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Transitions in the temporal parameters of sensory preconditioning during infancy

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Abstract

Sensory preconditioning (SPC) is a form of latent learning in which preexposure to co-occurring neutral stimuli (S_1 - S_2) permits subsequent learning to be transferred from one stimulus (S_1) to the other (S_2). We examined whether human infants exhibit developmental transitions in the temporal parameters of SPC by manipulating the preexposure regimen. Infants received simultaneous or sequential preexposure to puppets S_1 and S_2 (Days 1–2); saw target actions modeled on S_1 (Day 3); and were tested for deferred imitation with S_2 (Day 4). Although 6-, 9-, and 12-month-olds associated the puppets, there was a shift in the effective regimen from simultaneous to sequential preexposure—similar to prior findings with rat pups (Experiment 1). Experiment 2 revealed that human infants potentially exhibit another transition in SPC at 15 and 18 months of age. We consider the roles of ontogenetic shifts in infants' ecological niche, selective attention, and unitization in developmental transitions in SPC.

Keywords

sensory preconditioning; human infants; deferred imitation; association; temporal contiguity; ecological niche; long-term memory; stimulus preexposure; transfer test; latent learning

A question of fundamental importance for all species and ages is, *How do organisms acquire information about their environmental surround?* One mechanism is via associative learning—a universal learning process observed throughout both phylogeny and ontogeny. Associative learning, however, is typically cue-specific; learning does not generalize to other cues. In sensory preconditioning (SPC), an association between two stimuli (*preexposure*: S_1 - S_2) allows for a subsequently learned response to be transferred from the training stimulus (S_1) to the associated stimulus (S_2). Thus, SPC vastly expands the organism's associative network and exponentially increases the number of situations in which previous learning can be expressed. The S_1 - S_2 association, which mediates response transfer, is formed when the two stimuli merely co-occur, in the absence of any reinforcement.

A form of associative learning like SPC may be particularly useful during infancy when the first networks of associations are just beginning to be established and elaborated, and when memories are highly specific to their training stimuli. Human infants spend much of their waking moments simply observing their surround. Recent latent learning research suggests that during this time, they are constantly picking up information, only a small fraction of which they will ever express (Campanella & Rovee-Collier, 2005; Cuevas, Rovee-Collier, & Learmonth, 2006). The present study examined the development of associative learning via SPC during the first postnatal year-and-a-half in the human infant. Specifically, we asked whether there were ontogenetic shifts in the formation of an S_1 - S_2 association as a function of the timing regimen during S_1 - S_2 preexposure.

Sensory Preconditioning (SPC)

Sensory preconditioning is a well-established protocol in the field of associative learning and has been demonstrated across many species (see Thompson, 1972, for review). The SPC paradigm has three phases: (1) two stimuli (S_1 , S_2) are presented in close temporal or spatial contiguity (S_1 - S_2 ; e.g., Brogden, 1939); (2) a distinctive response is trained to one of the stimuli ($S_1 \rightarrow R$); and (3) the organism is tested with the other stimulus (S_2). The transfer of responding to the untrained stimulus ($S_2 \rightarrow R$) is taken as evidence that an association was formed between S_1 and S_2 during Phase 1. Because the association that is formed during Phase 1 remains latent until it is expressed in Phase 3, SPC is a form of behaviorally silent learning.

SPC in rat pups.

A review of the animal literature suggests that there may be ontogenetic differences in the parameters that support the formation of an association during phase 1 of SPC. In studies of SPC with adult organisms, S_1 and S_2 are typically preexposed sequentially (e.g., Brogden, 1947; Taylor, Joseph, Zhao, & Balsam, 2014). Although mature organisms exhibit evidence of SPC following simultaneous preexposure (Matzel, Held, & Miller, 1988; Rescorla, 1980), the magnitude of SPC is often greater with sequential preexposure (Hoffeld, Thompson, & Brogden, 1958; Silver & Meyer, 1954; Wynne & Brogden, 1962). A variety of factors, including anticipatory response systems and stimulus processing, have been theorized to contribute to differences in the behavioral expression of simultaneous versus sequential SPC in adults (see Matzel et al., 1988 and Rescorla, 1980 for review).

Spear and colleagues have found robust evidence of SPC throughout ontogeny; however, they have also discovered age-related shifts in the preexposure regimen (S_1 - S_2 pairings) that produces SPC. For instance, newborn rat pups tested in an appetitive conditioning paradigm exhibit SPC only following simultaneous preexposure to two odors; even immediate sequential preexposure to S_1 and S_2 , a 0-s interstimulus interval (ISI), disrupted SPC (Cheslock, Varlinskaya, High, & Spear, 2003). Simultaneous preexposure has also been effective for newborn rabbits (Coureaud, Tourat, & Ferreira, 2013) as well as 8- and 12-day-old rat pups tested with an aversive conditioning paradigm (Chen, Lariviere, Heyser, Spear, & Spear, 1991). Unlike newborns, however, 12-day-olds associated the two odors when they were separated by up to a 10-min delay; thus, exhibiting SPC after either simultaneous or

sequential preexposure. Perhaps the most intriguing findings from this study emerged when testing 21-day-old weanling rats. The 21-day-olds associated the two odors *only* when they were presented sequentially with a delay of up to 20 min. Thus, simultaneous preexposure was no longer effective at producing SPC by 21 days of age, revealing that in rat pups there is a shift from only simultaneous to only sequential learning during the preexposure phase of SPC.

Spear (1984) has proposed that very immature rat pups possess a special infantile disposition for “unitization” that facilitates the rapid formation of simultaneous, intra-event associations (Kucharski & Spear, 1985; Spear & Kucharski, 1984). Unitization is a process in which discriminably different stimuli are represented together as a single (“unitized”) stimulus.

Evidence of infantile unitization has been found in a variety of experimental preparations (e.g., potentiation, equivalence learning) using both within and cross-modal stimuli (for review see Spear, Kraemer, Molina, & Smoller, 1988). Because this special disposition disappeared after the second postnatal week, younger rat pups learned about simultaneously presented neutral stimuli better during this early period than older rat pups. It is often difficult, however, to determine whether unitization is the result of an “active” associative process, a “passive” perceptual process, or a combination of both processes (Molina, Hoffman, Serwatka, & Spear, 1991; Spear et al., 1988). It is unknown whether a similar disposition for unitization is present in human infants.

SPC in human infants.

Much of what we know about SPC in human infancy is based on work conducted by Carolyn Rovee-Collier and her colleagues. Although initial evidence of SPC in human infants was found within the context of operant conditioning using the mobile paradigm (Boller, 1997), the majority of subsequent SPC research has examined deferred imitation using the puppet task (e.g., Barr, Marrott, & Rovee-Collier, 2003; Giles & Rovee-Collier, 2011). In their initial investigation, Barr and colleagues (2003) simultaneously exposed 6-month-olds to two hand puppets (Phase 1: $S_1 \leftrightarrow S_2$); demonstrated target actions on S_1 (Phase 2: $S_1 \rightarrow R$); and tested for deferred imitation with S_2 (Phase 3: $S_2 \rightarrow R?$). In the absence of prior exposure, infants do not generalize responding to a different puppet until 21 months of age (Hayne, MacDonald, & Barr, 1997; Learmonth, Lamberth, & Rovee-Collier, 2004), but in the Barr et al. (2003) study, 6-month-olds who were simultaneously preexposed to S_1 and S_2 exhibited deferred imitation on S_2 —evidence of SPC. In comparison, an unpaired preexposure control group failed to imitate the target actions on S_2 .

