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The Effects of Intersensory Redundancy on Attention and Memory: Infants' Long-Term Memory for Orientation in Audiovisual Events

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This research examined the effects of bimodal audiovisual and unimodal visual stimulation on infants' memory for the visual orientation of a moving toy hammer following a 5-min, 2-week, or 1-month retention interval. According to the intersensory redundancy hypothesis (L. E. Bahrick & R. Lickliter, 2000; L. E. Bahrick, R. Lickliter, & R. Flom, 2004) detection of and memory for nonredundantly specified properties, including the visual orientation of an event, are facilitated in unimodal stimulation and attenuated in bimodal stimulation in early development. Later in development, however, nonredundantly specified properties can be perceived and remembered in both multimodal and unimodal stimulation. The current study extended tests of these predictions to the domain of memory in infants of 3, 5, and 9 months of age. Consistent with predictions of the intersensory redundancy hypothesis, in unimodal stimulation, memory for visual orientation emerged by 5 months and remained stable across age, whereas in bimodal stimulation, memory did not emerge until 9 months of age. Memory for orientation was evident even after a 1-month delay and was expressed as a shifting preference, from novelty to null to familiarity, across increasing retention time, consistent with Bahrick and colleagues' four-phase model of attention. Together, these findings indicate that infant memory for nonredundantly specified properties of events is a consequence of selective attention to those event properties and is facilitated in unimodal stimulation. Memory for nonredundantly specified properties thus emerges in unimodal stimulation, is later extended to bimodal stimulation, and lasts across a period of at least 1 month.

Keywords: infant memory, infant attention, intersensory redundancy, intersensory perception

The world provides a continuous flux of dynamic multimodal stimulation, yet we attend to only a small portion of that stimulation at any given time. What we attend to, and the processes that regulate our attention, in turn provides the input and basis for what we perceive, learn, and remember (Bahrick, in press; Kahneman, 1973; Klatzky, 1984; Neisser, 1976; Posner, 1984). Attention is thus the gateway to perceptual processing, learning, and memory.

Research in developmental psychology has typically focused on the relations among perception, learning, and memory (Gibson & Pick, 2000; Hayne, 2004, 2007; Kellman & Arterberry, 1998; Oakes & Bauer, 2007; Rovee-Collier, 1997), with somewhat less emphasis being placed on the development of attention (for reviews, see Colombo, 2001; Richards, 2000; Ruff & Rothbart, 1996). Consequently, little is known about the relation between attention and memory in early development. Research with adults, in contrast, has long established a clear link between attention and memory (see Baddeley, 1986; Posner & Rothbart, 1980). So, too, has comparative research. In avian species, for example, the same factors that facilitate selective attention and perceptual learning of specific properties of events also enhance memory for those event properties (Lickliter, Bahrick, & Honeycutt, 2004). Might this tight link between attention and memory be evident for human infants as well? The present research explored this question by investigating selective attention to the visually specified property of orientation of motion and its effect on memory for this property across a period of 1 month.

Recently, Bahrick and colleagues (Bahrick & Lickliter, 2000, 2002, 2004; Bahrick, Lickliter, & Flom, 2004) proposed and found empirical support for the intersensory redundancy hypothesis (IRH), a model of how selective attention is guided to different properties of events in early development. Intersensory redundancy refers to the temporally synchronous, collocated pattern of stimulation concurrently available to more than one sense modality (Bahrick & Lickliter, 2000, 2002; Lickliter & Bahrick, 2001, 2004). According to the IRH, intersensory redundancy available in multimodal stimulation is highly salient to humans and animals, and it recruits infants' attention toward amodal, redundantly specified properties of stimulation—such as tempo, rhythm, and syn-

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chrony—to a greater extent than does unimodal stimulation. This is known as *intermodal facilitation*. In contrast, under conditions where redundancy is unavailable (e.g., unimodal auditory, unimodal visual, or asynchronous stimulation), modality-specific properties (e.g., visual pattern, color, orientation, auditory pitch and timbre) are more readily perceived and attended than in multimodal stimulation. This is known as *unimodal facilitation* and is thought to occur because intersensory redundancy cannot compete for attention (Bahrick & Lickliter, 2000, 2002, 2004; Bahrick et al., 2004).

The effects of selective attention on perception and discrimination of various properties of objects and events in early development are now well established by both human and nonhuman animal studies (for reviews, see Bahrick, in press; Bahrick & Lickliter, 2002; Lickliter & Bahrick, 2000, 2004). For example, young infants selectively attend and discriminate the tempo and rhythm (at 3 and 5 months, respectively) of a toy hammer tapping in multimodal, redundant stimulation but not in unimodal visual or unimodal auditory stimulation (Bahrick, Flom, & Lickliter, 2002; Bahrick & Lickliter, 2000). Through further experience with events, older infants can discriminate tempo and rhythm (at 5 and 8 months, respectively) in both multimodal and unimodal stimulation (Bahrick & Lickliter, 2004). In contrast, infants' attention to properties that cannot be redundantly specified and that can be conveyed through only a single sense modality (e.g., color, pattern, pitch) is initially demonstrated in unimodal stimulation and is extended later in development to multimodal contexts (Bahrick, Lickliter, & Flom, 2006). This unimodal facilitation is observed when properties such as visual pattern and configuration (e.g., facial configuration), pitch, and orientation of an object are perceptually available visually but not acoustically.

