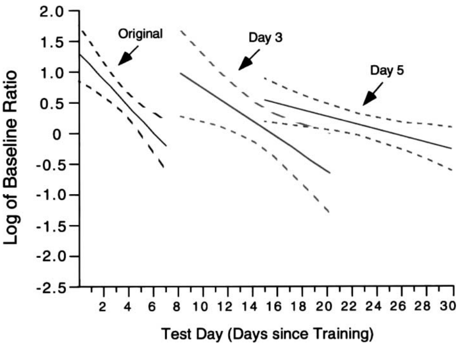

Fig. 2. Best-fit linear regressions of the log of the baseline ratios of infants in the simple forgetting condition and the day-3 and day-5 reinstatement groups as a function of the test delay. Dotted lines indicate the confidence interval of each linear function, $p = .05$.

t tests to determine if their decay rates differed significantly. These analyses confirmed what was evident from Fig. 2 and from the retention benefit produced by the various reinstatement conditions. As predicted, the slope of the day-5 function was significantly flatter than the slope of the day-3 function, $t(47) = 7.59$, $p < .0001$, and the slopes of the day-5 and day-3 functions were each significantly flatter than the slope of the original forgetting function (no reinstatement): *day-5 function*, $t(48) = 4.86$, $p < .0001$; *day-3 function*, $t(47) = 1.23$, $p < .0001$. These analyses reveal that presenting a reinstatement within the time window not only forestalled forgetting, as Campbell and Jaynes (1966) had observed, but also when the reinstatement occurred later within the time window, the slope of the subsequent forgetting function (its rate of decay) was significantly shallower.

General discussion

Because very young infants' memories are so short-lived relative to memories of older individuals, the consequences of the timing of a reinstatement within the time window are particularly dramatic. Three-month-olds who learn to move a mobile by kicking, for example, remember that task for only 5 days, but a reinstatement within that 5-day period (the time window) protracts their retention of the task. Most important, however, is the finding that the timing of the reinstatement within the 5-day time window markedly affects the extent of the retention benefit. Administering the reinstatement at the beginning of the time window, immediately after training (day 0), affords only a small retention benefit—1 additional day. Administering the reinstatement in the middle of the time window, on day 3, yields a retention benefit of 5 additional days, or twice the duration of original retention. And administering the reinstatement at the end of the time window, on day 5, yields a retention benefit of 16 additional days, or a duration of retention more than four times longer than infants otherwise remember. This exponential increase in the retention benefit as a result of the timing of the reinstatement within the time window is particularly remarkable considering that the reinstatement lasted only 3 min, it was the same for all reinstatement groups, and the timing difference between adjacent reinstatement groups was only 2 days or, at most, 3 days.

The differential retention benefit of presenting a reinstatement later in the time window is not unique to either the operant mobile task or 3-month-olds. We have recently obtained a similar effect using a deferred imitation task with 6-month-olds. At 6 months, infants can defer imitation of a sequence of actions that were modeled for 60 s for 1 day (but not for 2 days) if they had first imitated the actions immediately after the demonstration, when the time window opened (Barr, Vieira, & Rovee-Collier, 2001). However. when infants first imitated the actions 1 day later, at the end of the time window, they deferred imitation for 10 days after the demonstration (Barr, Rovee-Collier, & Campanella, 2005). Actively imitating the actions was not why infants' retention increased tenfold; infants who merely witnessed an adult model the actions again for 30 s 1 day later also successfully deferred imitation for 10 days. Because 6-month-olds who observe the demonstration for only 30 s cannot defer imitation even 1 day later (Barr, Dowden, & Hayne, 1996), merely *retrieving the memory* at the end of the time window must have been the critical factor in protracting retention. This finding is consistent with Wagner's (1981) suggestion that the retrieval of a memory representation to an active state in nonverbal organisms is analogous to verbal rehearsal.

The present findings also have parallels in classical conditioning studies with animals. Rescorla (1974), for example, reported that when animals were exposed to a more severe shock 1 day after fear conditioning with a moderately intense shock (the US), their conditioned fear increased significantly (an "inflation effect"). Because the more traumatic postconditioning stimulus was never paired with the original conditioned stimulus (CS), he concluded that the animals' memory of the original US had been retrieved and altered by the more intense shock. Subsequently, Hendersen (1985) demonstrated that the inflation effect was greater when the delay between conditioning and animals' subsequent exposure to the more severe shock was longer—on the order of several months—than when the delay was only 1 day. Hendersen also demonstrated that when a fear conditioning procedure was followed by a shock that was weaker than the US, the animals' memory of the US was deflated, and the magnitude of their fear was lessened. Again, as with the inflation effect, the "deflation effect" was greater when the delay between original fear conditioning and the post-training exposure to the weaker shock was longer. These results, then, support the generality of the nonuniformity principle: The same manipulation had a different impact on retention depending on when it occurred during the retention interval, and the later it occurred, the greater was its impact.