Subsequent SPC research has revealed that simultaneous preexposure expands the infant’s associative network both directly via the association formed between co-occurring stimuli (i.e., S_1 - S_2 association) and indirectly via multiple associatively-activated associations. For example, Cuevas et al. (2006) used a combination of simultaneous preexposure to two hand puppets and operant conditioning with a crib mobile in a distinctive context to determine if infants could associate two co-active memory representations. We found that 6-month-olds could form an association between two objects (mobile and puppet S_2) that were neither perceptually present nor had ever appeared together if the representations of those objects were simultaneously activated in memory by associated retrieval cues [$S_1 \rightarrow S_2$ and context

→ **mobile**). Thus, infants can form associations between objects and events by thinking about them at the same time. Likewise, Townsend (2007) found that 6-month-olds can use an associative chain formed via simultaneous preexposure ($S_1 \rightarrow S_2 \rightarrow S_3$ and $S_1 \rightarrow S_2 \rightarrow S_3 \rightarrow S_4$) to indirectly associate two puppets (S_1 and S_3 or S_1 and S_4) that were never presented together.

Further, the memory system of very young infants, 3-month-olds, is sufficiently mature to form associations between simultaneously presented stimuli (Phase 1 SPC) with periodic reminders prolonging the duration of this memory (Campanella & Rovee-Collier, 2005). In the absence of any reminders, 6- and 9-month-olds remember the association between two simultaneously presented puppets as long as 4 or 2 weeks, respectively (Giles & Rovee-Collier, 2011). These findings reveal that new learning acquired via mere observation can remain latent for a substantial period before it is finally expressed; and that similar to rat pups, younger human infants sometimes exhibit superior memory as compared to older infants (see Rovee-Collier & Giles, 2010).

Although there is robust evidence of SPC at 3 to 9 months of age following a simultaneous preexposure regimen (Barr et al., 2003; Campanella & Rovee-Collier, 2005; Giles & Rovee-Collier, 2011), research with older infants has not been successful (Bullman, Cuevas, & Rovee-Collier, 2006; Muentener, 2004). It is plausible that human infants and rat pups might exhibit parallel changes in the temporal parameters that promote association formation in the SPC paradigm such that sequential preexposure becomes more effective as infants get older. Despite its theoretical and applied significance for the formation of the early knowledge base, the development of SPC has never been systematically examined in the human infant. Thus, we modified the SPC procedure developed by Barr et al. (2003) to examine both simultaneous and sequential (at different ISIs) preexposure with 6-, 9-, and 12-month-olds in Experiment 1.

Experiment 1: 6- to 12-month-olds

In the present study, the primary research question was whether there are developmental changes in SPC during human infants' first postnatal year. Spear and colleagues have found age-related changes in SPC during the first three postnatal weeks in the rat pup; only a simultaneous preexposure regimen produced SPC for very young rat pups (Cheslock et al., 2003), and this preexposure regimen shifted to a sequential regimen in older rat pups (Chen et al., 1991). The lack of SPC following simultaneous preexposure at 12 month of age (Bullman et al., 2006; Muentener, 2004), but not at younger ages, provides evidence suggesting that a similar age-related shift in the effective preexposure regimen may also occur in human infants. Furthermore, although simultaneous preexposure is effective between 3 and 9 months of age, it is unknown whether young infants can also associate neutral cues that are preexposed sequentially.

In Experiment 1, independent groups of 6-, 9-, and 12-month-olds were either simultaneously or sequentially exposed to the puppets during the preexposure phase. We examined whether there were any age-related changes in the temporal parameters of preexposure that led to association formation (i.e., SPC). We hypothesized that human

infants would exhibit an age-related shift in the effective preexposure regimen from simultaneous to sequential preexposure analogous to findings with rat pups (Chen et al., 1991; Cheslock et al., 2003).

Method

Participants.—The sample consisted of 192 infants (103 boys, 89 girls) who were recruited through published birth announcements, commercial mailing lists, and by word of mouth. The participants were 24 six-month-olds ($M = 187.9$ days, $SD = 5.7$), 64 nine-month-olds ($M = 280.8$ days, $SD = 5.2$), and 104 twelve-month-olds ($M = 371.5$ days, $SD = 4.8$) who were assigned to groups (6 and 9 months: $n = 8$; 12 months: $n = 12$) as they became available for study. (One group included only eight 12-month-olds because seven infants had the same imitation score, and we experienced unusual difficulty recruiting 12-month-old participants). Participants were African-American ($n = 9$), Asian ($n = 23$), Caucasian ($n = 123$), Hispanic ($n = 14$), of mixed race ($n = 14$), Native American ($n = 1$), Other ($n = 4$), and not reported ($n = 4$). Their parents' mean educational attainment, reported by 92.2% of the sample, was 15.7 years ($SD = 0.9$), and their mean rank of socioeconomic index (SEI; Nakao & Treas, 1992), reported by 83.9% of the sample, was 71.38 ($SD = 14.40$). The SEI is a recommended source for occupational status; ranks of occupations range from 1 to 100, with higher-paying occupations (e.g., physician and lawyer) being assigned higher ranks.

Testing was discontinued on additional 6- to 12-month-old infants because of excessive crying ($n = 3$), failure to touch the puppet or remain in the test session ($n = 6$), illness ($n = 2$), scheduling conflict/weather ($n = 8$), parental interference ($n = 4$), experimenter error ($n = 11$), or falling asleep ($n = 1$).

Apparatus.—Three hand puppets (a black-and-white cow, a yellow duck, and a pink rabbit) were constructed for these experiments and were not commercially available (see Figure 1). The puppets were 30 cm in height and made of soft, acrylic fur. A removable felt mitten (8×9 cm) in a matching color covered each puppet's right hand. A large jingle bell was secured inside the mitten during the demonstration but was removed during testing. The puppets were counterbalanced within groups. During preexposure sessions, the puppets were displayed successively or side-by-side on a 1- or 2-post wooden hat stand, respectively. A Panasonic VHS-C camcorder on a tripod was used to videotape all sessions for later scoring by independent coders.

Procedure.—Infants were studied in their own homes at a time of day when they were likely to be playful, as reported by their caregivers. This time varied across infants but remained fairly constant across all sessions for a given infant. All sessions occurred in the same room.

Phase 1: Preexposure to S_1 - S_2 (formation of association).: On Days 1 and 2, infants received simultaneous or sequential exposure to puppets S_1 and S_2 for approximately 15 min/day. For simultaneous preexposure, the puppets were displayed side-by-side in the infant's full view for the entire session (Figure 2a). For sequential preexposure, puppet S_1

was displayed for 30 s, and after a specified delay (ISI: 0, 7.5, 15, 30, or 60 s), the experimenter replaced it with puppet S_2 for 30 s (Figure 2b). The S_1 - S_2 ISI and S_2 - S_1 ISI were the same (i.e., the intertrial interval (ITI) was equal to the ISI). This sequence was repeated for the remainder of the session (Example: S_1 -0 s- S_2 -0 s- S_1 -0 s...). Due to procedural limitations, the 0-s ISI, was actually 1 to 3 s.