To illustrate this point, Bahrick et al. (2006) assessed the development of infants' detection and discrimination of the orientation of motion (upward vs. downward) of a toy hammer tapping a rhythm in unimodal visual versus audiovisual stimulation. Because intersensory redundancy in audiovisual stimulation promotes selective attention to the rhythm and tempo of these events at the expense of other properties (Bahrick, Flom, & Lickliter, 2002; Bahrick & Lickliter 2000), attention to the orientation of object motion should be attenuated in bimodal, redundant stimulation and facilitated in unimodal visual stimulation. Findings supported this prediction, demonstrating significant discrimination of orientation in unimodal visual but not bimodal audiovisual stimulation for younger (3-month-old) infants. Across development, however, discrimination extended to multimodal stimulation. By the age of 8 months, with increased perceptual experience and attentional flexibility, infants could discriminate orientation of motion even in bimodal, redundant stimulation, during which salient amodal properties compete for attention.

The present research extended this investigation to the domain of memory. In particular, we examined under what conditions, and for how long, infants remember the orientation of object motion in dynamic events when they are presented multimodally (audiovisually) versus unimodally (visually). Do conditions that facilitate attention to specific aspects of stimulation, such as orientation, also enhance learning and memory for those aspects of stimulation? Research with avian embryos provides support for this view. Bobwhite quail chicks showed enhanced discrimination of temporal properties of a maternal call when stimulation was multimodal (a light flashed in time with the call) as compared with unimodal auditory (Lickliter et al., 2004). This resulted in enhanced memory for the maternal call, memory that lasted at least four times longer than that following unimodal auditory stimulation. In contrast to the animal study assessing conditions that enhance attention and memory in redundant, multimodal stimulation (intermodal facilitation), the present study assessed conditions that enhance attention and memory in nonredundant, unimodal stimulation (unimodal facilitation).

In the current study, we assessed memory across retention intervals of 5 min, 2 weeks, and 1 month. The choice of these intervals was based on research generated by Bahrick and colleagues' four-phase model of attention (Bahrick, Hernandez-Reif, & Pickens, 1997; Bahrick & Pickens, 1995). This research demonstrates that visual preferences shift across retention time from novelty to null to familiarity, reflecting decreasing memory accessibility. This model was generated from visual preference paired comparison studies assessing 3- and 5-month-old infants' memory for naturalistic object motions (circular vs. horizontal swinging; Bahrick et al., 1997; Bahrick & Pickens, 1995) and women performing everyday actions (Bahrick, Gogate, & Ruiz, 2002). Given sufficient familiarization time for successful encoding, recent memories (following short delays such as 5 min or 1 day) are exhibited by a preference for the novel event, intermediate memories (e.g., delays of 1–2 weeks) are exhibited by a null preference, and long-term memories (e.g., delays of 1–3 months) are expressed by a preference for the familiar event (Bahrick, Gogate, & Ruiz, 2002; Bahrick et al., 1997; Bahrick & Pickens, 1995). Presumably, memory eventually becomes inaccessible and is again reflected by a null preference (for a review, see Hayne, 2004). Memory research from other labs has also provided converging evidence for the four-phase model of attention in both infants and adults (e.g., Barr & Hayne, 2000; Courage & Howe, 1998, 2001; Richmond, Colombo, & Hayne, 2007; Spence, 1996).

The current study assessed whether unimodal facilitation of attention predicted by the IRH would extend to long-term memory for orientation information. We predicted that younger, but not older, infants would show enhanced memory for orientation in unimodal stimulation (where there is no attentional competition from salient intersensory redundancy). Thus, young infants (3- or 5-month-olds) were expected to show evidence of memory for orientation following unimodal visual familiarization (Experiment 1) but not following bimodal, audiovisual familiarization (Experiment 2). Older infants (9-month-olds), however, were expected to show memory for orientation following both unimodal visual and bimodal audiovisual familiarization, despite attentional competition from redundancy.

Second, we assessed memory for orientation across three delays (5 min, 2 weeks, 1 month) assessing the extent to which facilitated attention would translate into enhanced short-term memory and, in turn, to enhanced long-term memory. This also provided a further test of the four-phase model of attention. It was predicted that short-term memories (5 min) would be expressed as a novelty preference, intermediate memories (2 weeks) would be expressed as a null preference, and very-long-term memories (1 month) would be expressed as a familiarity preference.

