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Generalization of Learning in Three-and-a-Half-Month-Old Infants on the Basis of Amodal Relations

Lorraine E. Bahrick

Infants of 3.5 months ($N = 124$) were given the opportunity to learn to relate two objects and their natural, distinctive sounds during a training phase. The objects and sounds were united by temporal synchrony and amodal audiovisual information specifying object composition. Infants then participated in one of three types of transfer tests (requiring low, moderate, or high degrees of generalization) to measure the extent to which intermodal knowledge generalized to a new task and across events (familiar events; change in color/shape; change in substance, motion, and color/shape). Results indicated that infants tested with the familiar events and with events of a new color/shape showed learning and transfer of knowledge. In contrast, infants tested with events of a new substance, motion, and color/shape showed no generalization of learning. Thus, infants of 3.5 months appear to show a moderate degree of generalization of intermodal knowledge across events. Although this knowledge is not restricted to the events of original learning, it cannot yet be flexibly extended across a variety of contexts.

INTRODUCTION

Research indicates that detection of amodal information is one of the earliest and most important bases for perceptual development and learning (Bahrick 1992, 1994, 2001; Bahrick & Lickliter, 2000; Gibson & Pick, 2000; Lewkowicz, 2000; Lewkowicz & Lickliter, 1994; Walker-Andrews, 1997). Sensitivity to the temporal and spatial parameters of stimulation allows infants to abstract order from the dynamic flux of visual, acoustic, proprioceptive, and tactile stimulation of everyday experience. Infants must somehow parse this dynamic multimodal gestalt into meaningful events. The detection of amodal relations such as temporal synchrony, rhythm, and tempo common to sights and sounds enables infants to determine which patterns of auditory and visual stimulation belong together and constitute unitary events and which are unrelated (Bahrick, 2001; Bahrick & Pickens, 1994). Amodal auditory–visual relations serve as the basis for perceiving and learning about the substance and composition of objects (Bahrick, 1987, 1988, 1992), their changing distance (Pickens, 1994; Walker-Andrews & Lennon, 1985), the affect conveyed in faces and voices (Walker, 1982; Walker-Andrews, 1986, 1997), the gender and age of a speaker (Bahrick, Netto, & Hernandez-Reif, 1998; Walker-Andrews, Bahrick, Raglioni, & Diaz, 1991), and the relation between speech sounds and the objects they refer to (Gogate & Bahrick, 1998; Gogate, Bahrick, & Watson, 2000). Detection of amodal relations has been found to emerge developmentally prior to detection of arbitrary intersensory relations (Bahrick, 1992, 1994, 2001), and amodal relations have been found to serve as the basis for and can guide and constrain learning about other embedded, more specific relations (Bahrick, 2001; Gogate & Bahrick, 1998; Gogate et al., 2000; Hernandez-Reif & Bahrick, 2001). For example, synchronizing the motion of an object with its verbal label facilitates learning of the arbitrary relation between the object and label (Gogate & Bahrick, 1998). Thus, amodal relations are detected early in infancy and can serve as the basis for perceiving a diverse array of meaningful properties of events.

Despite the importance of detecting amodal relations for organizing, constraining, and promoting perceptual and cognitive development, less research has investigated the nature of intermodal learning (but, for examples, see Adolph, 1997; Bahrick, 1988; Eppler, 1995; Gogate et al., 2000; Morrongiello, Fenwick, & Nutley, 1998; Thelen, 2000; Thelen & Smith, 1994), and virtually no research has investigated the nature of generalization and transfer of training on the basis of amodal relations. The generalization of knowledge across domains, however, is a foundation for cognitive development. Once information is detected in one domain, it must be extended to other appropriate domains, events, and contexts and, of equal importance, it must not be extended to inappropriate domains, events, or contexts. What rules govern this process of generalization and how do they change developmentally and as a function of the nature of the information detected?

Some researchers (e.g., Brown, 1982: Brown & Campione, 1981; Flavell, 1963; Piaget, 1954; Rozin, 1976) have suggested that knowledge in young chil-

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dren is at first tied to the original learning context and only later becomes flexibly extended across domains. Flexible extension of knowledge is thought to be the hallmark of intelligent functioning (Rozin, 1976). How does the foundation for the flexible extension of knowledge emerge in infancy? Research in a number of domains suggests that the knowledge of young infants is not tightly tied to the learning context. Rather, infants develop generalized expectancies and show generalization of rules to new domains. For example, young infants categorize objects and events on the basis of similarity and can generalize to new exemplars of the category and discriminate those exemplars from members of other categories (Bahrick & Pickens, 1988; Hayne, 1996; Hayne, Rovee-Collier, & Perris, 1987; Kuhl, 1985; Mandler, 2000; Quinn & Eimas, 1996). Some researchers argue that categorization and concept formation may progress developmentally from global to more specific or basic levels (Mandler, 2000; Mandler & McDonough, 1983; Quinn & Johnson, 2000). Research on speech perception suggests that young infants can abstract statistical regularities in continuous speech that specify word boundaries and word structure. They can do this based on learning during a short exposure even with a new "language" (Aslin, Saffran, & Newport, 1998; Saffran, Aslin, & Newport, 1996), and can generalize a familiar structure to novel words (Marcus, Vijayan, Bandi Rao, & Vishton, 1999), implying implicit rule learning and generalization across speech sounds. Further, research in the area of object perception also suggests that infants form generalized expectations about the physical laws governing objects, their changes in locations, and their behaviors; and that when those expectations are violated, infants respond with increased interest (Baillargeon, 1987; Baillargeon, Spelke, & Wasserman, 1985; for a review, see Baillargeon, 1995). Little research, however, has directly investigated the nature and development of generalization and transfer of training in infancy.