For all infants, the preexposure session occurred during a free-play period in which parents provided their infant with toys and/or food. Infants were seated in a chair that restricted independent locomotion (e.g., highchair, bouncy seat). If the infant became fussy, parents were encouraged to interact with their infant. If the infant continued to fuss, then the infant was permitted to sit on his/her parent's lap for the remainder of the session. If necessary, the session was ended early (see supplementary material for distribution as a function of age and group). In all seating positions, the puppets remained out of the infant's reach.

One methodological consideration when manipulating the preexposure ISI is that groups will differ in either the number of paired presentations (in this context, how many times each puppet was presented) or in the duration of the preexposure session. As we increased the ISI for sequential preexposure groups, it was necessary to either increase the session duration (to hold the number of paired presentations constant) or decrease the number of paired presentations (to hold the session duration constant). Because of anticipated challenges associated with requiring infants to remain in a seated position for an extended amount of time (i.e., over 15 minutes), we decided to keep session length relatively constant across groups (range: 14–15.5 min/day). Thus, the number of paired presentations per session varied between groups (range: 5–15 pairings/day).

Table 1 provides an outline of our experimental groups, including the ISI between puppet presentations, the number of paired presentations, the session duration, and the puppet exposure duration (i.e., how long the puppets were in the infant's view). Because the sequential preexposure groups differed in both the ISI and number of paired presentation, our group labels include both pieces of information (i.e., *Groups 0s/15, 7.5s/12, 15s/10, 30s/8, 60s/5*). The first part of each group label represents the ISI (i.e., 0s, 7.5s, 15s, 30s, or 60s) and the second part of the group label represents the corresponding number of paired presentations per session (i.e., 15, 12, 10, 8, 5). A “-” is used for the simultaneous preexposure group label because the puppets remained in front of the infant for the entire session (*Group sim/-*).

At all ages, we began by testing both simultaneous and immediate sequential preexposure groups (*Groups sim/-* and *0s/15*). If there was evidence of SPC with a 0-s ISI, we then extended the ISI to 30 s (and then to 60 s, if needed) to find the upper limit of effective preexposure ISI. To determine if there was an optimal ISI at each age, we also halved the 30-s ISI to 15 s and 7.5 s for subsequent groups. At 12 months, despite mixed evidence of SPC with a 0-s ISI, we decided to proceed with testing additional groups as detailed above. Our rationale was based on hypothesized shifts from simultaneous to sequential SPC around 12 months with preliminary evidence supporting this hypothesis at 6 and 9 months.

Preexposure control groups: Number of paired presentations.: As noted above, by holding preexposure session duration relatively constant across groups, groups with longer ISIs had fewer paired presentations. In mature organisms, maximum SPC has been found after relatively few trials (i.e., 4 or 16) with the number of paired presentations affecting the magnitude but not occurrence of SPC (Hoffeld, Kendall, Thompson, & Brogden, 1960; Prewitt, 1967). It is unknown whether the number of paired presentations will similarly affect SPC in immature organisms; thus, we included additional pairing control groups. We did not know if the failure to exhibit SPC might have resulted from receiving too many (i.e., learned inhibition, learned irrelevance) or too few (i.e., no association formation) paired presentations. Thus, at each age, we determined which of our experimental sequential preexposure groups exhibited SPC, and then manipulated the number of paired presentations in selected pairing control groups. Our primary aim was to establish general principles regarding how the number of paired presentations affected SPC by selectively probing this association at each age. Our manipulations yielded a total of seven pairing control groups across ages (6 months: *Group 0s/8*; 9 months: *Groups 0s/8, 15s/15*, and *30s/15*; 12 months: *Groups 0s/8, 30s/4*, and *60s/10*) with session duration ranging from 8 to 29.5 min/day. Table 2 provides an overview of each pairing control group and corresponding experimental group (in bold font) for comparison purposes.

At 6 and 12 months, to determine if failure to exhibit SPC was related to having too many paired presentations, pairing control groups (*Group 0s/8*) received approximately half as many paired presentations as corresponding experimental groups that had failed to exhibit SPC (*Group 0s/15*). Next, we investigated whether the absence of SPC could be associated with too few paired presentations. At 9 and 12 months, we first examined whether an effective preexposure regimen (9 months: *Group 0s/15*; 12 month: *Groups 30s/8*) would still produce SPC when the number of preexposure trials was approximately halved (9 months: *Group 0s/8*; 12 months: *Group 30s/4*). In order to minimize the time that infants spent in the experimental session, and thus minimize the increased attrition that typically accompanies long sessions, we completed this indirect manipulation first. However, in both cases, infants no longer exhibited SPC. It was then necessary to increase the length of 9- and 12-month-olds' preexposure sessions. For selected experimental preexposure regimens that had not produced SPC (9 months: *15s/10* and *30s/8*; 12 months: *Group 60s/5*), the number of paired presentations in the pairing control groups was approximately doubled, but did not exceed 15 paired presentations per session (9 months: *15s/15* and *30s/15*; 12 months: *Group 60s/10*).

Phase 2: Demonstration on puppet S₁. On Day 3, a novel experimenter began the session by interacting with the infant for 5 min prior to the demonstration or until she elicited a smile. (A novel experimenter conducted the demonstration and deferred imitation test to preclude the possibility that the original experimenter would act as a retrieval cue.) The infant sat on the caregiver's knees while the experimenter knelt in front of the infant with puppet S₁ on her right hand. The experimenter positioned the puppet at the infant's eye level and approximately 80 cm from the infant's chest (out of the infant's reach), and modeled a sequence of three target actions: (1) remove the mitten from the puppet's right hand; shake the mitten three times to ring the bell inside; and (3) replace it on the puppet's right hand.

This sequence lasted 10 s and was repeated five more times (a total of 60 s) for 6-month-olds or two more times (a total of 30 s) for 9- and 12-month-olds. This sequence yields 24-hr retention from 6 to 18 months of age (Barr, Dowden, & Hayne, 1996; Learmonth et al., 2004).

Phase 3: Imitation test with puppet S₂. During the test (Day 4), the same experimenter held puppet S₂ as before but within the infant's reach (i.e., approximately 30 cm in front of the infant's chest). The bell was removed from the mitten. The infant was allowed 90 s (9- and 12-month-olds) or 120 s (6-month-olds) of visual and/or physical attention to the puppet from the time he or she first touched the puppet in which to imitate the previously modeled actions. Infants younger than 21 months do not generalize the modeled actions from one puppet to another whether they previously saw them unpaired or not at all (e.g., Hayne et al., 1997; Learmonth et al., 2004). If puppets S₁ and S₂ had been associated, then infants would exhibit deferred imitation on puppet S₂.