Experiment 1: Unimodal Visual Familiarization

Method

Participants. One hundred eight infants 3, 5, or 9 months of age (36 at each age) participated, and their data were included in the final analyses. The mean age of the 3-month-olds (17 girls, 19 boys) was 110 days ($SD = 2.4$). The mean age of the 5-month-olds (18 girls, 18 boys) was 156 days ($SD = 7.6$), and the mean age of the 9-month-olds (20 girls, 16 boys) was 271 days ($SD = 11.4$). Parents of the participants were initially contacted by telephone and received a certificate of appreciation following participation. Participants were recruited from Provo, Utah, and surrounding communities. Parents of the participants ranged between 21 and 43 years of age. Of the participants, 97% were White not of Hispanic origin and 2% were of Hispanic origin. All infants were full term and healthy and weighed at least 5 pounds at birth. The social economic status of the parents was not collected.

Thirty-six additional infants—fifteen 3-month-olds, ten 5-month-olds, and eleven 9-month-olds—participated, but their data were excluded from the final analyses. Eleven infants (four 3-month-olds, two 5-month-olds, and five 9-month-olds) failed to return following familiarization for the 1-month-delay memory test phase. No infants failed to return following either the 2-week or the 5-min delay. Fifteen infants (eight 3-month-olds, five 5-month-olds, and two 9-month-olds) were excluded due to excessive fussiness during the familiarization phase. No infants were excluded due to fussiness during the test phase. Two infants (one 5-month-old and one 9-month-old) were excluded due to experimenter error. Further, an attention criterion required that infants look at least 10% of the time to the least preferred display during the test trials (given the importance of infants noticing there were two video events side by side). If an infant failed to meet this criterion on either of the two test trials, that infant's data were excluded from the analyses. The data of eight infants (three 3-month-olds, two 5-month-olds, and three 9-month-olds) were rejected for failure to meet this criterion.

Stimulus events. Videotaped audiovisual events depicted a bright red toy hammer, moving up and down, striking a light-colored wooden surface in a distinctive rhythm at one of two tempos (for details, see Pickens & Bahrick, 1995, 1997). The hammer depicted movement in one of two orientations—striking upward versus downward—against a wooden surface (see Figure 1). The rhythm was irregular in structure and contained a repeating four-beat pattern with four impacts alternating with a four-beat measure of rests (XX O X X, where X represents a whole-beat impact, XX represents two half-beat impacts, and O represents a whole-beat rest). This rhythm was presented at one of two tempos (not taking into account the four-beat measures of rests), 110 beats per minute (bpm; 1.8 Hz) or 240 bpm (4 Hz). A control event was also presented and consisted of a green and white toy turtle whose arms spun, producing a clacking sound.

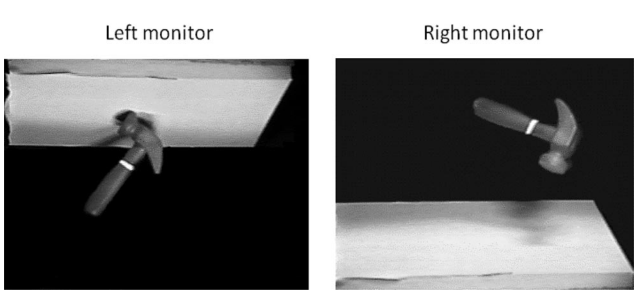

Figure 1. Static images of the dynamic events depicting the two different orientations during the test trials.

Apparatus. Infants sat in a standard infant seat facing two 19-in. (Sony KV-20M10) video monitors at a distance of approximately 55 cm. The infant seat and monitors were surrounded by black curtains. The curtains had two 7-cm apertures located toward the upper left and right corners of the video monitor that allowed observers to view the infant's visual fixations. A small toy placed between the two video monitors was used to attract the infant's visual attention toward the monitors between trials if needed. Stimulus events were videotaped with a Panasonic (WV 3170) color video camera and a Sony (EMC 105T) microphone. The events were edited with a Panasonic (VHS NV A500) edit controller that was connected to two Panasonic video decks (VTR AG 1950). The video decks were connected to two 19-in. (48-cm) color video monitors. The soundtrack was presented from a speaker located between the monitors at approximately 65 dB, as measured from the infant seat.

The observers, unaware of the hypotheses of the experiment and unable to view the visual events, depressed a button while the infant fixated on the event and released it while the infant looked away. The observers' button boxes were connected to a computer programmed to record visual fixations online. The computer signaled through a small earphone to a second experimenter, who controlled the presentation of the video displays, when to end each trial. The observations of the primary observer controlled the audiovisual presentations, and those of the secondary observer were used in the computation of interobserver reliability.

Procedure. Infants at each of the three ages were randomly assigned to one of the three retention intervals (5 min, 2 weeks, 1 month), one of two orientations (hammer striking upward or downward), and one of two familiarization tempos (110 or 240 bpm). All participants received a familiarization phase of 120 s. During familiarization the hammer was presented on one of two side-by-side monitors, and its lateral position alternated between monitors (from left to right or right to left) after 30, 60, and 90 s of familiarization. The left/right position of the hammer on the first familiarization trial was also counterbalanced across infants at each age. We chose to use a familiarization phase of 120 s, as previous studies (e.g., Bahrick et al., 1997; Bahrick & Pickens, 1995; Courage & Howe, 1998) have used similar familiarization durations and have shown that the attrition rate of younger (3-month-old) infants tends to increase when the familiarization phase is increased beyond 120 s.