It seems paradoxical that the greatest benefit to retention in the present study occurred when the reinstatement was presented at the end of the time window—a point when the training memory was presumably the weakest and just before it was forgotten altogether. Typically, greater temporal contiguity, not less, facilitates learning. The blocking phenomenon (Kamin, 1969), in which close temporal contiguity between a second CS and an expected US does not lead to the formation of an association between them, is a notable exception. Kamin concluded that the "mental effort" stimulated by a surprising or unexpected US is prerequisite for new learning and that in the blocking paradigm, the US is not surprising. Presently, however, the focus was not on the contiguity between successive events (e.g., a CS and US) within a single trial or even across trials within a single session (Balsam, Drew, & Yang, 2002; Gallistel & Gibbon, 2000; Wagner, 1976, 1981; Whitlow, 1976) but on the temporal relationship between the processing of an event that had already been encoded, stored, and retrieved and the event that retrieved it.

Bjork (Bjork, 1975; Landauer & Bjork, 1978) argued that greater retrieval difficulty, defined as the time since the last retrieval, enhances retention more. He originally drew evidence for this argument from studies of the spacing effect with college students; however, the current study differs from those studies in several ways. First, infants presently learned the operant task *before* the repetition. In typical experiments on the spacing effect, repetitions are an integral part of the study phase, and retention is not measured until adults are exposed to the repetitions (Bentin & Moscovitch, 1988; Toppino, 1991, 1993; Toppino, Kasserman, & Mracek, 1991; Wilson, 1976).

Second, the repetition in the present study was an abbreviated version of the original event rather than a complete replica of it. In fact, a reinstatement by itself generates neither new learning nor retention on the part of subjects who were not previously trained (Campbell & Jaynes, 1966; Galluccio, 2005; Galluccio & Rovee-Collier, 1999; Hartshorn, 2003; Spear & Parsons, 1976). Third, the interval between training and reinstatement was presently measured in days, whereas the interval that has generated the most robust data in studies of the spacing effect with adults is measured in seconds (i.e., approximately 15 s; for review, see Hintzman, 1974).

Finally, the abbreviated repetition in the present study spanned infants' entire forgetting function, but a comparable manipulation is impractical to use with adults, either human or animal, because they initially remember events for so long (Crowder, 1976; Gleitman, 1971). Because the width of the time window for a given event tracks its forgetting function (Rovee-Collier, 1995), a reinstatement treatment would be expected to extend retention after a very long delay in studies with adults, but the nonuniform benefit of administering reinstatement at different points within the time window, if it could even be specified, might be less dramatic for subjects who remember for so long in the first place.

In learning and memory research with animals, reinstatement has been used both as a reminder procedure to prolong retention (Campbell & Jaynes, 1966; Greenfield & Riccio, 1972; Riccio & Haroutunian, 1979) and as a tool for examining, for example, the integrity of the original CS–US association after extinction (Bouton, 1984, 1993, 1994; Bouton & Nelson, 1998; Rescorla & Heth, 1975). The present study documents the relevance of the time window construct–and particularly, the nonuniformity principle—for studies in which a reinstatement is presented during the retention interval. The surprising magnitude of the present effects, along with their documented generality across age, species, and task, strongly suggests that the timing of reinstatement in the retention interval, and probably the timing of other manipulations that entail memory retrieval as well, differentially affects the outcomes of studies on learning and memory.

References

Adler, S. A., Wilk, A., & Rovee-Collier, C. (2000). Reinstatement vs. reactivation effects on active memory. *Journal of Experimental Child Psychology, 75*, 93–115.

Balsam, P. D., Drew, M. R., & Yang, C. (2002). Timing at the start of associative learning. *Learning and Motivation, 33*, 141–155.

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

Barr, R., Vieira, A., & Rovee-Collier, C. (2001). Mediated imitation in 6-month-olds: Remembering by association. *Journal of Experimental Child Psychology, 79*, 229–252.

Barr, R., Rovee-Collier, C., & Campanella, J. (2005). Retrieval facilitates retrieval: Protracting deferred imitation by 6-month-olds. *Infancy*.