One exception has been research using the mobile conjugate reinforcement paradigm (e.g., Fagen & Rovee-Collier, 1983; for reviews, see Rovee-Collier & Hayne, 1987; Rovee-Collier, Hayne, & Colombo, 2001). In this method, infants are typically trained, in two sessions, to cause a mobile to move by kicking their leg. Memory for a variety of factors, including the nature of the training mobile and its context, is assessed following a delay by examining the level of the operant response. In these studies, infants typically show generalized responding to similar mobiles in similar contexts. Given that infants appear to delight in causing the crib mobile to move, however, it is somewhat surprising that responding is not broadly generalized to a wide variety of mobiles and contexts. In fact, transfer of the operant response appears to be remarkably specific in early infancy and relatively tied to the training mobile and its original learning context (Butler & Rovee-Collier, 1989; Hayne & Rovee-Collier, 1995; Hayne et al., 1987). For example, using a novel mobile or changing only two elements of the five-element mobile can completely disrupt memory (Hayne & Findlay, 1995; Hayne, Greco, Earley, Griesler, & Rovee-Collier, 1986; Rovee-Collier, Patterson, & Hayne, 1985), and training in the context of one distinctive crib liner and testing in the context of another can also disrupt responding (Borovsky & Rovee-Collier, 1990; Rovee-Collier, Griesler, & Earley, 1985). Variable training, however, in which infants are trained with different mobiles or different contexts, has been found to facilitate generalization and transfer of training to new mobiles or contexts (Greco, Hayne, & Rovee-Collier, 1990; Hayne et al., 1987; Shields & Rovee-Collier, 1992). Further, memory retrieval appears to become more flexible with age, such that a wider array of stimuli can serve as effective reminders (Hartshorn et al., 1998; Hayne, MacDonald, & Barr, 1997; Timmons, 1994), and specific details are apparently forgotten prior to more general aspects over time (Hayne & Rovee-Collier, 1995; Rovee-Collier & Sullivan, 1980). In one study (Timmons, 1994), 6-month-olds learned two operant tasks (a leg kick that activated a mobile and an arm pull that activated a music box). Although memory for the response–reinforcer pairing remained specific and distinct, transfer of a general rule (a response activates an object) was evident because each object effectively served as a retrieval cue for either task. Taken together, these findings provide a rich source of information about the nature of learning and generalization of an operant response in the context of a unique paradigm, and suggest that learning is relatively context and event specific, at least in early infancy. The extent to which these findings generalize to other domains and paradigms is not known, nor is the developmental picture clear (but see Hayne et al., 1997; Herbert & Hayne, 2000). Is knowledge in infancy initially tied to the context in which it is learned and only later flexibly extended, or is knowledge more global and easily generalized at first and then becomes more specific with experience (Bahrick, 2001; Gibson, 1969; Mandler, 2000; Mandler & McDonough, 1993; Quinn & Johnson, 2000)? The findings of research using the mobile conjugate reinforcement paradigm appear most consistent with the view that knowledge is initially specific and tied to the learning context, and through development becomes more flexibly extended. These findings appear to contrast with those of generalized expectancies and generalization of rules in areas such as categorization and speech perception discussed above.

In the domain of intersensory development, virtually nothing is known about these important questions. Once infants detect amodal regularities across visual and acoustic stimulation, when, to what extent, and under what conditions do they generalize this knowledge to new events and contexts? For example, how and when do infants generalize knowledge of invariant audiovisual relations specifying age, gender, or affect of speaker; object composition; substance; or number to new events? In one study (Bahrick, 1992), we investigated 3-month-old infants' ability to detect amodal temporal synchrony and amodal temporal microstructure that specified object composition and united the sights and sounds of objects impacting a surface. The infants were habituated to two objects—a single object and a cluster of smaller objects (compound object)—that were struck against a surface to produce natural impact sounds. During subsequent test trials, infants showed visual recovery to a change in synchrony and to a change in the pairing of the sound and object. Apparently they were able to detect the temporal synchrony and the temporal microstructure that specified the object composition; that is, whether it was a single or a compound object. Infants did this by detecting the temporal information common to the sights and sounds of the object's impact (see Bahrick 1988, 1992, 2001). Single objects produce impact sounds and trajectory changes that are single, discrete, and rapid, whereas compound objects produce impact sounds and trajectory changes that are more complex, prolonged, and have a more gradual onset. This temporal microstructure specifies the composition of the object and becomes an especially salient aspect of stimulation for infants by 3 months of age (Bahrick, 2001). In fact, 3-month-olds learn to match films and soundtracks of objects striking a surface on the basis of synchrony and temporal microstructure, and fail to show this intermodal learning when temporal microstructure is incongruent, even when the sights and sounds are synchronous (Bahrick, 1988). The present research extended this prior work by exploring the nature and extent of generalization of learning about these properties of events. Once infants learn to detect the audiovisual temporal microstructure in one event context, to what extent does this intermodal knowledge generalize to other similar events? Once infants learn that a single object produces a single, discrete impact sound and a compound object produces a complex, prolonged impact sound, to what extent does this knowledge generalize to new objects and contexts? Do infants perceive these temporal relations across a variety of events and domains, or is this intermodal knowledge at first bound to the context in which it was originally detected?

To begin to explore these questions, 3.5-month-old infants were given the opportunity, during a habituation procedure, to learn to relate a single object with its impact sound, and a compound object with its natural distinctive impact sound. Our goal was to examine whether infants who had abstracted the temporal synchrony and information that specified object composition during the training could use this information in a test phase to match films with their appropriate soundtracks and could generalize to novel events. To address these issues, infants participated in one of three types of generalization tests in a two-screen, intermodal preference procedure. The tests required low, moderate, or high degrees of generalization from the events of training. In the low-generalization condition, the test events were identical and only the test format differed from that of training. In the moderate-generalization condition, the test events were of a novel color and shape; and in the high-generalization condition, the test events were of a novel substance, motion, and color and shape. Age-matched control infants received habituation with irrelevant events and showed no evidence of matching the appropriate films and soundtracks. Because of this and because prior research with the same test method has shown that 3-month-olds showed no evidence of matching films and soundtracks on the basis of temporal synchrony and microstructure without prior training (Bahrick, 1988), any evidence of intermodal matching and generalization was considered primarily a result of learning during the habituation/training session rather than a result of prior knowledge.

METHOD

Participants. One hundred twenty-four infants (62 males, 62 females), 3.5 months of age ($M = 112.7$ days, $SD = 7.06$) participated in the study. Thirty-eight additional infants participated, but their data were not included because of experimenter error ($n = 4$), equipment failure ($n = 1$), excessive fussiness ($n = 20$), falling asleep ($n = 4$), failure to habituate ($n = 3$), or failure to meet the attention ($n = 1$) or habituation criteria ($n = 5$; see Procedure section for details). The infants were all healthy with no known complications of delivery, and had Apgar scores of 9 or above. The infants came from primarily middle-class families with parents who each had at least 12 years of education. Approximately 44% were White, 46% were Hispanic, 3% were Black, 2% were Asian, and 5% were of other ethnicities.

