The "Memory System" of Prelinguistic Infants[a]

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With the exception of some isolated studies in the first half of this century (e.g., Jones, 1930), the study of memory in infants, both animal and human, is a relatively recent pursuit. Although psychologists of many persuasions, ranging from Freud to Watson, attached considerable theoretical importance to the long-term effects of infants' early experiences, few attempted to document whether or not these experiences actually influenced behavior later in development. Indeed, evidence from three different lines of research on infantile memory suggested that they did not. First, research with children and adults consistently indicated that their earliest memories dated from the ages of 2–5 years (Campbell & Coulter, 1976; Wetzler & Sweeney, 1986). Second, conditioning studies with infants consistently yielded no evidence of learning when the interval between the CS and US (classical conditioning) or between the response and the reinforcement (operant conditioning) exceeded 2–3 sec (Lipsitt, this volume; Little, Lipsitt & Rovee-Collier, 1984; Millar, this volume; Millar & Watson, 1979), or when the interval between successive response–reinforcement repetitions exceeded 5–7 sec (Watson, 1972). Because two events cannot be associated unless the memory of the first event persists until the second event has occurred (Bolles, 1976; Revusky, 1971; Watson, 1984), these data suggested that the memorial abilities of infants were limited at best. Third, studies of novelty detection following habituation to a standard stimulus yielded no evidence of retention after delays exceeding 5–15 sec by infants younger than 1 year (Sherman, 1985; Stinson, 1971; Werner & Perlmutter, 1979). Taken together, these findings led to the general conclusion that the prelinguistic infant was incapable of storing memories over the long term (Kagan, 1984).

In recent years, evidence has accumulated that prelinguistic infants can retain information about the events in which they participated for periods of weeks and even months (see Rovee-Collier & Hayne, 1987, for review; Myers, Clifton & Clarkson, 1987; Perris, Myers & Clifton, in press). The disparity between these and earlier findings has been attributed by many researchers to the functioning of different types of memory systems. The terms used to capture the distinction between these 2 types of memory systems have included early- and late-maturing (Bachvalier & Mishkin, 1984; Schacter & Moscovitch, 1984), implicit and explicit (Schacter, 1987), procedural and declarative (Squire, 1986, 1987), semantic and

episodic (Tulving, 1972, 1983). Alternatively, some investigators have attributed functional dissociations in measures of retention to differences in the type of processing required during encoding and testing. These include data-driven and conceptually-driven processes (Jacoby, 1983; Roediger, this volume; Roediger & Blaxton, 1987) and unconscious and conscious processes (Mandler, 1989; Tulving, 1985). Convergent support for the existence of multiple memory systems has been drawn from functional dissociations in the memory performance of amnesic adult patients (for reviews, see Squire, 1987; Schacter, 1987), lesioned rats (Olton, 1983), and lesioned monkeys (Bachvalier, this volume; Bachvalier & Mishkin, 1984; Zola-Morgan & Squire, this volume).

In most of these systems, the different types of memory have been characterized in terms of whether retention is conscious or unconscious (intentional or automatic), the nature of what is retained (e.g., time and place information, skills), or both. Distinctions based on concepts such as "conscious recollection" or "a sense of familiarity or pastness" (i.e., "the feeling of having experienced something before"), however, are irrelevant in memory research with prelinguistic infants and animals, subject neither to direct verification nor rejection. Whether a 6- or 8-month-old human infant consciously recollects having experienced something before (e.g., Ashmead & Perlmutter, 1980; Mandler, 1984, this volume), for example, is a matter of speculation only, as is the assumption that familiarity-based recognition underlies the test performance of animals and prelinguistic infants on a visual paired comparison task. The procedures that can be used to assess retention in prelinguistic infants and animals are also relatively limited (3-month-olds, for example, cannot be tested in an object search task). In effect, prelinguistic infants have been saddled with labels for one or another particular memory system *by default.*

The only direct way to ask a nonverbal organism whether it remembers a prior event is to incorporate the instructions to remember into the structure of the task. This is usually accomplished by training the subject to perform a distinctive response in a particular setting and then observing whether the subject performs the response when returned to that setting after a delay. This procedure is analogous to the traditional *cued-recall paradigm* used with adults and children (Spear, 1978). Thus, the experimenter asks whether the subject remembers the significance of a classically conditioned stimulus (CS) by observing whether its presentation either *elicits* the conditioned reflex (CR) (Jones, 1930) or *modifies* an ongoing instrumental response (Estes & Skinner, 1941; Campbell & Campbell, 1962; Rudy & Cheatle, 1977). The experimenter asks whether the subject remembers the contingency between either a stimulus (e.g., a conditional discriminative stimulus) or a response and the reinforcement in an instrumental task by observing whether the subject continues to *emit* the response in the presence of the original information. In both instances, a response failure may reflect a memory deficit, a motivational change, a perceptual change, or a change in the response hierarchy.

Bahrick (1987) has differentiated between functional and cognitive approaches to understanding memory:

> By functional approaches I refer to theories that attempt to establish parsimonious relations between manipulated variables and memory performance without necessarily attempting to reach conclusions about internal processing. In contrast, cognitive approaches focus on the nature of the mental processing, the stages, the strategies, and the

nature of the mental representation. . . . The dominance of the cognitive *Zeitgeist* has led most investigators to be concerned about internal processing, but there exists much variation in emphasis, and it is possible to distinguish between investigations that directly address cognitive questions, and investigations that have primarily functional goals and treat cognitive questions as secondary (pp. 389–390).

Since 1976, we have pursued a *functional analysis* of infant memory. We have found that infants as young as 2–3 months of age form memories of their past experiences and that these memories are relatively enduring. In addition, we have found evidence for the following conclusions:

1. Infants' memories consist of collections or clusters of attributes that represent different aspects of an event. These attributes are not all equivalent and are forgotten and retrieved at different rates. As a result, the content of an active memory differs at different points in time.
2. Very young infants' memories are highly specific with regard to both the nominal stimulus per se and the context or environmental surround in which a training episode occurs, and they become even more specific with age.
3. The rate of memory processing increases with age.
4. The memory of an event can be modified by subsequent events that occur while the memory is active. There is a time window within which this modulation can occur.
5. Repeated retrieval of a memory within a given time window prolongs retention and alters the relative strengths (accessibility) of the components of the memory. Failure to retrieve a memory within the time window may result in a permanent retention deficit.

In addition to having cognitive implications for the "memory system" of prelinguistic infants (for review, see Greco, Hayne & Rovee-Collier, 1990; Rovee-Collier & Shyi, in press), these research findings also have neuropsychological parallels (see Squire, 1987). In this chapter, I review some of the evidence that led to our first two conclusions.

Throughout the chapter, the terms "remember" and "forget" refer to memory test performance that either does or does not reflect the effect of a prior experience, respectively, devoid of any implications for conscious recollection.