Bentin, S., & Moscovitch, M. (1988). The time course of repetition effects for words and unfamiliar faces. *Journal of Experimental Psychology: General, 117*, 148–160.

Bjork, R. A. (1975). Retrieval as a memory modifier: An interpretation of negative recency and related phenomena. In R. L. Solso (Ed.), *Information processing and cognition: The Loyola symposium* (pp. 123–144). Hillsdale, NJ: Erlbaum.

Bouton, M. E. (1984). Differential control by context in the inflation and reinstatement paradigms. *Journal of Experimental Psychology: Animal Behavior Processes, 10*, 56–74.

Bouton, M. E. (1993). Context, time, and memory retrieval in the interference paradigms of Pavlovian learning. *Psychological Bulletin, 114*, 80–99.

Bouton, M. E. (1994). Conditioning, remembering, and forgetting. *Journal of Experimental Psychology: Animal Behavior Processes, 3*, 219–231.

Bouton, M. E., & Nelson, J. B. (1998). The role of context in classical conditioning: Some implication for behavior therapy. In W. O"Donohue (Ed.), *Learning and behavior therapy* (pp. 59–84). Boston: Allyn & Bacon.

Bryan, R. G. (1980). *Retention of odor-shock conditioning in neonatal rats: Effects of distribution of practice*. Unpublished doctoral dissertation, Rutgers University, New Brunswick, NJ.

Butler, J., & Rovee-Collier, C. (1989). Contextual gating of memory retrieval. *Developmental Psychobiology, 22*, 533–552.

Campbell, B. A., & Jaynes, J. (1966). Reinstatement. *Psychological Review, 73*, 478–480.

Campbell, B. A., & Jaynes, J. (1969). Effect of duration of reinstatement on retention of a visual discrimination learned in infancy. *Developmental Psychology, 1*, 71–74.

Campbell, B. A., & Randall, P. K. (1976). The effect of reinstatement stimulus conditions on the maintenance of long-term memory. *Developmental Psychobiology, 9*, 325–333.

Crowder, R. G. (1976). *Principles of learning and memory*. Hillsdale, NJ: Erlbaum.

Gallistel, C. R., & Gibbon, J. G. (2000). Time, rate, and conditioning. *Psychological Review, 107*, 289–344.

Galluccio, L. (2005). Updating reactivated memories in infancy. I. Passive- and active-exposure effects. *Developmental Psychobiology*.

Galluccio, L., & Rovee-Collier, C. (1999). Reinstatement effects on retention at 3 months of age. *Learning and Motivation, 30*, 296–316.

Gleitman, H. (1971). Forgetting of long-term memories in animals. In W. K. Honig & P. H. R. James (Eds.), *Animal memory* (pp. 1–44). New York: Academic Press.

Greenfield, H., & Riccio, D. C. (1972). Conditioned reinstatement in rats: Effects of exposure distribution and type of cue. *Psychological Reports, 31*, 79–83.

Hartshorn, K. (2003). Reinstatement maintains a memory in human infants for 1–1/2 years. *Developmental Psychobiology, 42*, 269–282.

Hartshorn, K., & Rovee-Collier, C. (2003). Does infant memory expression reflect age at encoding or age at retrieval?. *Developmental Psychobiology, 42*, 283–291.

Hartshorn, K., Wilk, A. E., Muller, K. L., & Rovee-Collier, C. (1998). An expanding training series protracts retention for 3-month-old infants. *Developmental Psychobiology, 33*, 271–282.

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

Hendersen, R. (1985). Fearful memories: The motivational significance of forgetting. In F. R. Brush & J. B. Overmier (Eds.), *Affect, conditioning and cognition: Essays in the determinants of behavior* (pp. 43–53). Hillsdale, NJ: Erlbaum.

Hintzman, D. L. (1974). Theoretical implications of the spacing effect. In R. L. Solso (Ed.), *Theories in cognitive psychology: The Loyola symposium* (pp. 77–99). Hillsdale, NJ: Erlbaum.

Hitchcock, D. F. A., & Rovee-Collier, C. (1996). The effect of repeated reactivations on memory specificity in infancy. *Journal of Experimental Child Psychology, 62*, 378–400.

Kamin, L. J. (1969). Predictability, surprise, attention, and conditioning. In B. A. Campbell & R. M. Church (Eds.), *Punishment and aversive behavior* (pp. 279–296). New York: Appleton-Century-Crofts.