Stimulus events. The stimulus events were color video films of four pairs of audiovisual events (see Figure 1) that had been used in prior studies (Bahrick, 1992, 1994). Each pair of events depicted two types of objects: one composed of a single, solid element (single object) and the other composed of a cluster of smaller elements (compound object). All objects were shown striking against a surface in an erratic temporal pattern along with their natural impact sounds. Each single object produced a single, abrupt impact sound and a correspondingly abrupt trajectory change, whereas each compound object produced a slightly more prolonged, complex impact sound and a correspondingly complex trajectory change. The single and compound objects within a pair were of the same color and shape. Event pairs differed from one another, however, in terms of color and shape; or in terms of color, shape, substance (metal versus plastic), and type of motion (dropping versus striking). For example, one event set depicted metal objects suspended from a string, dropping against a surface in an erratic pattern. One of these pairs consisted of a large, orange, hexagonal nut and a group of small, orange, hexagonal nuts. The other pair differed from it only in terms of color and shape, and consisted of a large, yellow washer and a group of small, yellow washers. Previous research (Bahrick, 1992, Experiment 3) has shown that infants of 3.5 months are able to discriminate all the moving objects used in the present study on the basis of changes in color and shape, in procedures identical to those used here. In the present study, transfer of learning across events within a set that differed in terms of color and shape was considered to reflect a "moderate" degree of generalization. The other event set depicted plastic objects held from behind. The objects were struck against two surfaces in an erratic back-and-forth pattern. These events differed from those of the metal objects in terms of the type of motion and substance, as well as the color and shape of the objects. Transfer of learning across events from different sets was considered to reflect a "high" degree of generalization.

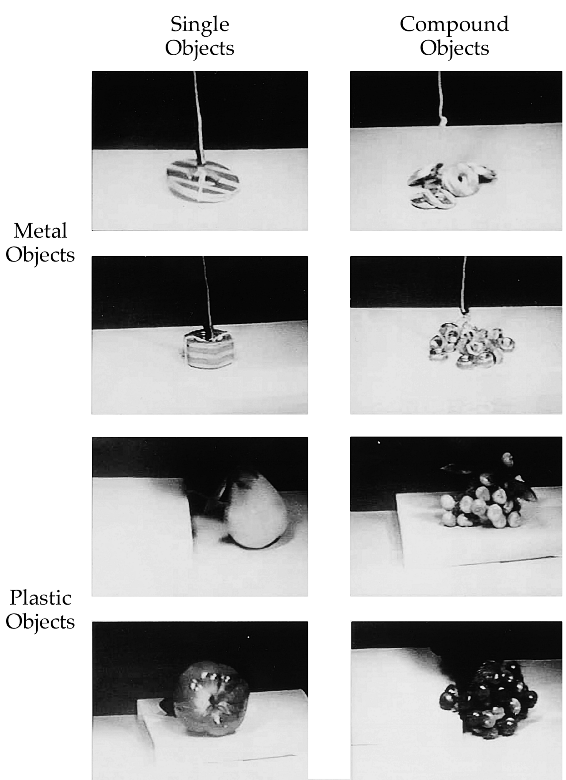

Figure 1 Photograph of the single and compound event pairs used. (Reprinted with permission from Bahrick, 1992.)

All events depicted objects striking against a surface in an erratic temporal pattern at an average rate of approximately 40 impacts per minute. Each pair of events made two types of amodal temporal structure available: temporal synchrony across impacts and temporal microstructure that specified the composition of the object (single versus compound). In addition to the primary stimulus events, a control stimulus was also used. It depicted a green and white plastic toy turtle, whose front legs spun and produced a whirring sound.

Apparatus. Events were videotaped using a Panasonic WV 3170 color camera and a Sony EMC-150T remote microphone (see Bahrick, 1992). They were presented using a Panasonic VHS AGA750 edit controller connected to three Panasonic decks (AG-7750 and AG-6500). By using three decks, displays could be changed without the time and noise resulting from changing cassettes across decks.

Infants were seated in a standard infant seat with two 19-inch (48 cm) video monitors (Sony KV-20M10) about 55 cm away. A set of bells was hung between the two monitors to direct infant attention to between the two screens during the test procedure. The video monitors were surrounded by black curtains and poster board. Three apertures—one to the upper right, one in the center, and one to the upper left of the monitors—allowed observers to view the infants' visual fixations to the displays. The soundtracks were played at about 65 dB and emanated from a speaker centered between and just beneath the two displays.

For conditions in which asynchronous sounds were presented, the natural soundtracks had been dubbed onto the video films so that they were out of phase with the motions of the objects and were unsystematically related to them. Inappropriate and synchronous soundtracks for each event were also used. They had been created by filming one event through the window of a soundproof box while recording the sounds of the other, simultaneously occurring event (see Bahrick, 1992).

A trained observer, unaware of the infant's condition, monitored the visual fixations to the displays by using a set of buttons connected to a personal computer in an adjacent room. During the habituation/training phase, the observer depressed a button while the infant fixated the video image. The computer was programmed to signal to the experimenter who controlled the video displays each time the infant looked away for 1.5 s, and after the infant reached the habituation criterion. During the two-screen test sequence, the observer depressed one button while the infant fixated the left-hand screen and another button while the infant fixated the right-hand screen. For the two-screen test and the habituation phases, a permanent record of the infant's visual fixation pattern was recorded on line.

Procedure. Infants were randomly assigned to one of three generalization conditions (low, moderate, or high; $n = 36$ in each condition), or to a control group ($n = 16$). All infants except the controls were first trained in an infant-controlled habituation procedure (Horowitz, Paden, Bhana, & Self, 1972) with a given pair of events depicting a single and a compound object. The events were played with their natural and synchronous sounds. The event pair was counterbalanced such that one fourth of the infants ($n = 9$) in each generalization condition ($n = 36$) received training with each of the four event pairs. During the habituation sequence, trials of the single and compound events alternated until infants reached the habituation criterion. The end of a trial was defined by a 1.5-s look away and a ceiling of 60 s was set as the maximum trial length. Once infants had met the habituation criterion (a fixation decrement of 50% or greater on two consecutive trials relative to the infant's fixation level on the first two trials), they then received two no-change posthabituation trials (to control for regression effects; for a discussion of these effects, see Bertenthal, Haith, & Campos, 1983). If an infant failed to meet the habituation criterion within 20 trials, that infant's data were excluded from the study. Following the posthabituation trials, infants received two test trials to assess whether they had indeed detected the temporal synchrony and temporal microstructure that specified object composition during the training phase. The synchrony test consisted of two trials in which the familiar events were played moving out of synchrony with their appropriate sounds. The test for temporal microstructure that specified object composition consisted of two trials in which the relation between the sounds and events was switched such that the single object moved in synchrony with the compound sound and the compound object moved in synchrony with the single sound. Controls received no change during the two test trials. One third of the infants within each event pair group ($n = 12$) each received test trials to assess detection of the change in synchrony or composition, or no change during test. Just prior to and after the habituation sequence, the attention control display (turtle) was presented as a warm-up trial and to check for fatigue. Infants were then removed from the seat.