TRAINING AND TESTING PROCEDURES

Our early research focused on retention of the conditioned response per se. More recently, however, our interest has turned to the information that infants encode during a training episode. Because infants do not have a verbal response to tell us what they remember about an event, we have to provide them with a motoric one. To this end, we teach infants an operant response, a footkick, that is reinforced by the movement of a particular crib mobile, the visual characteristics of which comprise the cue. Infants then "tell" us whether or not the visual information that is displayed on a test mobile 24 hours later is represented in the training memory in terms of whether or not they produce the learned response. If they do, then the visual information is represented in the memory; if they do not respond, then we infer that

it was not encoded. In effect, the test mobile is used as a probe to determine the memory's contents. In a similar fashion, we determine the rate at which the different aspects of the training event, which were initially encoded, are subsequently forgotten by manipulating the information on the test mobile and gradually increasing the interval between training and testing.

In addition to the visual information that is displayed directly on the mobile components (see FIG. 1a), in many experiments we vary the characteristics of the context or setting in which learning occurs, such as the crib or playpen liner (see FIG. 1b), a particular place in the room, or a particular room in the infant's house.

All studies are conducted in the infants' homes and usually involve two training sessions. For 2- and 3-month-olds, each session consists of a 9-minute reinforcement phase (acquisition) that is preceded and followed by a 3-minute nonreinforcement phase. During reinforcement phases, the mobile is linked to the infant's ankle by a ribbon (see FIGS. 1a-b), allowing the infant to control both the frequency and the intensity of mobile movement by the frequency and vigor of kicking ("conjugate reinforcement"). We emphasize that the *movement* of the mobile, and not merely its visual presence, is the reinforcement. Infants trained in this procedure learn rapidly, usually doubling or tripling their baseline level of responding within a few minutes. This increase in responding is due solely to the introduction of the contingency and not to behavioral arousal (Rovee-Collier & Fagen, 1981). During nonreinforcement phases, the ankle is attached to an "empty" mobile stand so that the infant can see the mobile but cannot move it. The initial nonreinforcement period of session 1 is the *baseline phase* during which the infant's rate of responding before training (the operant level) is measured.

For 6-month-olds, the experimental arrangement is the same except that infants are tested in a sling-seat, and sessions are shorter (see Hill, Borovsky & Rovee-Collier, 1988).

Retention Measures

Following the conclusion of training, each infant's retention is measured twice, during nonreinforcement periods, at the beginning and at the end of the retention interval (see FIG. 2). The nonreinforcement period at the end of training in session 2, after no delay, is the *immediate retention test phase*. During this phase, forgetting is expected to be negligible. We measure long-term retention during the nonreinforcement period at the end of the specified retention interval, usually 1–42 days later (the *long-term retention test phase*). Because both measures of retention are based solely on performance during nonreinforcement phases, when the mobile is *not* connected to the infant's ankle via the ribbon, retention measures do not reflect new learning or savings. Finally, we introduce a reacquisition phase after the long-term retention test to insure that poor test performance was not a result of poor motivation or illness on that particular test day.

Retention is analyzed in terms of two relative response measures based on individual performance (for reviews, see Rovee-Collier & Fagen, 1981, and Rovee-Collier & Hayne, 1987). The *baseline ratio* (each infant's long-term retention test rate divided by his/her baseline rate) reveals whether or not infants remember. If the mean baseline ratio significantly *exceeds* 1.00, then infants have displayed retention.

FIGURE 1. The experimental arrangement for 3-month-olds (**A**) and 6-month-olds (**B**).

FIGURE 2. The standard training and testing paradigm used in our studies of infant memory. Retention is measured during nonreinforcement periods at the conclusion of training (the immediate retention test) and again after a specified delay (the long-term retention test).

If their mean baseline ratio is not significantly greater than 1.00, then infants are responding at the same rate during the long-term test as they did before they were initially trained, and forgetting is said to be "complete." The *retention ratio* (each infant's long-term retention test rate divided by his/her immediate retention test rate) reveals *the extent* to which infants remember. A mean retention ratio equal to or greater than 1.00 indicates that infants continue to respond during the long-term retention test at the same rate as they had responded immediately after training (i.e., they exhibit "perfect" retention); lower retention ratios indicate poorer retention. Even if infants exhibit a significant impairment in retention between immediate and long-term testing (i.e., their mean retention ratio is significantly less than 1.00), their forgetting is *not* complete as long as they kick more often during the long-term test than they did before training (i.e., their mean baseline ratio is significantly above 1.00).

All data points are contributed by independent groups of infants tested only once. We rarely ask whether our test groups differ from one another. Groups may not have differed, for example, yet some or all may have remembered, or some or all may have forgotten. Instead, we seek a yes/no answer to the question of whether any given test group exhibits retention. To obtain this answer, we use *t*-tests to compare each group's mean baseline and retention ratio with theoretical baseline and retention ratios of 1.00 (no retention or perfect retention, respectively).

Simple Forgetting Paradigm

To study retention of a newly acquired memory, we simply assess retention at the end of a specified interval, as indicated in FIGURE 2. The retrieval cue or memory probe is presented at the time of the long-term test. At 3 months, infants' retention ratios approximate 1.00 for several days and then gradually decline. Forgetting is complete 6–8 days after training (Hayne, 1988; Sullivan, Rovee-Collier & Tynes, 1979). The forgetting function (see FIG. 3) is steeper at 2 months (Greco, Rovee-Collier, Hayne, Griesler & Earley, 1986) and shallower at 6 (Hill *et al.*, 1988). Increasing either the duration of a single session or the number of sessions significantly prolongs retention (Ohr, Fagen, Rovee-Collier, Hayne & Vander Linde, 1989; Vander Linde, Morrongiello & Rovee-Collier, 1985).

Reactivation Paradigm

To study retrieval of an available but inaccessible memory, we allow sufficient time to elapse after training that the newly acquired memory will be forgotten. We then expose the infant to a brief reminder (a memory prime) that corresponds to some attribute that is presumably represented in the memory of the original training episode. If it is, and if the reminder is sufficient, then the memory will be primed or reactivated, becoming accessible once more. Retention is assessed as before, at the beginning and the end of the retention interval. Although different delays may be interpolated between the reminder presentation and the long-term retention test, we usually test infants 24 hours later (see FIG. 4). Spear (1973) defined a reminder as a

retrieval cue that is presented *in advance of* the long-term retention test and a reactivation treatment as a prior-cuing procedure.

Our reactivation treatment is brief (3 minutes at 3 months, 2 minutes at 6 months) and consists of exposing infants to some component of the original training event that they were likely to have encoded as a part of their memory of that event. In the past, we have used either exposure to the mobile being moved noncontingently by the experimenter at the same rate that the same infant had moved it during each of the final 3 minutes of training (Rovee-Collier, Sullivan, Enright, Lucas & Fagen, 1980), the distinctive crib bumper that lined the sides of the crib during training (Rovee-Collier, Griesler & Earley, 1985), or both (Butler & Rovee-Collier, 1989; Hill *et al.*, 1988).