Following the familiarization phase, and a delay of 5 min, 2 weeks, or 1 month, infants participated in a two-choice visual preference test. Each test phase consisted of two silent, side-by-side, 60-s trials of the hammer moving in the familiar orientation on one monitor and in the novel orientation (i.e., rotated 180°) on the other monitor (see Figure 1). The lateral positions of the novel/familiar events were switched for the second test trial, and the initial lateral positions were counterbalanced across infants at each age.

Interobserver reliability was calculated by comparing the judgments of right- and left-looking scores across two observers for 38% of the subjects (across all ages). A Pearson product–moment correlation for the primary and secondary observers' scores was .97 (SD = .02) for the familiarization phase. During the test trials the Pearson product–moment correlation was .96 (SD = .01) for the 5-min delay, .94 (SD = .03) for the 2-week delay, and .96 (SD = .07) for the 1-month delay.

Results and Discussion

A preliminary analysis of variance (ANOVA) on duration of looking during the two test trials, with gender of the infant as the main factor, revealed no significant effect ($p > .1$). Thus, subsequent analyses were collapsed across participant gender. A second ANOVA examined whether infants' overall amount of looking during the test trials differed by age (3, 5, and 9 months), tempo of familiarization (110 or 240 bpm), or the hammer's orientation during familiarization (upward or downward). Results revealed nonsignificant effects of tempo, orientation, and all interactions ($ps > .1$). Results, however, did reveal a significant effect of age, $F(2, 96) = 14.9$, $p < .01$, $\eta_p^2 = .24$. Scheffe post hoc comparisons indicate that the 3- and 5-month-olds looked longer than the 9-month-olds during the test trials ($p < .01$), and the looking of the 3- and 5-month-olds did not significantly differ ($p > .1$). This latter result is consistent with prior findings that younger infants spend more time processing or exploring stimuli than do older infants (Fagan, 1974; Hale, 1990; Rose, 1983; Rose, Feldman, & Jankowski, 2002).

To address the main research questions regarding infant memory, we expressed results in terms of the proportion of total looking time (PTLT) infants looked to the novel orientation. Proportions were derived for each trial separately by dividing the time spent looking to the novel orientation by the time spent looking at both orientations. An overall PTLT was also derived by averaging across the two trials for each infant and then averaging over all infants. Proportions above .50 reflect novelty preferences, and proportions below .50 reflect familiarity preferences.

To assess infant memory for the orientation of the moving hammer, we compared the mean PTLTs against the chance value of .50 (an equivalent proportion of time spent looking toward each display) at each age. Infants' proportions of looking to the novel and familiar orientations are presented in Figure 2.

Results indicated that the 3-month-olds failed to show a significant novelty or familiarity preference at any of the three delay intervals ($ps > .1$). Although novelty preferences at the 5-min delay are in the predicted direction (see Figure 2), they failed to reach significance. The results of the 5-month-olds, however, revealed a significant novelty preference following a 5-min delay, $t(11) = 2.2$, $p = .017$, Cohen's $d = 1.3$, no preference following a 2-week delay, $t(11) = .74$, $p > .10$, and a significant preference for the familiar orientation following a 1-month delay, $t(11) = 3.1$, $p = .01$, $d = 1.9$. The results of the 9-month-olds mirror those of the 5-month-olds. Nine-month-olds showed a novelty preference after the 5-min delay, $t(11) = 7.3$, $p < .001$, $d = 4.4$, no preference after the 2-week delay, $t(11) = 1.2$, $p > .10$, and a familiarity preference after the 1-month delay, $t(11) = 5.4$, $p < .001$, $d = 3.3$.

These results indicate that following silent visual familiarization (i.e., unimodal visual) to a moving hammer, 5- and 9-month-olds showed evidence of memory for the orientation of motion by a shifting preference (from novelty to null to familiarity) across retention time, whereas 3-month olds showed no evidence of memory. The 5- and 9-month-olds demonstrated memory across a period of 1 month for a nonredundantly specified property (orientation of motion) in the context of unimodal stimulation. Further,