Following a 5-min delay, the two-screen generalization test began. Infants were returned to the infant seat, and the seat was centered between two video screens. Only infants who successfully completed the habituation phase were included in the generalization test. Infants participated in their preassigned test condition, assessing low, moderate, or high degrees of generalization. In the low-generalization condition, infants viewed the same events that they had received during training; only the testing format and nature of the test differed. In the moderate-generalization condition, infants viewed events from the same event set that depicted only a new color and shape. In the high-generalization condition, infants viewed events from the other event set that depicted a new color and shape, as well as new substance and type of motion. The format for all generalization tests was identical; only the events differed. During each trial, infants viewed a single and a compound event from a given event pair. Events were presented side by side across two identical blocks of six 15-s trials. The objects were each shown moving in an erratic temporal pattern, and the synchronous and appropriate soundtrack to one of them was played through the central speaker. During a trial block, infants received three trials with the soundtrack to one event, and three trials with the soundtrack to the other event. The soundtracks were played in a random order with the restriction that no soundtrack be played more than twice in succession. The two trial blocks were identical except that across blocks the lateral positions of the two films were switched. Half the infants in each generalization condition received the single object on the right-hand screen and the compound object on the left during the first block, and the reverse arrangement during the second block. The other half of the infants received the opposite arrangement.

The two trial blocks were designed to serve as separate measures of matching. Under some conditions infants require some time to demonstrate matching, and Block 2 is then the most informative measure (e.g., for younger infants and more difficult tasks, such as 4-month olds in Bahrick et al., 1998; 4-month-olds in Walker-Andrews et al., 1991). Under other conditions, infants catch on quickly and may show matching only in Block 1 (e.g., for older infants or easier tasks, such as 6-month-olds in Experiments 2 and 4 of Bahrick, 1983; 7-month-olds in Bahrick et al., 1998; 6-month-olds in Experiment 2, Walker-Andrews et al., 1991). The trials were also designed to allow for a meaningful secondary measure of matching, the proportion of first looks (PFL) to the matching film. Each trial began with one audible impact sound and immediately afterward the two films appeared simultaneously so that infants could use the nature of the sound to guide their first looks to the appropriate film. Thus, if infants were somewhat bored with the filmed events, they might nevertheless orient (look first) to the sound-matched film, even if the matching films did not elicit sustained attention (reflected in the proportion of the total looking time, PTLT measure).

Infants were expected to look preferentially to the sound-synchronized and appropriate film if they had detected temporal synchrony and microstructure that specified object composition during the habituation/training phase and were able to transfer this knowledge from the training phase to the two-screen preferential looking test phase. That is, if they could abstract the invariant relations and generalize the knowledge that a single object makes a single sound and a compound object makes a complex sound, then they should look appropriately during the two-screen generalization test. Thus, the primary dependent variable for the test phase was the PTLT to the sound-matched film. The secondary measure was the PFL.

In addition, a control group consisting of 16 infants participated in the two-screen preferential looking test without the opportunity to learn about the films and soundtracks during the prior habituation/training phase. Because they were not shown the single and compound events prior to the generalization test, the test involved novel objects and sounds and infants' performance reflected generalization from past experience with objects and events in their environments. Further, to roughly equate control infants for prior exposure to the experimental setup, the habituation task, and fatigue with those of the other conditions, control infants received habituation to irrelevant stimulus events (faces of males and females, $n = 7$; or one of two rhythms depicted by a plastic hammer tapping, $n = 9$) in the same format as described in the experimental conditions, including posthabituation and test trials. They then participated in the two-screen test, with event pair and lateral position counterbalanced as above. In the two-screen test, it was expected that control infants would show no evidence of matching the films and soundtracks following the irrelevant habituation. If that were the case, any evidence of matching in the experimental groups could be considered a result of the habituation/training. Table 1 depicts the general design of the experiment and describes conditions of the generalization test with respect to those of the habituation sequence.

For the habituation/training phase, infants' data were examined to determine whether two criteria had been met, one for habituation and the other for

Table 1 Study Design: Events and Conditions of the Generalization Test with Respect to Those of the Habituation Sequence[a]

Habituation Sequence: Habituation/Training Phase	Habituation Sequence: Visual Recovery Test	Intermodal Preference: Generalization Test
Alternating single and compound events ($n = 36$)	No-change control ($n = 12$) Synchrony change ($n = 12$) Composition change ($n = 12$)	Low: Change in test format only ($n = 36$)
Alternating single and compound events ($n = 36$)	No-change control ($n = 12$) Synchrony change ($n = 12$) Composition change ($n = 12$)	Moderate: Change in test format, and object color and shape ($n = 36$)
Alternating single and compound events ($n = 36$)	No-change control ($n = 12$) Synchrony change ($n = 12$) Composition change ($n = 12$)	High: Change in test format, object color and shape, motion, and substance ($n = 36$)
Irrelevant control events (faces talking or hammers tapping a rhythm; $n = 16$)	Change in face or rhythm ($n = 16$)	Control: Change in test format, object color and shape, motion, substance, sound, and event type ($n = 16$)

[a] Habituation/training phase and visual recovery test.

attention and fatigue. To ensure that infants had habituated to the two displays, data from infants whose mean posthabituation fixation level exceeded that of their mean initial fixation level (baseline) were excluded from the study ($n = 5$). To make certain that infants were not overly fatigued and unable to show visual recovery, the fixation time during the final control trial was compared with that of the initial control trial. The data of infants whose final fixation level was less than 20% of their initial fixation level were also excluded ($n = 1$). The remaining infants in the sample showed substantial looking levels on the final control trial (median = 99.5% of the initial fixation level; $M = 179\%$, $SD = 278\%$).