At 3 months, infants exhibit near-perfect retention during the long-term retention test 24 hours after a reminder whether it is presented 2, 3, or 4 weeks after the
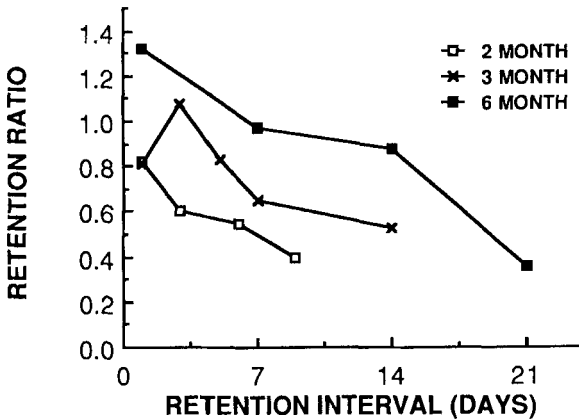

FIGURE 3. Retention ratios of independent groups of 2-, 3-, and 6-month-olds who were trained for 2 sessions and tested after retention intervals of 1 to 21 days in the simple forgetting paradigm. At 2 months, forgetting was complete 1–3 days after training; at 3 and 6 months, forgetting was complete after 7 and 14 days, respectively (i.e., mean baseline ratio not significantly > 1.00).

conclusion of training. In contrast, infants who have been trained but receive no reminder (no-reminder control group), and infants who receive the "reminder" without prior training (reactivation control group) exhibit little or no responding during the long-term test (Campbell & Jaynes, 1966; Hayne, Rovee-Collier & Perris, 1987; Sullivan, 1982).

CONCLUSION 1: FORGETTING AND RETRIEVAL
OF MEMORY ATTRIBUTES

Recall that 3-month-old infants exhibit perfect retention for 3–4 days after training when tested with their training mobile as the retrieval cue (see FIG. 3). If
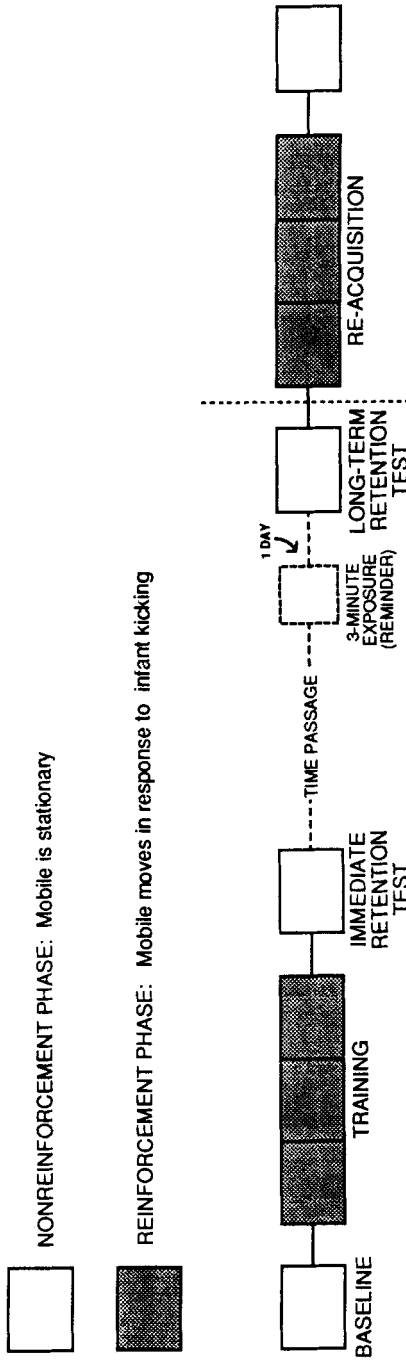
NONREINFORCEMENT PHASE: Mobile is stationary

REINFORCEMENT PHASE: Mobile moves in response to infant kicking

BASELINE TRAINING IMMEDIATE RETENTION TEST

TIME PASSAGE

1 DAY

3-MINUTE EXPOSURE (REMINDER)

LONG-TERM RETENTION TEST

RE-ACQUISITION

FIGURE 4. Timing of a reactivation treatment relative to training and testing. The reminder (a retrieval cue) is inserted into the standard simple-forgetting paradigm (see FIG. 2) after forgetting is complete and at some point (usually 1 day) before the long-term retention test. During the reactivation treatment (□), the mobile is moved at the same rate as the infant had moved it during the last 3 sec of the previous session—but since the mobile is not connected to the infant's leg, its movements here are not conjugately linked to the infant's kicks.

they are tested with a novel mobile just 1 day after training, however, they exhibit none. As the retention interval is progressively increased, infants increasingly generalize to a novel test mobile, and after a delay of 3 days, their response to it is indistinguishable from their response to the original training mobile (see FIG. 5). We conclude that the gradual improvement in their test performance to the novel mobile results from infants' gradual forgetting of the specific details of the training mobile; after a 3-day delay, their test responding is based on the general features that the novel mobile shares with the training mobile and that are still well-remembered. Thus, after delays of 3 days and longer, the 3-month-olds are responding to "a mobile" instead of to "a particular mobile" (Rovee-Collier & Sullivan, 1980). Adults similarly forget specific details more rapidly than general information about an event (Estes, 1973; Hasher & Griffin, 1978).

At 6 months, infants do not as readily forget the details of their training mobile: They discriminate a novel mobile from their training mobile for 2 weeks—the longest interval after which they remember the task. Despite their excellent retention of the details of the training mobile, if they are tested with it in a novel context (e.g., in the presence of a different playpen liner) just 1 day after training, they appear not to recognize their original mobile and exhibit no retention whatsoever (Borovsky &
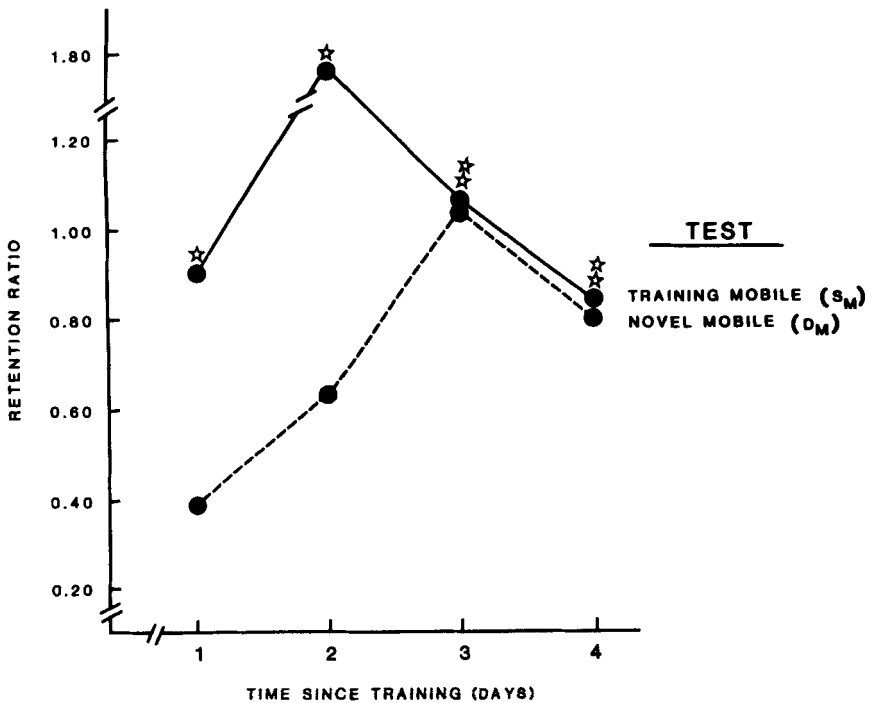