Coding and reliability. A trained observer coded the looking time of each infant in successive 30-s blocks during both preexposure sessions, while a second observer independently coded 18% of the sessions. The Pearson product-moment correlation between their joint looking-time scores in 30-s blocks was .93. An imitation score was calculated for each infant by summing the number of target behaviors (range = 0–3: remove the mitten, shake the mitten, attempt to replace the mitten on the puppet's right hand) that were produced during the test session. One observer scored all of the videotaped sessions; a second observer, who was blind to infants' group assignments, independently scored 24% of the videotaped sessions. The interobserver reliability was 96% ($kappa = .91$). When the two raters differed, the primary rater's score was assigned.

Results and Discussion

At all ages, preliminary analyses indicated that sex did not enter into any significant interactions or main effects, so data were collapsed across sex for all subsequent analyses.

Preexposure Phase.—In the present study, infants' imitation scores were our primary measure of interest. Detailed analyses of the preexposure phase looking time data can be found in Cuevas (2009). Information regarding cumulative looking time as a function of age and group can be found in the supplementary materials.

6-month-olds. A one-way analysis of variance (ANOVA) indicated that the groups did not differ in the total time looking at the puppets, $F(2, 21) = 3.17$, $p = .063$, $\eta_p^2 = .23$, during the preexposure phase¹. Six-month-olds looked at the puppets for a mean of 5.87 min ($SD =$

¹At all ages, some infants (6 months: $n = 12$; 9 months: $n = 24$; 12 months: $n = 44$; 15 months: $n = 16$; 18 months: $n = 20$) were missing a small fraction of preexposure data—most often measured in seconds—because the camcorder temporarily malfunctioned (or experimenter recording error), the infant's eyes were difficult to see, and/or the session ended early (see supplementary material for distribution as a function of group). However, some infants (6 months: $n = 5$; 9 months: $n = 14$; 12 months: $n = 11$; 15 months: $n = 3$; 18 months: $n = 6$) were missing more than 5 min of preexposure data. Secondary analyses of group differences in looking time excluded these infants and yielded a similar pattern of findings [6 months: $F(2, 16) = 3.26$, $p = .065$, $\eta_p^2 = .29$; 9 months: $F(7, 42) = 1.63$, $p = .20$; 12 months: $F(8, 84) = 2.78$, $p = .009$, $\eta_p^2 = .21$; 15 months: $F(4, 32) = 2.79$, $p = .043$, $\eta_p^2 = .26$; 18 months: $F(4, 30) = 3.97$, $p = .011$, $\eta_p^2 = .34$]. At 12 months, however, Tukey post hoc on this subset of participants, no longer revealed any significant between group differences.

3.08). Barr et al. (2003) and Cuevas (2005) also found that 6-month-olds spend relatively little time looking at the puppets during two 1-hr simultaneous preexposure sessions ($M = 7.04$ and 3.52 min, respectively).

9-month-olds.: A one-way ANOVA revealed that there was a significant difference between groups in the total time spent looking at the puppets¹, $F(7, 55) = 2.25$, $p = .044$, $\eta_p^2 = .22$. However, Tukey post hoc tests ($p < .05$) yielded no significant between group differences. Overall, 9-month-olds spent a mean of 5.05 min ($SD = 3.50$) looking at the puppets.

12-month-olds.: A one-way ANOVA indicated that total looking time differed significantly between groups¹, $F(8, 95) = 2.65$, $p = .011$, $\eta_p^2 = .18$. A Tukey post hoc test ($p < .05$) indicated that *Group 0s/15* ($M = 5.22$ min, $SD = 2.20$) looked at the puppets longer than *Group 60s/5* ($M = 2.72$ min, $SD = 1.03$). This finding was not surprising; the puppets were in view three times longer (15 min/day) for *Group 0s/15* than for *Group 60s/5* (5 min/day). Overall, 12-month-olds looked at the puppets for a mean of 4.07 min ($SD = 1.98$). Muentener (2004) had similarly found that 12-month-olds spent relatively little time ($M = 2.73$ min) looking at puppets that were presented simultaneously for 30 min in one session.

Deferred Imitation Test.—At each age, the mean imitation scores of the experimental and preexposure pairing control groups were compared to the mean test score of an age-matched *pooled baseline control group*. Infants in the *pooled baseline control groups* had seen neither a demonstration of the target actions nor either puppet prior to the test (i.e., the imitation test was their first session). Because the incidence of spontaneously performing the target actions in the population is low but non-zero, the mean baserate of a pooled baseline control group more closely approximates the population mean, decreasing the likelihood of Type I and Type II errors. The *pooled baseline control groups* presently contained 45 six-month-olds, 24 nine-month-olds, 46 twelve-month-olds, 41 fifteen-month-olds (Experiment 2), and 42 eighteen-month-olds (Experiment 2) who had participated in spontaneous baseline control groups in previous deferred imitation studies with the same stimuli and parameters (Barr & Hayne, 1999; Barr et al., 2003; Barr, Rovee-Collier, & Campanella, 2005; Barr, Muentener, & Garcia, 2007; Barr, Vieira, & Rovee-Collier, 2001, 2002; Barr, Wyss, & Somanader, 2009; Campanella & Rovee-Collier, 2005; Cuevas, 2009; Giles & Rovee-Collier, 2011; Learmonth et al., 2004; Learmonth, Lamberth, & Rovee-Collier, 2005). The mean test score of each group defined the baserate for the spontaneous (unlearned) production of the target behaviors at each age. The baserate at which infants of all ages spontaneously produce the target actions is low (.13 - .25).

6-month-olds.: At 6 months, a one-way ANOVA indicated that the mean imitation scores of the four groups differed significantly, $F(3, 65) = 8.49$, $p < .001$, $\eta_p^2 = .28$. We used directional Dunnett's t tests ($p < .05$) to determine which group, if any, had mean imitation scores significantly higher than the mean test score of the 6-month *pooled baseline control group*. The mean imitation score of the simultaneous preexposure group (*Group sim/-*) was higher than the mean test score of the *pooled baseline control group*, but the mean imitation scores of the immediate sequential preexposure groups (*Groups 0s/8* and *0s/15*) were not (Figure 3). The failure of the 0-s ISI groups to exhibit SPC does not appear to result from

too many paired presentations; the mean imitation scores of the immediate sequential preexposure groups did not differ when the number of pairings per day was reduced from 15 (*Group 0s/15*) to 8 (*Group 0s/8*; Tukey post hoc test, $p < .05$). Thus, 6-month-olds exhibited SPC only with a simultaneous preexposure regimen.