During the two-screen generalization test phase, infants' data were examined to ensure that they had, in fact, noticed both visual displays during each trial block. Infants were required to fixate the least preferred side at least 5% of the time during a trial block for their data to be included. No data were excluded for failure to meet this fixation criterion.

A secondary observer monitored infants' visual fixations for 17% of the sample (22 of the 124 infants) during the habituation/training phase and 29% of the sample (36 of 124 infants) during the generalization test. For each infant, fixation times were calculated independently on the basis of observations made by the primary and secondary observers. For the habituation phase, a Pearson product-moment correlation between the observations of the primary and secondary observers for the looking time on each trial served as the measure of reliability and averaged .98 (SD = .07). For the two-screen generalization test, the PTLT to the matching film was calculated for each trial based on separate data of each observer and a Pearson product-moment correlation between these proportions was derived. The mean interobserver reliability was .93 (SD = .07).

RESULTS

Measures. To assess whether infants detected temporal synchrony and temporal microstructure that specified object composition during the habituation/training phase, visual recovery to the two test displays was calculated. The mean number of seconds looking during the two no-change posthabituation trials was subtracted from the mean of the two test trials for each infant. This difference score reflected the change in looking time to the test displays relative to the infant's own fixation level to the two habituation displays just after the criterion was met. Recovery scores were averaged across infants within each condition to obtain a mean recovery score that reflected the degree to which infants detected the temporal information during the habituation/training phase. Recovery scores were tested using a t test against the chance recovery of 0 to determine whether infants showed significant evidence of detecting the temporal information.

The measure of primary interest was the PTLT to the sound-matched film during the two-screen intermodal generalization test. For the experimental groups, this reflected the extent to which infants were able to generalize knowledge about audiovisual temporal relations that was abstracted during the habituation/training phase to guide exploration during the test. Proportions were derived for each trial separately and then averaged to obtain a mean proportion across the six trials comprising Block 1 and the six trials comprising Block 2. A mean PTLT was also derived by averaging across the two blocks for each infant, but this measure was not significant for any group and is not discussed further. Proportions above .50 indicated greater looking to the sound-matched film, whereas proportions below .50 indicated greater looking to the sound-mismatched film. To determine whether matching was significant, t tests were conducted on the PTLTs against the chance value of .50.

The PFL directed toward the sound-matched film was also calculated as a secondary measure of intermodal matching. For each block, the number of trials on which infants looked first toward the sound-matched film was divided by the total number of trials in that block ($n = 6$). Proportions were derived for each block separately. As with the PTLTs, a mean PFL was also derived for the two blocks averaged, but was not informative and thus is not discussed further.

Irrelevant habituation control condition. Results of the control group were first analyzed to ascertain whether infants showed any evidence of matching the films and soundtracks on the basis of temporal relations during the two-screen generalization test without the benefit of prior exposure to the films and soundtracks. According to single sample t tests against the chance value of .50, infants' PTLTs indicated no significant departure from chance for either Block 1 ($M = .54$, $SD = .11$), $t(15) = 1.4$, $p > .1$, or Block 2 ($M = .49$, $SD = .07$), $t(15) = .39$, $p > .1$. Further, when first looks were examined, there was also no evidence of any matching behavior on either trial block. Thus, infants who received habituation with irrelevant events showed no evidence of matching the films and soundtracks during the two-screen generalization test. Any evidence of matching the films and soundtracks in the experimental groups could thus be considered a result of learning from the habituation/training phase.

Control participants also showed no evidence of a side bias in Block 1 or Block 2 when the PTLT to the right side was evaluated, $t(15) = .09$, $p > .10$, $t(15) = 1.32$, $p > .10$, respectively. They also showed no evidence of a preference for one event pair over another during Block 1 or Block 2, according to one-way analyses of variance (ANOVAs) with stimulus event pair as the factor, $F(3, 12) = 2.45$, $p > .10$; $F(3, 12) = .61$, $p > .10$, respectively.

Habituation/training phase. Results of the habituation/training for infants collapsed across the low-, moderate-, and high-generalization conditions are depicted in Figure 2. As can be seen from the figure, infants showed highly significant visual recovery to a change in temporal microstructure that specified object composition, $t(35) = 5.63$, $p < .001$, when tested against the chance value of 0 recovery. Although infants were familiar with both the single and compound sounds and the single and compound objects, they noticed when the sights and sounds of impact were mismatched, even though the sights and sounds were synchronous. Infants also showed significant visual recovery to a change in temporal synchrony, $t(35) = 3.81$, $p < .001$, when tested against the chance value of 0 recovery. Further, they showed significantly greater recovery in the synchrony and composition tests than did the no-change controls according to a Dunnett *t* test, $p = .001$, $p < .001$, respectively. Thus, infants showed robust evidence of abstracting the temporal information during training, to be used as a basis for matching during the generalization test. They did this after a mean 162-s ($SD = 74.6$) exposure to the events.

To determine whether visual recovery to synchrony and composition information differed a priori for infants assigned to the different generalization conditions, a two-way ANOVA on visual recovery scores with generalization condition (low, moderate, high) and type of visual recovery test (synchrony, composition) as main factors was conducted. Results indicated no significant main effect of generalization condition, $F(2, 66) = .46$, $p > .10$; no effect of test condition, $F(1, 66) = 1.06$, $p > .10$; and no interaction, $F(2, 66) = .30$, $p > .10$. Thus, infants assigned to the different generalization conditions did not differ in the degree to which they abstracted temporal synchrony or temporal microstructure that specified object composition during the habituation/training phase.