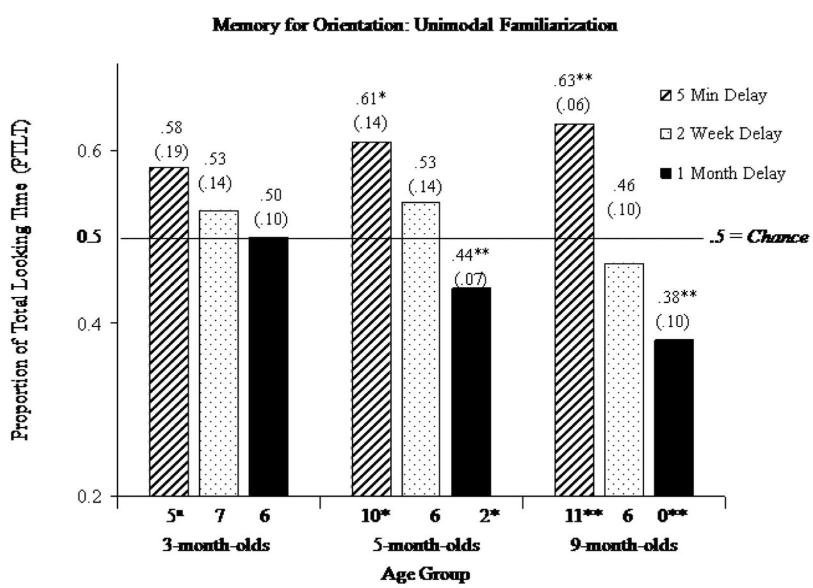

Figure 2. Experiment 1, unimodal stimulation: Mean proportion of total looking time (and standard deviation) to the novel visual orientation across retention intervals of 5 min, 2 weeks, and 1 month as a function of age. Values below bars represent number of subjects (out of 12) who showed a preference for the novel orientation. Asterisks indicate significance according to a nonparametric binomial test. * $p < .05$. ** $p < .01$.

the direction of preference as a function of retention time (novelty for short retention intervals and familiarity for long retention intervals) is consistent with prior research findings and predictions of the four-phase attention model (Bahrick et al., 1997; Bahrick & Pickens, 1995), according to which recent, highly accessible memories are expressed as a novelty preference and remote, less accessible memories are expressed as a familiarity preference.

The data were examined at the individual subject level to determine if the results were carried by a few infants with strong preferences. We examined the number of participants who exhibited a preference for the novel orientation (PTLT greater than 50%) at each age and delay using a nonparametric binomial test (see Figure 2). It was predicted that a high number of infants would show a preference for the novel orientation for the short (5-min) retention interval, whereas a low number of infants would show novelty preferences for the long (1-month) retention interval. Results at the individual subject level conformed to our predictions and converge with those of the group data. Together, the individual and group analyses of infant memory for orientation of motion parallel those found by Bahrick et al. (2006) for discrimination of this information in unimodal visual conditions.

We also analyzed whether infants differed across age in their memory for orientation. At the 5-min and 2-week delay conditions, infants' looking behavior did not differ, $F(2, 33) = 0.36$, $p > .1$, and $F(2, 33) = 1.16$, $p > .1$, respectively. At the 1-month delay condition, however, 5- and 9-month-olds' familiarity preferences reliably differed from those of the 3-month-olds, $F(2, 33) = 6.78$ $p = .003$, $\eta_p^2 = .29$. The fact that we did not see an age effect following a 5-min delay and that 3-month-olds showed relatively high but nonsignificant novelty preferences ($M = .58$, $SD = .19$, $p = .17$) suggests that the 3-month-olds may be in transition toward a novelty preference reflecting short-term memory.

Experiment 2 was conducted to test the prediction of the IRH that perception and memory for modality specific and nonredundantly specified properties is attenuated under conditions of bimodal stimulation, where redundancy competes for attention. Intersensory redundancy focuses attention on amodal properties at the expense of modality-specific properties of stimulation. Moreover, this attentional trade-off was expected to be most pronounced for younger infants, whose attention is less flexible and efficient and for whom cognitive load and task difficulty are high (Bahrick, in press; Bahrick, Lickliter, Castellanos, & Vaillant-Molina, in press). Experiment 2 thus examined the effects of bimodal stimulation on infant memory for visual orientation and compared them with the effects of unimodal stimulation from Experiment 1. It was predicted that in bimodal stimulation younger infants (3- and 5-month-olds) would show no evidence of memory for orientation, whereas older infants (9-month-olds), who can attend to both more salient and less salient properties of stimulation, would show evidence of memory.

Experiment 2: Bimodal Familiarization

Method

Participants. One hundred eight infants 3, 5, or 9 months of age (36 at each age) participated, and their data were included in the final analyses. The mean age of the 3-month-olds (16 girls and 20 boys) was 112 days ($SD = 1.7$). The mean age of the 5-month-olds (19 girls and 17 boys) was 154 days ($SD = 2.3$), and the mean age of the 9-month-olds (18 girls and 18 boys) was 268 days ($SD = 4.2$). Recruitment and inclusion criteria were identical to those of Experiment 1. Of the participants, 99% were White not of Hispanic origin and 1% were of Hispanic origin.

Twenty-eight additional infants participated (ten 3-month-olds, eleven 5-month-olds, and seven 9-month-olds), but their data were excluded from the final analyses. Thirteen infants (nine 3-month-olds, three 5-month-olds, and one 9-month-old) were excluded due to excessive fussiness during the familiarization phase. Two 9-month-olds were excluded due to fussiness during the test phase. Three infants (one 3-month-old, one 5-month-old, and one 9-month-old) were excluded due to experimenter error. Eight infants (five 5-month-olds and three 9-month-olds) were excluded for failure to return following the 1-month delay between the familiarization and test phases of the experiment. Finally, two 5-month-olds were excluded for looking less than 10% to the least preferred display during one of the test trials.