FIGURE 5. Retention ratios of independent groups of 3-month-olds tested with either their training mobile (Sm) or a novel mobile (Dm) after retention intervals of 1, 2, 3, or 4 days. Stars indicate that retention test performance is significantly above baseline (i.e., mean baseline ratio significantly > 1.00).
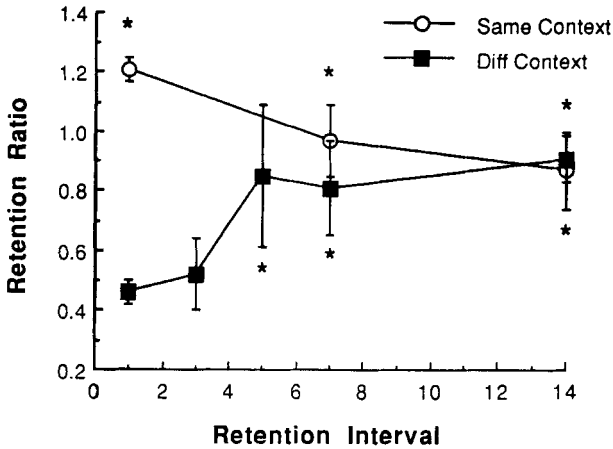
FIGURE 6. Retention ratios of independent groups of 6-month-olds tested with the training mobile in the presence of a different playpen liner (DIFF) after retention intervals of 1, 3, 5, 7, or 14 days or in the presence of the original liner (SAME) after intervals of 1, 7, or 14 days. Stars indicate that retention test performance is significantly above baseline (i.e., mean baseline ratio significantly > 1.00).

Rovee-Collier, 1990; Rovee-Collier & Shyi, 1990; Shyi, 1990). Thus, a novel test context impairs retrieval of the otherwise highly accessible training memory. As the retention interval is progressively increased, however, 6-month-olds increasingly respond to the training mobile in a novel test context, and 5 days later, their retention is excellent whether they are tested in the original context or in a novel one (see FIG. 6). Because a change in the specific details of the training context impairs memory retrieval progressively less over time, we conclude, as before, that memory attributes representing specific details—this time, details of the training context—are forgotten more rapidly than those representing general features (Borovsky & Rovee-Collier, 1990).

Although infants remember general information longer than specific details, once the attributes representing general information about the training episode have also been forgotten, the memory will not be recovered via the presentation of a reminder if either the mobile or the context is novel at the time of the reactivation treatment (Borovsky & Rovee-Collier, 1990; Butler & Rovee-Collier, 1989; Hayne *et al.*, 1987; Hill *et al.*, 1988; Rovee-Collier & Hayne, 1987). This result is paradoxical in that generalized attributes were the last to cue retrieval before forgetting was complete (Rovee-Collier & Sullivan, 1980). We think it likely, however, that the reactivation procedure and the simple forgetting test tap different, albeit not completely independent, types of memory processes. Memory reactivation appears to involve an automatic *perceptual identification* process, akin to priming in adults, that is initiated by detection of a retrieval cue that is represented in the original memory; a simple forgetting test, in contrast, requires not only perceptual identification-based retrieval but also *recognition* of the activated memory contents. This analysis is based on the suggestion by Musen and Treisman (1990) that perceptual

priming effects after different delays are all-or-none, but memory recognition decays with time.

In addition to being forgotten at different rates, different types of memory attributes are retrieved at different rates as well. This is most clearly observed during the recovery of an inactive memory. FIGURE 7 shows the time course of the recovery of a forgotten memory at 3 months following a reactivation treatment. Infants tested 1 day after a reminder respond equivalently to a novel test mobile and the original training mobile, as they had just before the newly acquired memory had been forgotten. From this result, we conclude that the first attributes that are recovered
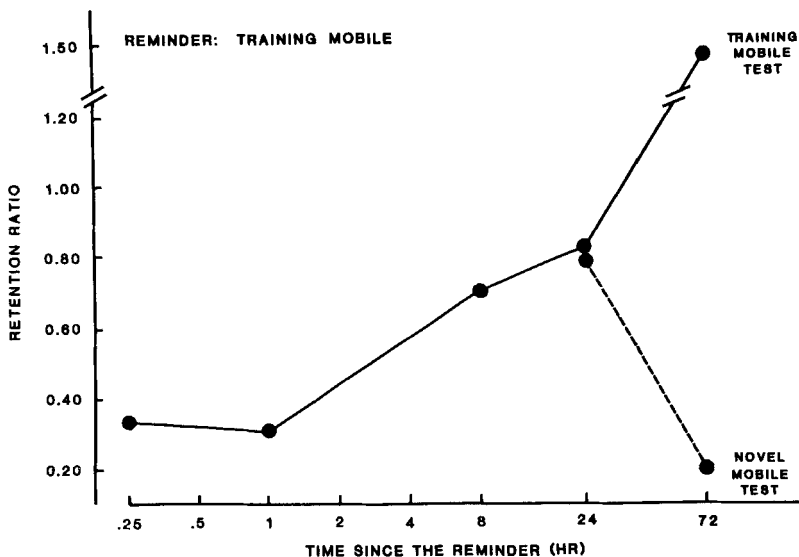

FIGURE 7. Retention ratios of independent groups of 3-month-olds who received a reactivation treatment with their training mobile 13 days following the conclusion of training and were tested with the same mobile after delays ranging from 0.25–72 hours (*solid line*). Performance after the 2 shortest delays is not significantly above baseline. The *dashed line* depicts retention of independent groups who were trained and reminded with their original mobile and tested with a novel mobile 24 or 72 hours later. Infants generalized to a novel test mobile 24 hours after the reminder but discriminated a novel test mobile 72 hours afterwards (i.e., mean baseline ratio not significantly > 1.00).

are those representing the general features of the mobile. Three days after the reminder, however, attributes representing the specific details of the training mobile have been recovered: At this point, infants respond to the original mobile and discriminate a novel one (Rovee-Collier & Hayne, 1987).

More generally, these data suggest that memory attributes that take longer to be forgotten are reactivated first by a reminder (i.e., they remain more accessible), despite the fact that only a specific instance of the original memory representation is effective in reactivating them—a "last-out, first-in" principle. These data also reveal that the contents of both newly acquired and reactivated memories differ at different

points in time. As a result, the point in time when retention is tested will affect conclusions regarding what infants of different ages are capable of encoding and remembering.