Landauer, T. K., & Bjork, R. A. (1978). Optimum rehearsal patterns and name learning. In M. M. Gruneberg, P. E. Morris, & R. N. Sykes (Eds.), *Practical aspects of memory* (pp. 625–632). London: Academic Press.

Leaton, R. N. (1976). Long-term retention of the habituation of lick suppression and startle response produced by a single auditory stimulus. *Journal of Experimental Psychology: Animal Behavior Processes, 2*, 248–259.

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

Rescorla, R. A. (1974). Effect of inflation of the unconditioned stimulus value following conditioning. *Journal of Comparative and Physiological Psychology, 86*, 101–106.

Rescorla, R. A., & Heth, C. D. (1975). Reinstatement of fear in an extinguished stimulus. *Journal of Experimental Psychology: Animal Behavior Processes, 1*, 88–96.

Riccio, D. C., & Haroutunian, V. (1979). Some approaches to the alleviation of ontogenetic memory deficits. In N. E. Spear & B. A. Campbell (Eds.), *Ontogeny of learning and memory* (pp. 289–309). Hillsdale, NJ: Erlbaum.

Rovee, C. K., & Rovee, D. T. (1969). Conjugate reinforcement of infant exploratory behavior. *Journal of Experimental Child Psychology, 8*, 33–39.

Rovee-Collier, C. (1995). Time windows in cognitive development. *Developmental Psychology, 31*, 147–169.

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

Rovee-Collier, C., Evancio, S., & Earley, L. A. (1995). The time window hypothesis: Spacing effects. *Infant Behavior and Development, 18*, 69–78.

Rovee-Collier, C., Hartshorn, K., & DiRubbo, M. (1999). Long-term maintenance of infant memory. *Developmental Psychobiology, 35*, 91–102.

Scott, J. P. (1958). Critical periods in the development of social behavior in puppies. *Psychosomatic Medicine, 20*, 42–54.

Scott, J. P. (1962). Critical periods in behavioral development. *Science, 138*, 949–958.

Scott, J. P., & Marston, M. V. (1950). Critical periods affecting the development of normal and maladjustive social behavior in puppies. *Journal of Genetic Psychology, 77*, 25–60.

Shaughnessy, J. J. (1977). Long-term retention and the spacing effect in free-recall and frequency judgments. *American Journal of Psychology, 90*, 587–598.

Spalding, D. (1873). Instinct, with original observations on young animals. *MacMillan's Magazine, 27*, 282–293.

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

Toppino, T. C. (1991). The spacing effect in young children's free recall: Support for automatic-process explanations. *Memory & Cognition, 19*, 159–167.

Toppino, T. C. (1993). The spacing effect in preschool children's free recall of pictures and words. *Bulletin of the Psychonomic Society, 31*, 27–30.

Toppino, T. C., Kasserman, J. E., & Mracek, W. A. (1991). The effect of spacing repetitions on the recognition of memory of young children and adults. *Journal of Experimental Child Psychology, 51*, 123–138.

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

Underwood, B. J., Kapelak, S. M., & Malmi, R. A. (1976). The spacing effect: Additions to the theoretical and empirical puzzles. *Memory & Cognition, 4*, 391–400.

Vander Linde, E., Morrongiello, B. A., & Rovee-Collier, C. (1985). Determinants of retention in 8-week-old infants. *Developmental Psychology, 21*, 601–613.

Wagner, A. R. (1976). Priming in STM: An information-processing mechanism for self-generated or retrieval-generated depression in performance. In T. J. Tighe & R. N. Leaton (Eds.), *Habituation: Perspectives from child development, animal behavior, and neurophysiology* (pp. 95–128). Hillsdale, NJ: Erlbaum.

Wagner, A. R., Jr. (1981). SOP: A model of automatic memory processing in animal behavior. In N. E. Spear & R. R. Miller (Eds.), *Information processing in animals: Memory mechanisms* (pp. 5–47). Hillsdale, NJ: Erlbaum.

Medin, D. L., Jr. (1976). The dynamics of episodic processing in Pavlovian conditioning. In W. A. Roberts & R. T. Davis (Eds.), *Processes of animal memory* (pp. 203–227). Hillsdale, NJ: Erlbaum.

Williams, E., & Scott, J. P. (1953). The development of social behavior patterns in the mouse, in relation to natural periods. *Behavior, 6*, 35–64.

Wilson, W. P. (1976). Developmental changes in the lag effect: An encoding hypothesis for repeated word recall. *Journal of Experimental Child Psychology, 22*, 113–122.