Secondary analyses (see Table 2) were also conducted to evaluate the performance of infants during the habituation phase on five measures: (1) baseline, defined as the average length of fixation on the first two habituation trials; (2) the mean number of trials required to reach habituation; (3) the mean number of seconds to habituation, summed across trials; (4) the mean length of fixation on the two criterion trials; and (5) the mean length of fixation on the two (no-change) posthabituation trials. Analyses of variance were conducted separately for each of these measures to determine whether the experiences of infants assigned to the different generalization conditions differed from one another in any way. Results indicated no significant main effect of condition for any of the factors, $p > .10$, all tests. Thus, the performance of infants who were assigned to the low-, moderate-, and high-

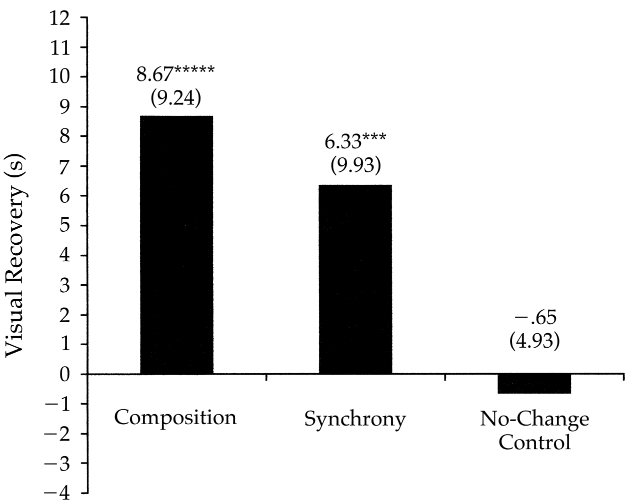

Figure 2 Training phase: Mean visual recovery time and *SD*s (in parentheses) for trials depicting a change in audiovisual composition, a change in synchrony, and no change during the habituation phase. *** $p < .001$; ***** $p < .00001$.

Table 2 Mean Looking and *SD*s for Five Measures of Habituation Performance as a Function of Generalization Condition

	Generalization Condition							
	Low		Moderate		High		Overall	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Baseline[a]	33.6	18.3	32.3	16.4	32.5	14.8	32.8	16.4
Criterion[b]	6.39	4.2	7.28	6.4	6.23	3.9	6.64	4.9
No-change posthabituation[c]	7.4	4.8	6.4	4.8	6.9	3.7	6.9	4.4
No. trials to habituation	7.6	1.8	7.8	2.6	7.6	1.8	7.7	2.1
Time to habituation (s)	149.5	81.2	157.3	78.8	158.5	60.2	155.1	73.4

[a] Baseline is the mean length of fixation across the first two habituation trials.
[b] Criterion looking is the mean length of fixation across the two habituation criterion trials.
[c] Posthabituation is the mean length of fixation across the two no-change posthabituation trials.

generalization conditions was equivalent with respect to initial and final interest in the stimuli and amount of processing time during the habituation phase.

Further, the experience of the infants in the irrelevant habituation control group was also compared with that of the experimental infants on all five of the measures. An ANOVA also indicated no main effects of condition for any of the measures when the control group was included, $p > .10$, all tests. Thus, prior to participating in the two-screen test, infants in the control group showed no difference from those in the experimental groups with respect to initial and final interest or total processing time to their respective stimulus events.

Generalization test phase. Results of the two-screen generalization test for infants in the experimental conditions are depicted in Figure 3. Analyses were first conducted on these data to determine whether looking to the matching films differed across conditions. Separate analyses of variance were performed on the PTLTs for Block 1 and Block 2, with generalization condition (low, moderate, high) as a factor. Results indicated a significant main effect of generalization condition for Block 1, $F(2, 105) = 4.0$, $p = .02$, and for Block 2, $F(2, 105) = 4.67$, $p = .01$. Thus, infants showed different degrees of matching (generalization) according to the disparity between their training events and their test events during each block of trials. Tukey tests were conducted to examine the nature of these effects. For Block 1, infants in the moderate-generalization condition had a higher PTLT than those in the low-generalization condition, $p = .02$. For Block 2, infants in the low-generalization condition showed significantly higher matching than those in the moderate- and high-generalization conditions, $p = .02$, each test.

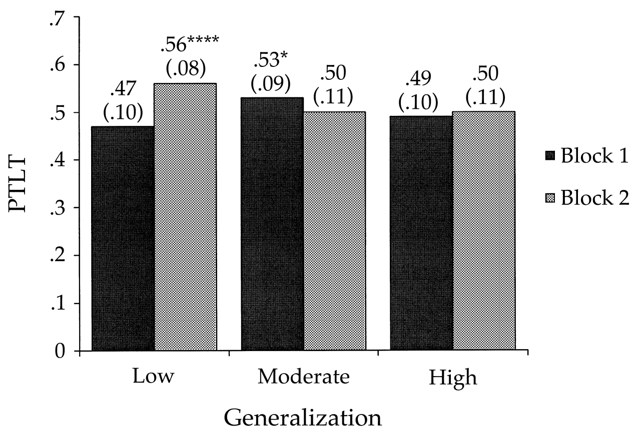

Figure 3 Generalization of learning: Mean proportion of total looking time (PTLT) to the sound-specified display for Block 1 and Block 2 as a function of generalization condition. * $p < .05$; **** $p < .00005$.

To interpret these effects and address the main research question (i.e., "Under which conditions did infants show evidence of generalization?"), the data were examined to determine which of the means reflected significant matching of the films and soundtracks. Single sample *t* tests on the PTLTs against the chance value of .50 were conducted for each generalization condition. As can be seen in Figure 3, analyses revealed significant evidence of matching the films and soundtracks for infants in the low- and moderate-generalization conditions, but not for those in the high-generalization condition. Infants in the low-generalization condition, who received no change in stimulus events, showed a significant PTLT to the matching film during Block 2, $t(35) = 4.66$, $p < .001$, and no evidence of matching for Block 1. In fact, in Block 1, infants showed a marginally significant mismatching effect, $t(35) = -1.85$, $p = .07$. This may reflect an initial attenuation of interest in the same stimulus events that infants had just received for habituation, and consequent exploration of the novel two-screen testing format and novel temporal relations provided by the mismatching familiar event. For the PFL measure, a similar pattern of results was found for infants in the low-generalization condition. Infants showed a significant proportion of first looks to the matching film during Block 2, $t(35) = 3.35$, $p = .002$, and no evidence of matching during Block 1. Infants in the moderate-generalization condition, who were tested with stimuli that differed in color and shape from their training stimuli, also showed evidence of matching, but matching was not as robust as for infants in the low-generalization condition. Infants in the moderate generalization condition demonstrated a significant PTLT to the sound-matched film during Block 1, $t(35) = 2.06$, $p = .05$, and no evidence of matching during Block 2. A similar pattern of results was found for the first look measure for these infants. They showed a significant PFL to the sound-matched film during Block 1, $t(35) = 2.10$, $p = .04$, but not during Block 2. In contrast with infants in the low- and moderate-generalization conditions, infants in the high-generalization condition who were tested with stimulus events that differed the most from their training events, showed no evidence of matching according to either the PTLT or the PFL measure, all $ps > .10$.