Finally, we emphasize that memory attributes appear to be organized in collections or clusters (Estes, 1973). Timmons (1990) trained 6-month-olds either to move a mobile or activate a music box by either kicking or arm-pulling (all possible combinations) in the same, highly distinctive context. Three days after training the first simple cue-response pair (task 1), infants were trained on the second cue–response pair (task 2). Three days after the second task, infants were tested with one of the two cues. Control groups were tested 3 days after learning just one cue–response pair or the other. Timmons found that infants produced the cue–appropriate response, whatever it was, whether it was the first paired associate infants had learned or the second one. There was no recency effect. Control groups also responded with the cue-appropriate response but did not generalize this response to the previously unseen cue.

In a second study, Timmons allowed identically trained groups to forget both tasks for 3 weeks and then presented one of the two cues as a reminder. This time, *all* infants were tested with the mobile 1 day later. As expected, infants reminded with the mobile performed the mobile-appropriate response (either arm-pulling or kicking) during the retention test with the mobile, just as infants had during the simple forgetting test 3 days after the conclusion of training. However, infants reminded with the music box *also* performed the mobile-appropriate response during the long-term test with the mobile.

Because the infants in the latter group were not reminded with the mobile, and the mobile memory was forgotten at the time of the reminder, we conclude that the memory attributes representing the music box were associated with those representing the mobile via the common context in which the cue–response pairs had originally been acquired. In this way, exposure to the music-box reminder in that context reactivated its corresponding memory attributes which, in turn, reactivated the memory attributes corresponding to the mobile, enabling the mobile memory to be accessed and its response to be performed when it was presented as a retrieval cue during the ensuing long-term test. This is the first demonstration of an associative network in infants.

CONCLUSION 2: THE SPECIFICITY OF INFANTS' MEMORIES FOR CUE AND CONTEXT

Cue Specificity

We reported above that a novel mobile is not an effective retrieval cue at either 3 or 6 months, whether presented 1 day following training in a simple forgetting paradigm or as a reminder after forgetting is complete (Hayne *et al.,* 1987; Hill *et al.,* 1988; Rovee-Collier & Sullivan, 1980). The degree of specificity of the memory representation of the training cue (the mobile) is illustrated by the finding that if more than just a single novel object is substituted into the original 5-object training

mobile after a 1-day retention interval, neither 2- nor 3-month-olds exhibit retention, which otherwise is perfect (Hayne *et al.,* 1986). Similarly, if more than just a single object is altered on the mobile used as a reminder at 3 months, the forgotten memory will not be reactivated (Rovee-Collier, Patterson & Hayne, 1985). These findings are consistent with the principle of encoding specificity (Tulving & Thomson, 1973): The effectiveness of a retrieval cue is determined by the extent to which the retrieval context reinstates the encoding context.

In all studies described thus far, the same mobile was used throughout training. If infants receive category training with a novel mobile in each session, however, then another novel test mobile not only will cue retrieval 1 day after training both at 3 months (Fagen, Morrongiello, Rovee-Collier & Gekoski, 1984; Hayne *et al.,* 1987) and at 6 (Shields, 1989) but also will serve as an effective reminder at both ages (Hayne *et al.,* 1987; Shields, 1989).

Contextual Specificity

Infants' memories are also highly differentiated with respect to the "extrinsic context" (Baddeley, 1982), that is, the environmental surround or physical setting where training occurs. Although the context does not directly influence or interact with the requirements of the central task, it does act as a conditional discriminative stimulus that predicts its occurrence. The finding that exposure to the context alone can reactivate a forgotten memory at 3 months (Rovee-Collier *et al.,* 1985) confirms that *contextual information is encoded as part of the memory representation of the training episode.* The highly distinctive context apparently acts to cue retrieval of the memory attributes that represent the specific details of the mobile (Butler & Rovee-Collier, 1989). At 3 months, this function can only be observed after delays of 3 days or longer. Recall that after this delay, infants trained in the relatively indistinct and familiar context of their own cribs have forgotten the specific details of the training mobile (see FIG. 5: novel-mobile group). When 3-month-olds are trained and tested in a highly distinctive context that is uniquely associated with the training episode, however, they do *not* generalize responding to a novel test mobile after retention intervals of 3 days or longer. Infants can accomplish this discrimination only if they remember the specific details of the training mobile.

We conclude, therefore, that the unique and distinctive context serves as a retrieval cue for those otherwise forgotten details. Likewise, if 3-month-olds are trained, reminded, and tested in a highly distinctive context, then they also do *not* generalize to a novel mobile 24 hours after a reminder (Rovee-Collier & Hayne, 1987). Recall that infants trained and tested in the familiar context of their home cribs, without a distinctive crib liner present during the experimental sessions only, do generalize to a novel test mobile 24 hours after a reminder (see, for example, FIG. 7).

Altering the test context produces an even more dramatic effect on memory retrieval at 6 months than at 3 (Borovsky & Rovee-Collier, 1990; Hill *et al.,* 1988; Rovee-Collier & Shyi, in press; Shyi, 1990). Even though 6-month-olds exhibit near-perfect retention after 2 weeks (see FIG. 3) and discriminate a novel mobile from the training mobile after that same delay, if tested in an altered context, they stare "blankly" at the training mobile without responding, appearing not to recog-

nize it "out of context," after a retention interval of only 1 day! Also, at 6 months, once the training episode has been forgotten, it cannot be reactivated by an otherwise effective reminder (e.g., the training mobile) that is presented in a novel context (Borovsky & Rovee-Collier, 1990; Shields, 1989).

Despite the debilitating effect of a novel context on memory retrieval, if 6-month-olds are initially trained in a novel context for each of 2 sessions and tested 1 day later with the original mobile in another novel context, then their retention is excellent. Even after variable-contextual training, however, the training mobile does not reactivate the forgotten training memory if it is presented as a reminder in another novel context 3 weeks later (Amabile, 1990). Thus, despite the plasticity of memories for contextual information over the short term, once the memory has been forgotten, its reactivation requires a context that was represented in the original training memory.

Recall that after progressively longer retention intervals, 6-month-olds increasingly generalized to a novel playpen liner (see FIG. 6) in the same fashion that 3-month-olds, trained and tested without a unique and distinctive liner, increasingly generalized to a novel mobile (see FIG. 5). As infants age and their visual field expands, they appear to incorporate increasingly more local contextual information into the focal task (Rovee-Collier, Earley & Stafford, 1989). This account suggests that, with age, memory retrieval is increasingly likely to be constrained by spatially more remote contextual information, such as distant landmarks (Acredolo, this volume; Acredolo & Evans, 1980; Rudy, Stadler-Morris & Albert, 1987).