9-month-olds.: At 9 months, a one-way ANOVA revealed that the mean imitation scores of the nine groups differed significantly, $F(8, 79) = 3.10$, $p = .004$, $\eta_p^2 = .24$. Dunnett's t tests ($p < .05$) indicated that the simultaneous (*Group sim/-*), immediate sequential (*Group 0s/15*), and 15-s ISI (*Group 15s/15*) preexposure groups had mean imitation scores significantly higher than the mean test score of the 9-month *pooled baseline control group*, but *Groups 0s/8*, *7.5s/12*, *15s/10*, *30s/8*, and *30s/15* did not (Figure 4). This pattern of results suggests that the number of paired presentations influenced SPC at 9 months. Although a 0-s ISI was an effective preexposure regimen, 9-month-olds failed to exhibit SPC when the number of paired presentation per session was reduced from 15 (*Group 0s/15*) to 8 (*Group 0s/8*). Similarly, when the ISI was 15 s, 9-month-olds exhibited SPC only when the number of paired presentation per session was increased from 10 (*Group 15s/10*) to 15 (*Group 15s/15*). Although we did not manipulate the number of paired presentations for the 7.5-s ISI group (*Group 7.5s/12*), half of the 9-month-olds in this group exhibited SPC; based on the aforementioned findings, we hypothesize that with a few more paired presentation per session (i.e., an increase from 12 to 15), 9-month-olds would have also exhibited significant SPC when the ISI was 7.5s. However, the 30-s ISI was not an effective preexposure regimen even when the number of paired presentations per session was increased from 8 (*Group 30s/8*) and to 15 (*Group 30s/15*), indicating potential limits in the ISIs that 9-month-olds can successfully associate sequentially presented neutral stimuli. In sum, 9-month-olds exhibit SPC after both simultaneous and sequential preexposure regimens, and additional paired presentations extends the delay over which they can associate successively presented stimuli.

12-month-olds.: At 12 months, a one-way ANOVA indicated that the mean imitation scores of the 10 groups differed significantly, $F(9, 140) = 2.24$, $p = .023$, $\eta_p^2 = .13$. Dunnett's t tests ($p < .05$) revealed that the 7.5-s (*Group 7.5s/12*), and 30-s (*Group 30s/8*) sequential preexposure groups had mean imitation scores that were higher than the mean test score of the 12-month *pooled baseline control group*, but *Groups sim/-*, *0s/8*, *0s/15*, *15s/10*, *30s/4*, *60s/5* and *60s/10* did not (Figure 5). Although a 30-s ISI was an effective preexposure regimen, 12-month-olds failed to exhibit SPC when the number of paired presentation per session was reduced from 8 (*Group 30s/8*) to 4 (*Group 30s/4*). The 60-s ISI, on the other hand, was not an effective preexposure regimen even when the number of paired presentations per session was increased from 5 (*Group 60s/5*) and to 10 (*Group 60s/10*). Furthermore, infants' failure to exhibit SPC when the ISI was 0 s does not appear to result from too many paired presentations per day; the mean imitation scores of the immediate sequential preexposure groups did not differ when the number of pairings per day was reduced from 15 (*Group 0s/15*) to 8 (*Group 0s/8*; Tukey post hoc test, $p < .05$). In sum, 12-month-olds exhibited SPC only with sequential preexposure regimens.

At 12 months, the effective preexposure ISIs increased nonmonotonically; infants exhibited SPC when the ISI was either 7.5 or 30 s but not 0 or 15 s. Although animal studies have

yielded different optimal ISIs for latent (S-S) and reinforced learning (see Thompson, 1972, for review), patterns are typically monotonic. For instance, with a single preexposure trial to two odors, 12-day-old rat pups exhibited SPC with ISIs of 0 s and 10 min, and 21-day-olds did so with ISIs of 0 s and 20 min (Chen et al., 1991). Similarly, Brogden and colleagues' foundational SPC work with adult cats revealed that the optimal ISI for tone-light "preconditioning trials" was 4 s with shorter and longer ISIs being less effective (Hoffeld et al., 1958; Wynne & Brogden, 1962). Thus, our nonmonotonic pattern of effective preexposure regimens at 12 months was unexpected and is potentially related to variability in 12-month data and statistical power. Whereas approximately half of the infants in the 0-s to 30-s ISI groups (i.e., *0s/15*, *7.5s/12*, *15s/10*, *30s/8*) associated puppets S₁ and S₂ (i.e., imitated any target action on S₂), only relatively few infants in the simultaneous and 60-s ISI groups did so. These data imply that individual differences contributed to the nonmonotonic pattern of effective ISIs at 12 months. Therefore, one consideration for future SPC research with older infants is that larger sample sizes are potentially necessary to have sufficient statistical power to account for variability and detect SPC.

Individual differences in SPC were unrelated to latency to first touch the puppet during the test phase ($r_s = -.28 - .21$, *ns*). Cuevas (2009) obtained parent-reported motor and verbal skill data from a subset of 12-month-olds infants in Experiment 1; however, these measures were not associated with individual differences in SPC. Individual differences in SPC are not unique to our data with 12-month-olds. In a review of research on SPC with mature organisms, Thompson (1972) had noted that "...in any given experiment it [*SPC*] is a highly variable phenomenon between Ss in the same condition...[*which is*] in distinct contrast to the much lower within-group variability in ordinary reinforced learning" (p. 117). Thus, in our final set of analyses, we examined whether looking time during the preexposure phase accounted for individual differences in SPC.

Strength of SPC.: Thompson (1972) hypothesized that the strength of SPC is associated with the amount of stimulus orienting during the preexposure phase. In line with previous SPC research with 6- and 12-month-olds (Barr et al., 2003; Cuevas, 2005; Muentener, 2004), we examined whether time spent looking at the puppets (i.e., a potential measure of orienting) was related to infants' subsequent imitation scores (i.e., strength of SPC). At each age, Pearson product-moment correlations failed to find an association between individual looking times and imitation scores (6 months: $r(22) = .17$, *ns*; 9 months: $r(61) = .11$, *ns*; 12 months: $r(102) = .07$, *ns*; see Cuevas, 2009 and supplementary material for separate analyses for each experimental group)². Our findings are consistent with other infant SPC work with smaller sample sizes (Barr et al., 2003; Cuevas, 2005; Muentener, 2004); it appears that once infants have formed an association between the two puppets, additional time spent looking at them did not make the association stronger. Although our total looking time data did not support Thompson's hypothesis, "total looking time" is not necessarily a precise measure of infant attention as infants can continue to look toward a stimulus although they are no longer attentive (see Richards, 2008, for review). Thus, future work using a combination of behavioral, physiological, and brain measures would be ideal to more comprehensively

²Secondary analyses excluded infants with more than 5 min of missing preexposure data and yielded the same pattern of findings [6 months: $r(17) = .16$, *ns*; 9 months: $r(48) = .14$, *ns*; 12 months: $r(91) = .07$, *ns*; 15 months: $r(35) = -.09$, *ns*; 18 months: $r(33) = -.05$, *ns*].

assess infant attention during the preexposure phase and test Thompson's SPC-orienting hypothesis.

In sum, the present results reveal that 6- to 12-month-olds associated two puppets that were in their visual surround without any external reinforcement, but there were age-related shifts in the effective preexposure regimen. The developmental pattern of S_1 - S_2 association formation at 6, 9, and 12 months of age parallels findings with rat pups (Chen et al., 1991; Cheslock et al., 2003). Specifically, newborn rat pups and 6-month-old human infants associated two neutral cues *only* when they were presented simultaneously; 12-day-old pups and 9-month-old human infants associated neutral cues when they were presented *either* simultaneously or sequentially; and 21-day-old pups and 12-month-old human infants associated the cues *only* when they were presented sequentially. After 21 days of age and throughout adulthood, rats associate two odors only after sequential preexposure (Spear & Kucharski, 1984). However, in human infants, there is initial evidence that simultaneous preexposure is potentially effective at 18 months of age (Muentener, 2004). Thus, in Experiment 2, we examined whether human infants exhibit another associative shift in the temporal parameters of preexposure during the second postnatal year.