Apparatus and procedure. Experiment 2 was identical in all respects to Experiment 1 with the exception that the events were audible during the 120-s familiarization phase. That is, infants heard the impact sounds produced by the hammer as it struck the wooden surface. The test trials, however, were identical to those of Experiment 1 and were presented silently, allowing for a direct comparison of results between Experiments 1 and 2. Prior research with these events has demonstrated that 5-month-old infants show robust generalization from audiovisual familiarization/habituation to visual-only test trials (Bahrick & Lickliter, 2000).

Reliability in Experiment 2 was again calculated by comparing the judgments of right- and left-looking scores across two observers for 34% of the participants (across all ages). A Pearson product–moment correlation for the primary and secondary observers' scores was .98 ($SD = .03$) for the familiarization phase. During the test trials the Pearson product–moment correlation was .97 ($SD = .02$) for the 5-min delay, .95 ($SD = .04$) for the 2-week delay, and .92 ($SD = .06$) for the 1-month delay condition.

Results and Discussion

A preliminary ANOVA with gender of the infant as the main factor was performed on the duration of infant looking during the two test trials. This analysis did not reach statistical significance ($p > .1$); thus, subsequent analyses were collapsed across participant gender. A second ANOVA examined whether infants' overall amount of looking during the test trials differed by age (3, 5, and 9 months), tempo of familiarization (110 or 240 bpm), or the hammer's orientation during familiarization (upward or downward). Results of Experiment 2 paralleled those of Experiment 1 by revealing a significant effect of age, $F(2, 96) = 23.99$, $p < .01$, $\eta_p^2 = .33$. Scheffe post hoc comparisons indicate that the 3- and 5-month-olds looked longer than the 9-month-olds during the test trials ($p < .01$), and the looking of the 3- and 5-month-olds did not significantly differ ($p > .01$).

In order to assess infant memory for the orientation of the moving hammer, we again compared the mean PTLTs to the novel orientation against the chance value of .50 at each age (see Figure 3). Results indicate that the 3- and the 5-month-olds failed to show a significant novelty or familiarity preference at any of the three delay conditions ($ps > .1$). The 9-month-olds, however,

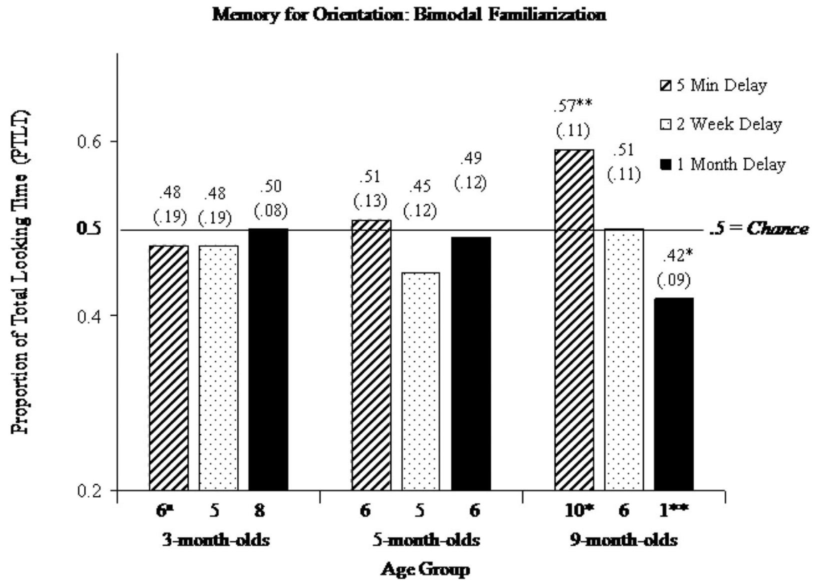

Figure 3. Experiment 2, bimodal stimulation: Mean proportion of total looking time (and standard deviation) to the novel visual orientation across retention intervals of 5 min, 2 weeks, and 1 month as a function of age. Values below bars represent number of subjects (out of 12) who showed a preference for the novel orientation. Asterisks indicate significance according to a nonparametric binomial test. $^{*} p < .05$. $^{**} p < .01$.

revealed a significant novelty preference following a 5-min delay, $t(11) = 3.9$, $p = .003$, $d = 2.3$, no preference following a 2-week delay, $t(11) = .20$, $p > .10$, and a significant preference for the familiar orientation following a 1-month delay, $t(11) = 3.0$, $p = .012$, $d = 1.8$, with the direction of preferences conforming to the four-phase model of attention (Bahrick et al., 1997; Bahrick & Pickens, 1995). Together, these findings indicate that following bimodal familiarization to a moving hammer, only the 9-month-olds showed memory for the visually specified property of orientation. Memory was evident at both the short and long retention intervals.