Recently, we asked whether all aspects of the context are equivalent in constraining retrieval. To answer this, we tested 6-month-olds 1 day after training with the original mobile in the presence of a liner on which either a single dimension of the information on the liner (the shape of the figures, the color of the figures, or the color of the background) was altered, or the chromatic relation between the figure and background was reversed. Infants generalized responding when the shape-only of the figures was changed from a square to a triangle, but not when it was changed from a square to a circle or a stripe. They also generalized when the color only of the figure was changed, but they discriminated (i.e., did not respond) when the background color only was changed. Because of the latter finding, we attributed their discrimination of a reversal in the chromatic relation between figure and ground to the change in the background color.

When the training liner was removed altogether during the 1-day test, leaving the familiar context of the infant's own playpen and living room (or bedroom) as the test surround, infants again exhibited no retention, staring "blankly" at the mobile. Thus, the ineffectiveness of an altered test context does not stem from its novelty but from the fact that it is not represented in the original training memory. Finally, although 1-day retention was excellent when the figures (distractors) were removed from the liner altogether, forgetting was not alleviated when the original mobile was presented as a reminder in the presence of the blank liner 3 weeks later (Rovee-Collier & Shyi, in press).

These data reveal that (1) infants do not encode the context wholistically, (2) all components of the training context are not functionally equivalent in cuing retrieval (see also Hayne et al., 1987), and (3) no single "critical feature" (Treisman & Gelade, 1980) is essential for retrieval. The finding that retention was perfect when the

figures were removed from the liner altogether is consistent with the finding that its background color is sufficient to cue retrieval 24 hours after training. More contextual support is apparently needed to reactivate a memory once it becomes wholly inaccessible.

In all of the preceding studies, the context was defined in terms of a distinctively colored and patterned liner draped about the infant's crib or playpen (see FIG. 1b) for the duration of each session. As a natural analogue of the crib liner manipulation with 3-month-olds, we trained and tested 3-month-olds in their home cribs but reminded them with the training mobile in a location that was familiar but not a part of the original training episode (e.g., either where they were typically fed or in their bedrooms but not in their cribs). The reminder was not effective unless infants were exposed to it in the place where they had been trained (Rovee-Collier & Hayne, 1987).

We have also trained and tested 3-month-olds in their bedrooms in a portable crib that we draped with a highly distinctive liner. When these infants were tested 1 day later in the portable crib-plus-liner in their kitchens, memory retrieval was unaffected; retention was perfect, as it had been when their crib liners had been changed 1 day after training (Butler & Rovee-Collier, 1989) and when the distractors had been removed from the playpen liners of 6-month-olds 1 day after training (Rovee-Collier & Shyi, in press). However, when the 3-month-olds were trained and tested in the portable crib-plus-liner in their bedroom but were *reminded* in the portable crib-plus-liner in their kitchen, the reminder was not effective; the memory was not reactivated— just as a reminder had been ineffective in the presence of a different crib liner. The considerable specificity with which the retrieval context must match the encoding context at 3 months is further illustrated by the finding that when infants were trained and tested in their own liner-draped crib and were reminded in the liner-draped portable crib that we placed in exactly the same location where their own crib had stood, the reminder was ineffective. The portable crib is both *smaller* and *lower* than a regular crib, perhaps offering a different perspective of the room. For whatever reason, infants clearly "knew" that they were in a different place, and, as a result, the reminder did not work.

In summary, information about the setting or place in which training occurs is readily picked up and encoded by infants at 3 months and becomes even more important in gating retrieval at 6 months. These findings reveal that young infants learn *what happens in what place* long before they are able to locomote from one place to another or to learn the spatial relations between those places. Distinctive contextual information that is unique to the training episode appears to buffer the training memory against generalized retrieval in inappropriate settings. Not only does this forestall inappropriate behavior, but it also protects the memory from extinction or other forms of modification.

These findings and others (Boller, Rovee-Collier, Borovsky, O'Connor & Shyi, 1990; DuFault & Rovee-Collier, 1990; Hayne, 1988; for review, see Rovee-Collier & Shyi, in press) indicate that how long an event is remembered depends upon the memory contents at the time it is accessed, the context in which retrieval has occurred, and the number of times it has been retrieved. Because recent evidence indicates that different components of active memories can be selectively strengthened or weakened (Greco & Rovee-Collier, 1988) and that the contents of memories

can be modified by new information encountered during or subsequent to retrieval (Boller & Rovee-Collier, 1990; Borza & Rovee-Collier, 1989; Greco *et al.*, 1990), it is probably impossible to determine whether an original memory is permanently retained or is eventually lost.

CONCLUDING COMMENTS

Our ongoing research is an attempt to characterize the "memory system" of prelinguistic infants. In a number of respects, the findings described above and elsewhere (Rovee-Collier & Shyi, in press) provide rough behavioral parallels for neuropsychological predictions regarding memory formation and the course of early memory development (Squire, 1987, pp. 32–40). Other of our data (e.g., on context and memory modulation via passive exposure), however, are difficult to reconcile with existing neuropsychological (e.g., Nadel, Willner & Kurz, 1985; Nadel & Zola-Morgan, 1984; Schacter & Moscovitch, 1984) and cognitive (Mandler, 1984, this volume) theories of memory development. Of the many different multiple memory systems that have been proposed, most if not all invoke conscious awareness as a distinguishing characteristic—a distinction I reject, as this condition is not amenable to empirical verification in nonverbal organisms, whether animal or human.

Instead of asking "what" memory systems infants of different ages do or do not have, my research asks "what" information infants of different ages encode and "how" they subsequently access and use that information. In general, I question the utility of invoking multiple memory systems as long as a single memory system or processing mechanism can account adequately for existing data. Finally, I question the validity of attributing memory processing at different points in infant development to different memory systems, particularly given the dearth of information about the fundamental data base of infant memory and the limited number of tasks used to study it.

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DISCUSSION

H. L. ROEDIGER: Just a technical question, although it might have considerable theoretical interest. Often your retention ratios would be higher than 1. In particular, in one of the last slides you showed it was almost 2.

C. ROVEE-COLLIER (*Rutgers University, New Brunswick, NJ*): Yes.

ROEDIGER: Is that "hypermnesia," or whatever you want to call it, or is that some type of technical artifact that I couldn't pick up?