Secondary analyses were also performed to evaluate the data from the two-screen generalization test for evidence of side and stimulus bias. Two two-way ANOVAs were performed with condition (low, moderate, high) and event pair (orange metal, yellow metal, red plastic, yellow plastic) as factors on the PTLTs of Block 1 and Block 2 to determine if there was any preference for one event pair over another. Results indicated no significant effect of event pair, or interaction of event pair and condition, for Block 1, $F(3, 96) = .46$, $p > .10$; $F(6, 96) = 1.6$, $p > .10$, respectively. For Block 2, however, there was a significant effect of event pair, $F(3, 96) = 4.40$, $p = .006$, in which matching was greatest for the red plastic objects and lowest for the orange metal objects. This difference was significant according to a Tukey test, $p = .007$. This stimulus effect, however, did not impact the conclusions regarding matching because event pair did not interact with condition, $F(6, 96) = 1.72$, $p > .10$, and event pair was counterbalanced within each condition. Further, to detect any evidence of side bias, the PTLTs to the right side (irrespective of sound) were tested against the chance value of .50 for infants in each generalization condition. Results indicated no significant departure from chance for any of the conditions in either Block 1 or Block 2, all ps $> .10$.

DISCUSSION

The data in the present study provide the first evidence of generalization on the basis of amodal relations in the domain of audiovisual perception. Prior research has demonstrated that intermodal learning occurs on the basis of amodal temporal relations (e.g., Bahrick, 1988; Gogate & Bahrick, 1998), but it was not known when, under what conditions, or to what extent generalization across contexts and events occurred on the basis of these relations. The present findings provide insight into the conditions that promote versus limit generalization of intermodal knowledge. They suggest that the similarity of events to those of original learning is an important factor in promoting intermodal generalization. Further, generalization, at least by 3.5 months of age, is constrained rather than broad, and is limited to events that share a number of dimensions with those of the training context.

In this study, 3.5-month-old infants were habituated to both a single and a compound object striking a surface, and producing natural, appropriate, and synchronous sounds. This habituation served as a training phase and provided the opportunity for infants to abstract temporal synchrony and temporal microstructure that specified object composition. This temporal information could be generalized as a basis for matching films and soundtracks in a two-screen generalization test with events that were (1) the same as the habituation/training events; (2) different in color and shape only; or (3) different in substance, type of motion, color, and shape. These tests were considered to require low, moderate, or high degrees of generalization, respectively. Thus, in the low-generalization condition, only the task and the test format differed from training to test. Infants experienced a change from an infant-controlled habituation task to an intermodal matching task, and from a single-screen audiovisual display to a display with two simultaneous events along with one soundtrack. In the moderate- and high-generalization conditions, the task, test format, and stimulus events differed from training to test, with the stimulus events of the high-generalization condition differing most from those of training. Because control infants who received habituation with irrelevant events showed no evidence of matching the films and soundtracks during the generalization test, successful matching during the test was assumed to be a result of generalization from the habituation/training phase.

Results of the habituation/training phase revealed clear evidence of infants' detection of the temporal relations. After a mean 162-s exposure to the events, infants demonstrated robust visual recovery to a change in synchrony and to a change in temporal microstructure that specified object composition. Thus, infants abstracted the temporal information that was critical for successful performance in the generalization tests that followed. Further, these findings replicated those of our prior habituation studies with infants of this age (Bahrick, 1992, 2001), in which they also detected both temporal synchrony and temporal information for object composition in similar tests.

Results of the generalization test phase addressed this study's main research question and revealed several important findings. First, infants in the low-generalization condition, who received the same events but a different task and context, showed striking evidence of generalization. They matched the films of the single and compound objects with their appropriate soundtracks by looking first and more to the sound-specified films in the second block of the test phase, $p < .001$. These results replicate and extend those of Bahrick (1988), which demonstrated intermodal learning to a new task and new stimulus events. The present results provide evidence that 3.5-month-olds show intermodal learning on the basis of amodal relations when the same events are used during training and test. Infants can abstract amodal temporal information during a training phase and then show evidence of learning on the basis of these relations by matching the soundtrack to the appropriate one of two familiar events.

Moreover, evidence of intermodal learning with familiar events was demonstrated across a change in task and test format. During habituation/training, infants were exposed to audiovisual events one at a time, along with their appropriate soundtracks, as might occur in natural exploration of the environment. This task recruits attention to single, multimodal events. During test, infants viewed two events side by side, along with one soundtrack that was synchronous and appropriate to the composition of one of the events. This is more difficult than the habituation task in that it requires active exploration, more mobile attention, and matching a sound to one of two visual alternatives. Typically infants can detect intermodal relations in a habituation task at a younger age than in a two-screen intermodal preference task (Bahrick, 1987, 1988, 2001; Bahrick & Pickens, 1994). Thus, in the low-generalization condition, 3.5-month-old infants showed generalization of learning across tasks and test formats, and this generalization was quite robust.

Results also revealed generalization of intermodal knowledge to novel events. Infants in the moderate-generalization condition showed evidence of matching the films and soundtracks on the basis of amodal temporal information, but matching was not as apparent as in the low-generalization condition in which the familiar events were used and the effect size was unusually large. Infants in the moderate-generalization condition directed a greater proportion of total looking time to the matching film during the first block of trials, $p = .05$. Thus, after abstracting temporal synchrony and temporal microstructure that specified object composition in the habituation/training phase, infants were able to use this information to guide their visual exploration to the acoustically specified objects when confronted with a new set of events. When they heard the soundtrack of the single object, they looked more to the single object, and when they heard the soundtrack of the compound object, they looked more to the compound object. Infants did this even though these objects differed in color and shape from those experienced during training. Prior research (Bahrick, 1992, Experiment 3) had demonstrated that infants of this age could discriminate all the color/shape changes in these events.

The results of the present study provide the first direct evidence of infants' ability to abstract and generalize intermodal knowledge to novel events. Evidence of transfer of training has been previously demonstrated in the sense of abstracting information about an object or event in one modality and generalizing that information to a different sense modality (e.g., for tactile to visual transfer see Gibson & Walker, 1984; Hernandez-Reif & Bahrick, 2001; Meltzoff & Borton, 1979). Intermodal learning, however, has not been previously shown to generalize from one set of events to another. After only a few minutes of exposure to single audiovisual events, infants can abstract amodal temporal information and generalize this knowledge to guide intermodal exploration of a novel set of events. This capability emerges by 3.5 months, and is fundamental to the development of perception and cognition.