Experiment 2: 15- and 18-month-olds

In Experiment 2, we tested additional groups of 15- and 18-month-old infants with the preexposure regimens that were effective for our 6- to 12-month-old experimental groups. Testing was not extended beyond 18 months because infants spontaneously generalize the target actions from one puppet to another by 21 months of age. Muentener (2004) found that 18-month-olds exhibited a trend towards simultaneous SPC after 30 min of exposure on a single occasion. Based on evidence of simultaneous SPC at 18 months of age we hypothesized that by 18 months, infants would exhibit SPC after both simultaneous and sequential preexposure, analogous to findings with mature organisms in a variety of paradigm (Matzel et al., 1988; Rescorla, 1980).

Method

Participants.—The sample consisted of 81 infants (35 boys, 46 girls) who were assigned to groups ($n = 8$) as they became available for study. One group, *Group 30s/8*, included nine 18-month-olds. The participants were 40 fifteen-month-olds ($M = 463.2$ days, $SD = 5.6$) and 41 eighteen-month-olds ($M = 553.2$ days, $SD = 5.8$). Infants were African-American ($n = 1$), Asian ($n = 12$), Caucasian ($n = 45$), Hispanic ($n = 6$), of mixed race ($n = 11$), and Other ($n = 2$), and not reported ($n = 4$). Their parents' mean educational attainment, reported by 91.4% of the sample, was 15.8 years ($SD = 0.7$), and their mean SEI, reported by 76.5% of the sample, was 74.98 ($SD = 15.71$).

Testing was discontinued on additional infants because of excessive crying ($n = 6$), failure to touch the puppet or remain in the test session ($n = 15$), illness ($n = 1$), scheduling conflict/weather ($n = 4$), parental interference ($n = 3$), experimenter error ($n = 1$), or equipment failure ($n = 2$).

Procedure.—The procedure and apparatus were the same as for 9- and 12-month-olds in the experimental groups (i.e., *Groups sim/-; 0s/15; 7.5s/12, 15s/10, 30s/8*) from Experiment 1.

Results and Discussion

Preexposure Phase.

15-month-olds. A one-way ANOVA indicated that total looking time differed significantly between groups¹, $F(4, 35) = 3.09$, $p = .028$, $\eta_p^2 = .26$. A Tukey post hoc test ($p < .05$) revealed that *Group 0s/15* ($M = 5.23$ min, $SD = 2.46$) looked at the puppets longer than *Group sim/-* ($M = 2.88$ min, $SD = 1.10$). Overall, 15-month-olds looked at the puppets for a mean of 3.87 min ($SD = 1.62$).

18-month-olds. A one-way ANOVA revealed that total looking time differed significantly between groups¹, $F(4, 36) = 4.30$, $p = .006$, $\eta_p^2 = .32$. Tukey post hoc tests ($p < .05$) indicated that *Group 0s/15* ($M = 6.30$ min, $SD = 3.50$) looked at the puppets longer than *Groups sim/-* ($M = 3.32$ min, $SD = 1.45$), *15s/10* ($M = 2.96$ min, $SD = 1.05$), and *30s/8* ($M = 3.11$ min, $SD = 0.95$). Overall, 18-month-olds looked at the puppets for a mean of 3.99 min ($SD = 2.21$). Muentener (2004) had similarly found that 18-month-olds spent relatively little time ($M = 3.06$ min) looking at puppets that were presented simultaneously for 30 min in one session.

Deferred Imitation Test.—As in Experiment 1, at each age, the mean imitation scores of the experimental and preexposure control groups were compared to the mean test score of an age-matched *pooled baseline control group*. The baserate at which 15- and 18-month-old infants spontaneously produce the target actions is low (.17 - .19).

15-month-olds. A one-way ANOVA indicated that the mean imitation scores of the six groups were not significantly different, $F(5, 75) = 1.33$, *ns*. Dunnett's *t* tests confirmed that none of the groups had mean imitation scores significantly higher than the mean test score of the 15-month *pooled baseline control group*. Surprisingly, none of the preexposure regimens were effective at producing SPC at 15 months of age (Figure 6).

18-month-olds. At 18 months, a one-way ANOVA revealed that the mean imitation scores of the six groups differed significantly, $F(5, 77) = 2.84$, $p = .021$, $\eta_p^2 = .16$. Dunnett's *t* tests ($p < .05$) revealed that the 7.5-s (*Group 7.5s/12*), and 15-s (*Group 15s/10*) sequential preexposure groups had mean imitation scores that were higher than the mean test score of the 18-month *pooled baseline control group*, but the 0-s (*Group 0s/15*), and 30-s (*Group 30s/8*) sequential preexposure groups did not (Figure 6). Interestingly, a marginally significant trend ($p = .075$) emerged for the simultaneous preexposure group (*Group sim/-*) in comparison to the *pooled baseline control group*. The 18-month simultaneous preexposure group is the only group at any age to exhibit a marginally significant trend, and we confirmed that this comparison would have been significant with less stringent post hoc analyses. Our findings are consistent with Muentener's (2004) work indicating that 18-month-olds exhibit a trend towards simultaneous SPC when using different preexposure parameters than the present study (i.e., an opaque presentation box with a transparent panel

for a single 30-min session). Thus, 18-month-olds exhibited SPC following sequential preexposure regimens with preliminary evidence that simultaneous preexposure potentially also reemerges as an effective SPC regimen.

Strength of SPC.: At each age, separate Pearson product-moment correlations were performed between individual looking times from the preexposure phase and subsequent imitation scores (15 months: $r(38) = -.05$, *ns*; 18 months: $r(39) = -.08$, *ns*)² and within each experimental group (see supplementary material). As with 6- to 12-month-olds in Experiment 1, we did not find any significant associations between 15- and 18-month-olds' imitation scores and looking times. Our findings are also consistent with previous SPC work with smaller sample sizes at 18 months of age (Muentener, 2004).

These analyses reveal that during the second postnatal year, infants exhibit additional transitions in the temporal parameters that support SPC. Although 15- and 18-month-olds were tested with preexposure regimens that were effective for younger infants (Experiment 1), only 18-month-olds exhibited SPC. Consistent with our hypotheses and work with adults (Matzel et al., 1988; Rescorla, 1980), both simultaneous (marginally significant trend; see also Muentener, 2004) and sequential preexposure regimens were effective at 18 months. It is likely that the effects of simultaneous preexposure would be more robust if the paradigm could be extended to older ages; however, infants begin to generalize the target actions from one puppet to another by 21 months of age (Hayne et al., 1997). The null results at 15 months are particularly intriguing; based on our findings at 12 months, we had anticipated that at the minimum, one of the sequential preexposure regimens would have supported SPC in 15-month-olds. When considering our preexposure phase within the broader context of the 15-month-old's "ecological niche", it might not be compatible with the recent developmental milestone of walking independently (see General Discussion). It is plausible that shorter preexposure regimens would have been ideal at this transitional point in development; future work is necessary to investigate how changes in the preexposure parameters (e.g., duration, number of pairings) affects SPC during the second postnatal year.