ROVEE-COLLIER: No. First of all, I should say that we take our immediate measure of retention during a nonreinforcement period, and one way you could get a high retention ratio is if the infant were extinguishing in that period and then showed spontaneous recovery the following day. We make sure this does not occur by curtailing that final nonreinforcement period at the end of training to only 3 min. Performance in that 3-minute period is equivalent to performance during the 3-min period at the end of training in acquisition, so that we don't have an underestimate of acquisition at that point. We just say that if their retention ratio is 1 or higher by the beginning of the next session, then infants may be *highly motivated* to play the game, while by the end of the previous session, they were "settling down." Typically, infants start out kicking at a very high rate in the first session and then they settle down and begin to pattern their behavior instead. You saw that they patterned their behavior in the videotape. That baby wasn't kicking the entire time—he was "fooling around" with the mobile, toying with it and watching it spin quietly before pumping it up again. What the infant does depends on whether the crocodile object, for example, spins and unwinds; watching the mobile dance and spin is sort of like watching clouds taking new shapes and forms. So, in a way, I think what you are seeing in their enhanced performance during the long-term test is a motivational difference. But, there is also another difference or factor that can lead to enhanced test performance, and that is the fact that the memory following a reminder is recovered very slowly. It comes back more slowly at 3 months than it does at 6 months (see FIG. 1). At 6 months of age, the memory peaks 4 hours after the reminder; there is no evidence of retention after a half-hour. At 3 months, there is no evidence of retention until 8 hours later, about half the infants are showing some retention then. What is going on at this peak? What this reflects is that different kinds of attributes are being retrieved at different rates. So, you can't say retention is perfect at 3 months, 24 hours after a reminder, when the retention ratio is 1.00, because at this point in the retrieval function, only attributes representing general information have been reactivated. Although you *have to* remind the infants with the original mobile, once they have been reminded successfully, they generalize to a novel mobile during a transfer test 24 hours after reminding. But 3 days later, when their retention ratios peak, infants now discriminate a novel mobile from the mobile with which they were trained, which is remarkable. This suggests to me that the memory attributes representing the specific details of the training mobile are being retrieved at a much slower rate than were its general features in the original memory. What is interesting is that infants forget specific details before they forget the gist of the general features, like adults, and these details are slower to be retrieved. We are trying to test 6-month-old infants

at the peak of recovery and see if we can see whether, in fact, this is again the case or not. So in addition to motivational differences being reflected in the retention measure, there are different attributes in the memory contents at those different points in time.

ROEDIGER: There are some very analogous human results up to this last little bit, but just in general, to the effects of a test on later retention.

L. P. ACREDOLO (*University of California, Davis, CA*): One of the obvious points of interest to Lynn [Nadel] and me has to do with context effects at 3 and 6 months of age, and what happens when you move the babies from one room to another. This might be a way to test or to get some handle on the degree to which they have a relational knowledge of that environment.

ROVEE-COLLIER: We have studied these sorts of changes with 3-month-olds, and are beginning to do it now with 6-month-olds, getting the same effects. But I don't think infants at these ages have the kinds of relational knowledge that they acquire later. I think, instead, that they learn *what* happens *where:* This is "where I eat;" this is "where I sleep." Now, I don't know if they know how to get to these places; it seems unlikely before the advent of independent locomotion.

ACREDOLO: That is exactly what I would like to know. That is, is there a point at which it becomes irrelevant, the position of the crib in that space, so that in fact it isn't specific to the learning situation, it is a more general context (i.e., "I'm now in the same room,") rather than in exactly the same egocentric display. Whether you would find this in older babies would be irrelevant.

ROVEE-COLLIER: You know, what really surprises me is that the context is so specific at 3 months, and it is even more specific at 6 months. At 3 months changing the context doesn't matter after 1 day. At 6 months, changes wipe out retention after 1 day altogether. It is really remarkable because these babies are not just sitting there during the test and staring and looking at the new crib liner; rather, they are sitting there gaping, mouths open, at the mobile. Information about the setting is just being picked up in their periphery. What is more remarkable is that at 6 months they can discriminate the training mobile from a novel one for as long as they can remember the task—after 2 weeks—yet they appear not to recognize it after just 1 day if the context is altered.

L. NADEL (*University of Arizona, Tucson, Arizona*): Let me just ask you about this point, about relational aspects of the pattern on the bumper. You could presumably use a bumper that had 4 different patterns on it, rather than all the same, and then just change the relations among those patterns. Would that break the context effect?

ROVEE-COLLIER: Well, it is conceivable that it might. One of the kinds of manipulations we have made is to train infants in the presence of, for example, green squares on a yellow background, and change the test context to green triangles on a yellow background, and they respond perfectly 24 hours later. But if you change the forms to green circles, they don't respond at all, nor do they if you change the form to green stripes. If you take the forms off altogether, they're terrific (Rovee-Collier & Shyi, in press). But if you train them with the squares spread out in a grid, and then you test them with the squares, lined up in columns, as stripes, you can ask, are they seeing the individual components, or are they seeing the gestalt?

J. FUSTER (*UCLA School of Medicine, Los Angeles, CA*): I think your results might

be accounted for by temporal continuity and spatial continuity in the formation of the representational order of memories. I think you could follow the same argument at a more primitive level, namely the level of the establishment of the sensory order. That is, in lower levels of the nervous system, single qualities of sensation are associated also with other qualities of sensation by contiguity of space and time. Even at these primitive levels there is a degree of learning by co-occurrence and by contiguity. I am not the first one to say that. Perhaps the one who has best articulated these ideas is Friedrich von Hayek (1952). In other words, the Hebbian principles may have operated already in primary sensory areas in the course of phylogeny, in the same way as they govern the association of sensations in the course of the development of the individual.[c]

ROVEE-COLLIER: The interesting thing about your comment is that there are some constraints. The constraint is that following category training with discriminably different yellow-block mobiles on each day, if you introduce the metal butterfly, *nonmoving,* close in time, infants don't respond to it 24 hours later. If you introduce it *moving* within the same time frame, then they do respond to it 24 hours later. This butterfly is a wind chime, but we stuff it with tissue paper to keep it from ringing. When we remove the tissues, the wind chimes can ring. If you expose the ringing, moving butterfly to infants immediately after training and test again with the butterfly, silent and stationary, infants do *not* associate the ringing butterfly with the training memory. We see this as decreasing the *net similarity* between exposure to the butterfly and the training event. But then, if you let infants move and ring it very briefly themselves, with a minimal amount of contingency experience that is not enough to train them (i.e., infants who get *just* that without category training don't respond the next day to it), they once again respond! So you can shift the butterfly in or out of the memory by common *functional* information, but not by contiguity. I think the really critical question is how do infants know when one event is over and some other event begins? This is a problem of time perception and perceptual development. What is a session for the infant? How does an infant define a session? We (the experimenters) define a session by our procedures, but what is a *real* session? When I walk in, the babies smile at *me,* and occasionally they kick. Am *I* the beginning of this session? Am I associated with, or a part of, their session memory?

P. SOLOMON (*Williams College, Williamstown, MA*): Carolyn, do you know anything about context for time as opposed to place (temporal context as opposed to spatial context)?

ROVEE-COLLIER: Well, that is a very interesting question, and there was a terrific chapter by Gorfein (1987), I believe, in a book that came out of a conference, "A hundred years of Ebbinghaus."[d] He was very interested in the temporal context within which events happen. Medin has argued very strongly that the unit of analysis probably changes and, unless you know what the unit of analysis is and how the

[c]HAYEK, F. VON 1952. The Sensory Order. University of Chicago Press. Chicago.

[d]GORFEIN, D. S. Explaining context effects on short-term memory. *In* Memory and Learning: The Ebbinghaus Centennial Conference. D. S. Gorfein & R. R. Hoffman, Eds.: 153–172. Erlbaum. Hillsdale, NJ.

subject is perceiving it, you have a real problem.[e] So, at 3 months, retrieval is very protracted, and very young infants need very long interstimulus intervals (ISIs). I don't think these observations are random events; I believe younger infants must integrate over substantially longer intervals.