Infants also showed limitations to appropriate generalization. In contrast with the above findings, when infants received events that differed most from those of their training events (in terms of color, shape, substance, and type of motion), they showed no evidence of matching the films and soundtracks on the basis of temporal information. Despite the fact that these events shared critical properties of the training events, and that infants were able to detect the temporal information that was critical for intermodal matching, infants failed to show generalization to these novel events in the matching task. The novel test events, just like those of familiarization, portrayed a single and a compound object striking a surface in an erratic temporal pattern, along with sounds that were appropriate and synchronous with each event. Although infants detected the critical temporal information during training, they showed no evidence of using this information.

It is not clear whether the observed constraints on generalization arose from an inability to detect the appropriate temporal information in the new events during the test phase; whether the temporal information was abstracted but failed to guide visual exploration; whether there was an inhibition against generalization due to the novelty of the events; or whether it was a matter of selective attention to other novel aspects of the events, task, or context. In any case, at 3.5 months, infants failed to show broad generalization of intermodal knowledge when events differed markedly from those that they had just experienced during exploration and abstraction of this knowledge.

Together, the results of the intermodal generalization tests portray a clear and systematic pattern. Infants appear to show a successively decreasing ability to generalize from training, as the test events and format depart from those of training. That is, evidence of intermodal matching was found when the test events were identical to those of training and only the test format differed. When the test events differed in color and shape, moderate, yet still significant evidence of intermodal matching was evident. When the test events differed along more dimensions than those of training, or when the training events were irrelevant to those of the test, infants showed no intermodal matching at all.

The failure of infants to show broad generalization from the events of training to those of the matching test also provides independent and converging evidence with that of the control group. Taken together, the data of the control and broad generalization groups demonstrate that the matching shown by infants in the low- and moderate-generalization conditions was primarily a result of specific experience with the events of training rather than a result of prior experience. Thus, successful matching was not primarily a result of generalization from prior interactions with objects and events in the world. It required training with the same or very similar events just prior to test. The failure of infants in the high-generalization condition suggests that training with sufficiently novel events (even though the events depict the critical temporal relations) in conjunction with prior experience with multimodal events in the environment (that also depict these temporal relations) is not sufficient for successful object–sound matching at 3.5 months of age.

These findings of limitations to generalization are consistent with findings of infants' performance in the mobile conjugate reinforcement paradigm (for a review, see Rovee-Collier & Hayne, 1987), in which memory was found to be specific to a variety of properties of the training, including its context (crib bumpers) and the specific elements of the mobile. If these aspects were altered, memory was disrupted (Borovsky & Rovee-Collier, 1990; Hayne & Findlay, 1995; Hayne et al., 1986).

The present evidence of successful generalization of intermodal knowledge across tasks and events is in contrast, however, with findings of memory specificity in the mobile conjugate reinforcement paradigm, in which little generalization was found, especially prior to 6 months of age. The present results are more consistent with findings from other domains that suggest generalization across tasks, contexts, and events in early infancy. For example, young infants generalize across exemplars to form categories, and recognize a change in category for both auditory and visual information examined separately (Bahrick & Pickens, 1988; Hayne, 1996; Kuhl, 1985; Mandler, 2000; Mandler & McDonough, 1993; Quinn & Johnson, 2000). They abstract rules regarding patterns in speech and appear to apply them to new stimuli (Aslin et al., 1998; Marcus et al., 1999; Saffran et al., 1996). Infants also appear to generalize knowledge about the laws of physical causality (for a review, see Baillargeon, 1995). Little research, however, has been directly concerned with the nature of learning and generalization in these domains in infancy, and the conditions under which young infants do and do not show generalization of knowledge.

Generalization of knowledge, however, is thought to be a hallmark of intelligent functioning and a foundation for cognitive development (Brown, 1982; Rozin, 1976). Similarly, perception of amodal relations is fundamental to cognitive and perceptual development (Bahrick, 1988, 1992, 2001; Gibson, 1969; Lewkowicz & Lickliter, 1994). Thus, investigation of generalization of knowledge of amodal relations is central for understanding the development and organization of early perceptual and cognitive competence.

The present research has demonstrated that by 3.5 months of age, knowledge about intermodal relations appears to be neither tied to the events of original learning, nor extended broadly across contexts and events. Rather, knowledge appears to be extended across events that are similar in appearance to those of training, but not yet to appropriate events that show greater differences from those of training, even when these novel events share the critical properties of the training events. Although the ability to flexibly extend knowledge across appropriate domains is fundamental for cognitive and perceptual development, the ability to not extend knowledge across inappropriate domains is also crucial for the development of veridical perception and cognition (for a similar view, see Bjorklund, 1997). It appears that by 3.5 months of age, infants generalize intermodal knowledge to appropriate events, but also underextend their knowledge across event domains. The present findings suggest that when infants encounter an event, they differentiate the intermodal relations as well as the details of the events. Apparently, on the basis of these details, they both generalize to similar events and inhibit generalization to very dissimilar events, even when the novel events share the same amodal relations. This "under extension" of knowledge may be adaptive at this point in development for promoting veridical perception and for limiting overgeneralization across inappropriate events and contexts. It may also allow time for differentiation of the relations in question across a greater variety of events and contexts prior to forming more generalized expectancies. Given sufficient experience with a variety of events in the natural environment, infants presumably form general expectancies and a knowledge base about intermodal relations. Perceptual learning with events that display similar properties likely educates attention and facilitates rapid abstraction of amodal relations that unite the audiovisual stimulation of novel events. After this point, when infants encounter novel objects and events such as those of the present study, they would show intermodal matching more rapidly (and without the benefit of prior training) by quickly abstracting the available invariant temporal relations and allowing knowledge to guide attention.

These issues will be better addressed by understanding the developmental pattern of how the generalization of knowledge unfolds. The developmental picture during the first year of life, however, remains to be investigated. Is knowledge first tied to the context and events of original learning, and then gradually extended with development, as suggested by Brown (1982) and Rozin (1976) in the domain of child learning; or is knowledge in infancy more global when it is first abstracted and then becomes increasingly more specific with development and experience, as suggested by Gibson's (1969) theory of differentiation? These issues are topics of current investigation.

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ADDRESS AND AFFILIATION

Corresponding author: Lorraine E. Bahrick, Department of Psychology, Florida International University, Miami, FL 33199; e-mail: bahrick@fiu.edu.

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