General Discussion

Using a SPC paradigm, we found that 6- to 18-month-old infants associated two puppets that merely co-occurred in their visual surround—without any external reinforcement; however, there were developmental transitions in the effective preexposure regimen. There was a shift from simultaneous to sequential SPC during the first postnatal year (Experiment 1) as well as initial evidence of yet another transition in SPC during the second postnatal year (Experiment 2). Moreover, preexposure to neutral stimuli in close temporal proximity on two relatively brief (15 min) occasions allowed infants to transfer their learning of the modeled actions from one stimulus to the other by 6 months of age—more than a year earlier than infants are able to transfer such learning in the absence of preexposure. By 9 months of age, when infants first exhibit evidence of SPC following sequential preexposure, increasing the number of paired presentations also extended the delay over which infants could associate successively presented stimuli. These findings are consistent with a growing body of literature indicating developmental reversals in which younger organisms exhibit exuberant learning and/or memory as compared to older developing/mature organisms (e.g.,

Chen et al., 1991; Godard, Baudouin, Schaal, & Durand, 2016; Gross, Gardiner, & Hayne, 2016).

From the perspective of Carolyn Rovee-Collier, a pioneer in the field of infant learning and memory, our findings could be interpreted within the framework of an ecological model of memory development (Rovee-Collier & Cuevas, 2009; Rovee-Collier & Giles, 2010; Spear, 1984). According to this model, "...at every point in development, organisms are perfectly adapted to meet the ecological challenges posed by their changing niche. As ecological demands change, so do their adaptive strategies and the physiological mechanisms that evolved to support them." (Rovee-Collier & Cuevas, 2009, p. 171). Thus, in terms of our findings, age-related shifts in the effective preexposure regimen for human infants may reflect changes in infants' selective attention as a function of their ecological niche. In the following sections, we discuss our findings in respects to infants' changing ecological niche and the hypothesized role of independent locomotion; we also consider co-occurring methodological factors and underlying mechanisms, such as unitization, attentional engagement, and neural circuitry.

In the present study, 6-month-olds failed to associate the puppets if they were presented immediately sequential (0-s ISI); only simultaneous preexposure was effective at producing SPC. Being unable to locomote, 6-month-olds spend most of their time observing their surround, essentially learning "*what goes with what*" (Bhatt & Rovee-Collier, 1994; Rovee-Collier, 1996). Thus, the 6-month-old's ecological niche is particularly well-suited to the simultaneous association of neutral stimuli. Spear et al. (1988) proposed that an infantile disposition for unitization might account for superior formation of simultaneous odor-odor associations in preweanling rat pups (Chen et al., 1991; Cheslock et al., 2003). In other words, young organisms "unitize" simultaneously presented stimuli by representing discriminably different stimuli as a single stimulus. We found that simultaneous preexposure was effective at all ages except 12 and 15 months; by this account, 6- and 9-month-olds unitize simultaneously presented stimuli and 12- and 15-month-olds do not. Further, the potential reappearance of simultaneous SPC at 18 months could be accounted for via an "active" associative process rather than a "passive" unitization process. It is unclear, however, whether human infants exhibit unitization.

With the onset of independent locomotion, infants successively encounter a greater number and variety of environmental stimuli as they increasingly navigate from place to place; they associate what they encounter in one context with what they encounter in the next, enabling them to learn "*what comes after what*." Our findings revealed that at 9 months, infants form associations between neutral stimuli encountered both simultaneously and sequentially. However, simultaneous SPC may not be as robust at 9 months as in younger infants; there is evidence that 6-month-olds form simultaneous associations more rapidly (Cuevas, Giles, & Rovee-Collier, 2009) and can remember them longer than 9-month-olds (Giles & Rovee-Collier, 2011). Taken together, these findings suggest that the period of exuberant learning via simultaneous SPC transitions to sequential SPC between 9 and 12 months of age. Accordingly, by 12 months of age, when infants' niche is primarily characterized by a high level of locomotor activity, they form new associations only between neutral stimuli they encounter sequentially—not simultaneously (Experiment 1). A sequential preexposure

regimen more closely mimics their ecological niche than does the simultaneous preexposure regimen.

A methodological challenge in the present study was the appropriateness of our preexposure paradigm for older, locomoting infants. With the onset of independent locomotion, infants become increasingly resistant to remaining seated in one place for an extended period of time. Thus, another factor to consider when comparing our simultaneous and sequential preexposure regimens, is that older infants may succeed in the sequential preexposure because it reengages their attention relative to the simultaneous preexposure. Moreover, although infants were not explicitly directed to look at the puppets during the preexposure phase, the puppets remained stationary for the entire simultaneous preexposure regimen whereas for the sequential preexposure regimens, the puppets were repeatedly switched. Since 15-month-old infants have just gained great mobility when they start to walk independently, they may require even more directed attention than was offered for either simultaneous or sequential preexposure regimens as none of our regimens were effective at this age. Because our preexposure phase requires infants to remain in one location for an extended period of time, it is potentially incompatible with the new walker's ecological niche. Although overall looking time measures failed to reveal either (a) differences in looking time for simultaneous and sequential preexposure groups or (b) associations between looking time and strength of SPC; more precise measures of infant attention are likely needed to investigate potential attention-SPC associations (see Richards, 2008, for review).

We chose to leave the simultaneously presented puppets stationary (i.e., without discrete trials), as we considered this preexposure regimen to have high ecological validity in terms of what infants typically encounter in the context of their daily routine. Additional research is necessary to determine whether under conditions that promote directed attention (e.g., repeatedly presenting the puppets simultaneously in discrete trials), older infants would also exhibit robust evidence of simultaneous SPC. Previous work with 12- and 18-month-olds has manipulated the way in which puppets were simultaneously exposed (Muentener, 2004). Although most procedures were ineffective, including 3 min of simultaneous preexposure to “dancing” puppets (i.e., a condition that would be predicted to promote high levels of attentional engagement); 18-month-olds exhibited a trend towards simultaneous SPC when the puppets were placed in an opaque presentation box with a transparent panel for 30 min. These findings are similar to our simultaneous SPC finding with two 15-min preexposure sessions. Perhaps a preexposure regimen that more closely mimics the 12- to 18-month-old's routine of moving among multiple locations would establish SPC more effectively with fewer individual differences. Furthermore, an eyeblink conditioning preparation might provide an optimal paradigm to examine the ontogeny of SPC; the preparation is appropriate for infants, children, and adults and permits “traditional” neutral stimuli such as tones and lights to be used (e.g., Herbert, Eckerman, & Stanton, 2003; see Woodruff-Pak & Steinmetz, 2000, for review). We hypothesize that measuring SPC within an anticipatory response system would result in different effective preexposure ISIs, though the overall developmental pattern would be the same.

Although we focus on the role of independent locomotion in promoting changes in the infant's ecological niche; it is undoubtedly one of many contributing factors (e.g., language, executive skills). Cuevas (2009) failed to find evidence that motor or verbal skills were related to SPC in a subset of 12-month-olds from Experiment 1. However, these null findings are potentially related to small sample sizes and limitations in parent-report motor and verbal skills checklist measures. Additional research is necessary to validate the primary factors that contribute to shifts in SPC and the infant's ecological niche. For instance, a more stringent examination of the role of independent locomotion in SPC would hold age constant and assess independent groups of infants at different stages of independent locomotion (e.g., crawlers vs. non-crawlers; walkers vs. non-walkers).