SOLOMON: Let me ask a more pointed question. The effects you get by manipulating the visual context, can you get any of those effects by testing the infants at very different times of the day?

ROVEE-COLLIER: Well, that is a very interesting question. I didn't originally believe that to be the case, but there is this one bump in the retrieval-after-a-reminder curve at 6 months that is remarkable and has changed my thinking. It is hard to arrange tests at different times after a reminder. There is an 8-hour post-reminder point that was disastrous at 6 months. It was right at the end of the day. To test 8 hours after a reminder you have to go in the morning to present the reminder, and you have to come back late in the day. In the morning, infants are doing different things than they are 8 hours later. In the morning, the baby is happy; late in the day, the baby is screaming. In the morning the father is happy and the mother is happy; late in the day, they are screaming too! When we came back after 8 hours, infants showed no retention at all. But 24 hours later, retention was terrific again. I don't know if this is a circadian effect, or if it has something to do with temporal context, or the social context.

SOLOMON: It would be nice to see if you could move that forward 8 hours in time and still get it.

A. MELTZOFF (*University of Washington, Seattle, WA*): The nature of this sort of representation, of course, is very interesting. You mention that the port-a-crib was lower, so the babies had a different view. Might it also be that it didn't have on the baby's sheets so that it smelled different, or that the mattress was different so that it felt different? It's not particularly different from your interpretations; it's the same. I just wondered whether it might be multi-modal representation, as it were, not just a different liner, a different sheet, different feel.

ROVEE-COLLIER: Our suggestion was that it was the visual characteristic. From one day to the next, the smells in some of these homes are so remarkably different, this seems unlikely.

MELTZOFF: But babies can recognize their own crib by the smell of their own sheets.

ROVEE-COLLIER: Yes, I think they *do* know when they are not in their own cribs. Indeed, that was our original conclusion, but I was so struck by the effect because the setting is incidental. It is incidental because the mobile is the same and works the same way regardless of which crib, or room, they are in.

C. KOPP (*University of California, Los Angeles, CA*): Your context effects are remarkable. What about differences between subjects in terms of rate of kicking, how aroused they are, or how motivated they are?

ROVEE-COLLIER: Well, we always go at a time of day when mothers tell us they are ready to play.

KOPP: But even that readiness. . .

[e]MEDIN, D. & T. J. REYNOLDS. 1985. Cue–context interactions in discrimination categorizations and memory. *In* Context in Learning. P. D. Balsam & A. R. Tolmie, Eds.: 323–356. Erlbaum. Hillsdale, NJ.

ROVEE-COLLIER: Yes, and they do have different baseline rates, which is why we convert our data to ratios in order to eliminate individual differences in initial response rates. We also have some restrictions and some requirements for whom we include. If a baby does not respond at all during baseline, it is never going to learn the task, so we don't continue. We also have an upper limit on responding because we require infants to respond at least 1½ or 2 times above baseline in order to be included in the experiment. This would be difficult to achieve with a very high baseline rate. In both cases, we can't ask infants to remember something that they have not initially learned.

R. CLIFTON (*University of Massachusetts, Amherst, MA*): I have admired this paradigm for a long time and I have wondered if maybe the reason it works so beautifully is that this situation is so much under the baby's control. Just from all you have just said, if there is a Fat Albert, well, he might wake up and eventually do it, or in the case of a hyperactive infant he *can* double his kicks. There is no other paradigm we have discussed in this conference where the baby has really controlled the amount of movement of his own kicking.

ROVEE-COLLIER: The reason that this works well for cross-age comparisons is that you don't have to worry about equating reinforcement, because the baby is producing his own level of reinforcement and can "shop" for whatever he wants. At that moment, if he feels like making it go fast, he can make it go fast. At another moment, perhaps he will prefer to simply watch it spin. Some babies are very satisfied with just a little jiggle. At different ages they can produce whatever intensity of stimulation they want, so you don't really have to worry about that problem.

A. DIAMOND (*University of Pennsylvania, Philadelphia, PA*): Not only do they get to kick at the rate they want, they get the amount of effect they want, and they get it right away, it's *immediately* linked.

CLIFTON: Exactly.

ROVEE-COLLIER: I think it is a matching behavior. I have discussed this with Andy [Meltzoff].

A. SHIMAMURA (*University of California, Berkeley, CA*): In terms of a stimulus–response contingency, I wonder if the response contingency is "move my leg and the thing will move," or "move the string and the thing will move."

ROVEE-COLLIER: It is "move my leg and the thing will move." That is clear. At both 6 months and 3 months, there are noncontingent controls who see the movement. One could ask, "Are they merely getting aroused by seeing the mobile move, and as long as it is moving, they are excited?" That doesn't happen. If both arms and both legs are attached to strings, they never increase the rate of moving their arms. If only one leg is attached, they eventually reduce responding in the leg that doesn't work the mobile. This is amazing because if they moved both legs the mobile would move, as long as they moved the leg that has the ribbon connected to it!

W. OVERMAN (*University of North Carolina, Wilmington, NC*): Is that true of vocalizations also? I noticed the infant was squealing as he was kicking. Is that a superstitious behavior?

ROVEE-COLLIER: The squealing comes in later. The baby you saw in the videotape had a lot of superstitious behaviors in acquisition. It is a real pain for awhile.

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SHIMAMURA: I guess my question was a more specific one. In terms of after one learns that the foot length will move the object. . .

ROVEE-COLLIER: . . . do they learn that the ribbon does it?

SHIMAMURA: Yes. If you move the ribbon to the hand on the retraining with the same original mobile, will they just shake their leg or will they learn faster than baseline rates to move their hand to get the mobile to move?

ROVEE-COLLIER: No. These are independent of each other—they only kick their legs (Timmons, 1990). We can't use their hands after they have kicked their legs. We can do their hands first, which we have to do, because once they go to kick their legs they brace themselves with their hands and they will never move their hands. But I don't think the 3-month-olds even see the ribbon, to be quite honest about it, because they never take their eyes off the mobile.

J. DELOACHE (*University of Illinois, Urbana, IL*): I am very interested in the context effects. The ones you describe all seem to be familiar contexts; the baby's crib is what the context is. Do you think the same thing would happen if you brought babies into a lab and had them in a certain apparatus?

ROVEE-COLLIER: The data that Rachel [Clifton] has collected provides the answer. I will tell you that the familiar context is *not* the key; more critical is that the context is distinctive and one that they don't normally encounter except in training or testing. For example, were they to encounter something similar in the training context, it might retrieve the memory, and the memory could be modified. Hayne (1988) could not do her two-reminder study at 3 months *unless* she used a distinctive context. It just didn't work. So I think that any time you put infants into a situation that is unique and different, and they don't return to that situation for awhile, then the memory is probably buffered against retrieval before the test in that context, and that is probably what happened in Rachel's study (Perris *et al.,* in press).