We also analyzed whether novelty/familiarity preferences differed across age at each retention interval. In the 5-min delay condition, 3- and 5-month-olds' looking did not differ significantly (*p*s >.1), but PTLTs of the 9-month-olds differed from those of the 3-and 5-month-olds, $F(2, 33) = 4.7$, $p = .03$, $\eta_p^2 = .19$. In the 2-week delay condition, infants' looking behavior did not differ across age, $F(2, 33) = 1.33$, $p > .1$. In the 1-month delay condition, again, 3- and 5-month-olds' looking did not differ significantly (*p*s >.1), but PTLTs of the 9-month-olds differed from those of the 3- and 5-month-olds, $F(2, 33) = 4.21$, $p = .04$, $\eta_p^2 = .16$.

Comparison across Experiments 1 and 2. Further analyses were conducted to compare memory for visual orientation when infants were provided unimodal (Experiment 1) versus bimodal (Experiment 2) familiarization. If memory for nonredundantly specified properties emerges first in the context of unimodal stimulation and is later extended to bimodal stimulation, one would expect younger infants (5 months) to show greater memory when provided unimodal stimulation (Experiment 1) compared to bimodal stimulation (Experiment 2) and older infants (9-month-olds) to show little difference in memory across conditions of bimodal and unimodal stimulation. To test this hypothesis, we predicted a significant interaction between delay condition and type of stimulation in a comparison of 5- and 9-month-olds' PTLT to the novel orientation in the 5-min and 1-month delay conditions. Because 3-month-olds failed to show a reliable preference at any delay and 5- and 9-month-olds showed no significant preference at the 2-week delay in either experiment, these groups were not included in the analyses.

Infants' PTLTs to the novel orientation were evaluated in an AVOVA, with type of stimulation (unimodal, bimodal), age (5 months, 9 months), and delay (5 min, 1 month) as between-subjects factors. The main effects of type of stimulation and age did not reach significance (*p*s > .1). Not surprisingly, results did indicate a significant effect of delay, $F(1, 88) = 49.3$, $p < .001$, $\eta_p^2 = .36$. That is, across age and condition, infants showed greater PTLTs to the novel orientation ($M = 0.58$, $SD = 0.09$) following the 5-min delay and smaller PTLTs to the novel orientation (i.e., familiarity preferences; $M = 0.43$, $SD = 0.08$) following the 1-month delay. Results also revealed the predicted interaction between type of stimulation and delay condition, $F(1, 88) = 9.7$, $p = .002$, $\eta_p^2 = .10$. After the 5-min delay, PTLTs were greater for the unimodal condition than the bimodal condition (indicating novelty preferences), whereas after the 1-month delay PTLTs were smaller in the unimodal condition than the bimodal condition (indicating familiarity preferences). These findings are consistent with our predictions and those of the four-phase attention model (Bahrick et al., 1997; Bahrick & Pickens, 1995) regarding the direction of visual preferences as a function of retention time.

Central to predictions of the IRH, results also revealed a significant interaction between age and delay condition, $F(1, 88) = 6.5$, $p = .012$, $\eta_p^2 = .07$. Analyses of simple effects demonstrated that, at the 5-min delay, 5-month-olds' PTLTs to the novel orientation were significantly greater in the unimodal condition ($M = .61$, $SD = .14$) than the bimodal condition ($M = .51$, $SD = .13$),

$t(22) = 2.97$, $p = .02$, $d = 1.6$ (indicating a greater novelty preference). In contrast, at the 1-month-delay, 5-month-olds' PTLTs to the novel orientation were significantly smaller in the unimodal condition ($M = .44$, $SD = .07$) than the bimodal condition, indicating a greater familiarity preference ($M = .49$, $SD = .12$), $t(22) = 2.07$, $p = .048$, $d = 0.47$. Thus, 5-month-olds showed greater recent memory (indexed by a novelty preference) and greater remote memory (indexed by a familiarity preference) following unimodal visual familiarization than following bimodal, audiovisual familiarization. However, consistent with our predictions of developmental improvements in memory for orientation in bimodal stimulation, 9-month-olds showed no difference as a function of type of stimulation in their novelty preferences at the 5-min delay nor in their familiarity preferences at the 1-month delay (ps $>.1$). That is, they showed significant memory for orientation regardless of whether they were familiarized with bimodal redundant or unimodal nonredundant stimulation.

These findings, which are consistent with predictions of the intersensory redundancy hypothesis (Bahrick & Lickliter, 2000; Bahrick et al., 2004) and extend to the domain of memory, have previously been demonstrated for perception (Bahrick et al., 2006). That is, in early development, unimodal stimulation enhances perception and memory for nonredundantly specified, modality-specific properties, such as visual orientation. With increasing age and experience, attention and memory become more flexible and efficient, and infants are able to perceive and remember nonredundantly specified properties under conditions of both unimodal and bimodal stimulation.