It is also possible that the neural circuits supporting SPC changes over development, contributing to developmental transitions in SPC. There is a growing body of literature indicating differences in the neurotransmitters and neural structures involved associative learning for preweanling and postweanling rats (e.g., Shionoya et al., 2006; see Kim & Richardson, 2010 for review). In mature organisms, lesions to the hippocampus and surrounding area (i.e., fimbria, perirhinal cortex) eliminate or reduce SPC (Nicholson & Freeman, 2000; Port, Beggs, & Patterson, 1987; Port & Patterson, 1984; Talk, Gandhi, & Matzel, 2002; but see Ward-Robinson et al., 2001); however, the neural circuitry of SPC in developing organism has yet to be examined. The extended hippocampal region (including the dentate gyrus) exhibits a protracted period of development in both rodents and primates (e.g., Bayer, 1990; Bekenstein & Lothman, 1991; Seress & Abraham, 2008), and could potentially underlie age-related shifts in SPC during infancy.

Our findings call attention to the value of varied experience for learning early in infancy. We demonstrated that early in life, infants rapidly form relatively enduring associations between stimuli or events they merely see together (i.e., without explicit reinforcement for doing so), even though those associations may not be immediately expressed. The same basic learning and memory process persists throughout infancy, but the temporal constraints on forming associations and the content of what infants learn change with age. Infants can also overcome cue-specific responding by merely observing two cues together in their surroundings (i.e., SPC). Although we presently assessed the manner in which only one association is formed, infants readily form *numerous new associations* in the same way every day. The new associations can be linked to existing associations in a complex mnemonic network, and the links are strengthened each time activation spreads through the network. This process is the mechanism by which the early knowledge base is formed and expanded, but we still have much to learn about it. Because associations are latent, and nonverbal infants may never express but a small fraction of them, it is impossible to know what they have learned and remember. Sensory preconditioning is an associative process that vastly expands the number of situations in which infants can transfer previous learning.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

Author Note

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Figure 1.
The three hand puppets that were used in both experiments (yellow duck, pink rabbit, black-and-white cow). Puppets were counterbalanced within groups.

Figure 2a-b.

The experimental arrangement used with 6- to 18-month-old infants. *(a)* Simultaneous preexposure. Shown here is a 6-month-old sitting in front of the two hand puppets (yellow duck and pink rabbit) on the wooden hat stand during SPC (Phase 1). *(b)* Sequential preexposure. Shown here is a 6-month-old sitting in front of either S_1 (pink rabbit) or S_2 (yellow duck) during SPC (Phase 1). The interval between puppet presentations varied as a function of experimental group.

Figure 3.

The mean imitation scores ($+1\ SE$) of independent groups of 6-month-old infants as a function of preexposure regimen. *Left panel:* The mean imitation scores of the experimental groups. *Right panel:* The mean imitation scores of the pairing control group. An asterisk indicates that a test group exhibited significant deferred imitation (i.e., SPC), that is, its mean imitation score was significantly higher than the mean test score of the 6-month *pooled baseline control* group (*dashed line*). The fraction above each error bar indicates the proportion of infants in each group that exhibited deferred imitation.

Figure 4.

The mean imitation scores (± 1 SE) of independent groups of 9-month-old infants as a function of preexposure regimen. *Left panel:* The mean imitation scores of the experimental groups. *Right panel:* The mean imitation scores of the pairing control groups. An asterisk indicates that a test group exhibited significant deferred imitation (i.e., SPC); its mean imitation score was significantly higher than the mean test score of the 9-month *pooled baseline control* group (*dashed line*). The fraction above each error bar indicates the proportion of infants in each group that exhibited deferred imitation.

Figure 5.

The mean imitation scores (± 1 *SE*) of independent groups of 12-month-old infants as a function of preexposure regimen. *Left panel:* The mean imitation scores of the experimental groups. *Right panel:* The mean imitation scores of the pairing control groups. An asterisk indicates that a test group exhibited significant deferred imitation (i.e., SPC); its mean imitation score was significantly higher than the mean test score of the 12-month *pooled baseline control* group (*dashed line*). The fraction above each error bar indicates the proportion of infants in each group that exhibited deferred imitation.

Figure 6.

The mean imitation scores (± 1 SE) of independent groups of 15- and 18-month-old infants as a function of preexposure regimen. *Left panel:* The mean imitation scores of the 15-month-old groups. *Right panel:* The mean imitation scores of the 18-month-old groups. An asterisk indicates that a test group exhibited significant deferred imitation (i.e., SPC); its mean imitation score was significantly higher than the mean test score of the 15- and 18-month *pooled baseline control* groups (*dashed line*). A cross mark indicates a marginally significant trend ($p < .10$). The fraction above each error bar indicates the proportion of infants in each group that exhibited deferred imitation.

Table 1.

Outline of the Preexposure Regimen Parameters for the Experimental Groups (Experiments 1 and 2).

Experimental Group	ISI	# Pairings	Session Duration	Duration of Puppet Exposure
sim/-	Simultaneous	-	15 min	15 min
0s/15	0 s *	15	15 min	15 min
7.5s/12	7.5 s	12	14.88 min	12 min
15s/10	15 s	10	14.75 min	10 min
30s/8	30 s	8	15.5 min	8 min
60s/5	60 s	5	14 min	5 min

Note. Number of paired presentations, session duration, and duration that infants are exposed to the puppets are listed per session. ISI = interstimulus interval between puppet presentations;

* = immediate successive exposure group.

Table 2.

Outline of the Preexposure Regimen Parameters for the Pairing Control Groups and Corresponding Experimental Groups (Experiment 1).

Age	Group Type	Group	ISI	# Pairings: ↑ or ↓	Session Duration	Duration of Puppet Exposure
6 months	Exp.	0s/15	0 s *	15	15 min	15 min
	Control	0s/8	0 s *	8 ↓	8 min	8 min
9 months	Exp.	0s/15	0 s *	15	15 min	15 min
	Control	0s/8	0 s *	8 ↓	8 min	8 min
	Exp.	15s/10	15 s	10	14.75 min	10 min
	Control	15s/15	15 s	15 ↑	22.25 min	15 min
	Exp.	30s/8	30 s	8	15.5 min	8 min
	Control	30s/15	30 s	15 ↑	29.5 min	15 min
12 months	Exp.	0s/15	0 s *	15	15 min	15 min
	Control	0s/8	0 s *	8 ↓	8 min	8 min
	Exp.	30s/8	30 s	8	15.5 min	8 min
	Control	30s/4	30 s	4 ↓	8 min	4 min
	Exp.	60s/5	60 s	5	14 min	5 min
	Control	60s/10	60 s	10 ↑	29 min	10 min

Note. Up and down arrows indicate if the number of paired presentations was increased or decreased compared to corresponding experimental group (bolded text). Number of paired presentations, session duration, and duration that infants are exposed to the puppets are listed per session. Exp. = experimental group; ISI = interstimulus interval between puppet presentations;

* = immediate successive exposure group.