General Discussion

The present study examined the memory of 3-, 5-, and 9-month-olds for the visual orientation of a moving object when provided either unimodal visual stimulation (Experiment 1) or bimodal audiovisual stimulation (Experiment 2) followed by a short (5-min), intermediate (2-week), or long (1-month) retention interval. Results indicate that following unimodal visual familiarization, 5- and 9-month-old infants (but not 3-month-olds) demonstrated memory for orientation by a novelty preference after the 5-min delay, a null preference after the 1-week delay, and a familiarity preference after the 1-month delay. In contrast, following bimodal audiovisual familiarization, only the 9-month-olds showed memory, again with a novelty preference (5-min delay), a null preference (1-week delay), and a familiarity preference (1-month-delay). Consistent with predictions of the IRH (Bahrick & Lickliter, 2000, 2002; Bahrick et al., 2004), these results demonstrate that at 5 months of age, memory for nonredundantly specified properties, such as orientation, is facilitated in unimodal as compared with bimodal stimulation, whereas by 9 months of age, infants can remember nonredundantly specified properties in both unimodal and bimodal stimulation. These results also demonstrate that infant memory is expressed as a shifting preference, from novelty to null to familiarity, across retention time, consistent with predictions of the four-phase model of attention (Bahrick et al., 1997; Bahrick & Pickens, 1995). Memory for orientation emerges in unimodal stimulation (by 5 months of age) and is later extended to bimodal stimulation (by 9 months of age). It lasts across a period of at least 1 month in 5- and 9-month-old infants, and long-term memory is indexed by a familiarity preference.

These results provide the first extension of the IRH from selective attention and perceptual processing to the domain of memory for human infants (Bahrick et al., 2006) and converge with findings for nonhuman animals (Lickliter et al., 2004). Together, they demonstrate a tight link between attention, perceptual processing, and memory. Both attention and memory for nonredundantly specified properties (e.g., orientation of motion) are promoted in the context of unimodal stimulation and attenuated in bimodal stimulation. In the latter case, there is competition from intersensory redundancy, which directs attention to salient amodal properties such as rhythm, tempo, and synchrony (see Bahrick, Flom & Lickliter, 2002; Bahrick & Lickliter, 2000, 2002). Further, infants show developmental improvements in memory for nonredundantly specified properties of events that parallel the improvements found for attention in our prior study (Bahrick et al., 2006). Thus, as efficiency and flexibility of attention improve with age and experience, older infants can detect and remember nonredundantly specified properties even in the context of competition from intersensory redundancy.

Although the present results showed no evidence of memory for orientation at 3 months of age, 3-month-olds did show a nonsignificant preference ($M = .58$) in the direction of novelty, following the 5-min retention interval of Experiment 1 (unimodal visual familiarization). One possibility is that 120 s of familiarization was not sufficient for 3-month-olds to show memory for orientation. Indeed, Bahrick et al. (2006) reported that 3-month-olds discriminated the two orientations in these same events following habituation (an average of 200 s processing time). It is also possible that the 5-month-olds, when provided a longer period of bimodal familiarization in Experiment 2, would also show memory for orientation. Longer familiarization time enhances perceptual processing and, in turn, learning and memory (e.g., Bahrick, Gogate, & Ruiz, 2002; Bahrick & Newell, 2008; Courage & Howe, 2001; Hayne, 2007; Rose, Feldman, & Jankowski, 2007).

Together with our prior findings demonstrating the powerful effects of intersensory redundancy on perception and learning (see Bahrick, in press; Bahrick & Lickliter, 2002), the present findings of unimodal facilitation of memory indicate that not all properties of events are attended, processed, and learned equally well. The environment typically provides more stimulation than can be attended at any given moment, and thus attention must be selective and economical (for discussion, see Bahrick, in press; Gibson, 1969). Thus, more salient information is attended, perceived, and remembered, at the expense of less salient information. In unimodal stimulation, nonredundantly specified properties of events are more salient, promoting attention, perception, and memory for those properties. In multimodal stimulation, redundantly specified amodal properties are more salient, promoting attention, learning, and memory for those properties. This attentional trade-off is most evident when perceivers are young, cognitive load is high, or tasks are difficult in relation to skills of the perceiver (e.g., learning new material; see Bahrick, Lickliter, et al., in press). This attentional trade-off also has important implications for facilitating learning in applied settings. It suggests that material to be learned should be appropriately matched with the learning context (unimodal vs. multimodal) to best promote learning and memory for the specific properties of stimulation.

Finally, until recently most research examining infant perceptual and cognitive development was conducted from a "unimodal" perspective. That is, studies of visual perception were conducted separately from those on auditory perception even on similar content (e.g., face processing and voice processing have typically been studied independently; see, e.g., Bremner & Fogel, 2001; Haith & Benson, 1998). Studies of multimodal perception then emerged as a distinct area of research and consequently are not yet well integrated with studies of unimodal perception. The intersensory redundancy hypothesis provides a basis for integrating the study of unimodal and multimodal perception and the study of attention and perception with that of learning and memory development. Our prior research (e.g., Bahrick, in press; Bahrick & Lickliter, 2000; Bahrick, Lickliter, & Flom, 2004; Flom & Bahrick, 2007) and the findings reported here provide initial steps toward these important goals.

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