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Intersensory Redundancy Facilitates Discrimination of Tempo in 3-Month-Old Infants

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ABSTRACT: *L. Bahrick and R. Lickliter (2000) proposed an intersensory redundancy hypothesis that states that information presented redundantly and in temporal synchrony across two or more sensory modalities selectively recruits infant attention and facilitates perceptual learning more effectively than does the same information presented unimodally. In support of this view, they found that 5-month-old infants were able to differentiate between two complex rhythms when they were presented bimodally, but not unimodally. The present study extended our test of the intersensory redundancy hypothesis to younger infants and to a different amodal property. Three-month-olds' sensitivity to the amodal property of tempo was investigated. Results replicated and extended those of Bahrick and Lickliter, demonstrating that infants could discriminate a change in tempo following bimodal, but not unimodal, habituation. It appears that when infants are first learning to differentiate an amodal stimulus property, discrimination is facilitated by intersensory redundancy and attenuated under conditions of unimodal stimulation.* Dev Psychobiol 41: 352–363, 2002. DOI 10.1002/dev.10049

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We live in a world of objects and events that are multimodal and dynamic. Organisms make sense of this flux of stimulation by perceiving events that are unitary despite changing stimulation to multiple sensory systems. Research has demonstrated that young human infants are capable of perceiving unitary multimodal events by detecting amodal properties in stimulation. That is, they detect information that is not specific to a particular sensory modality, but conveyed by more than one sense (redundant across the senses). For example, in the first half year of life, infants detect the relationship between a face and a voice on the basis of temporal synchrony, rhythm, and tempo as well as certain types of spectral information common to the movements of the mouth and timing of the speech sounds (Dodd, 1979; Kuhl & Meltzoff, 1984; Lewkowicz, 1996, 1998; Mendelson & Ferland, 1982). Infants also detect amodal information specifying affective expression across the visual and acoustic stimulation of speech (Walker-Andrews, 1997) as well as information specifying the age and gender of a speaker (Bahrick, Netto, & Hernandez-Reif, 1998; Walker-Andrews, Bahrick, Raglioni, & Diaz, 1991). In perceiving moving objects, infants detect amodal temporal information specifying the substance and composition of an object across the sights and sounds of its impacts against a surface (Bahrick, 1983, 1988, 1992) as well as the common tempo of

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action and rhythm (Allen, Walker, Symonds, & Marcell, 1977; Bahrick & Lickliter, 2000; Lewkowicz, 2000; Spelke, 1979; Spelke, Born, & Chu, 1983). These experiments demonstrate that within the first 6 months of postnatal development, infants are skilled perceivers of amodal information uniting stimulation across sensory modalities. Further, research demonstrates that detection of amodal information can provide the basis for and guide perceptual learning in early development (Bahrick, 1988, 2001; Bahrick & Pickens, 1994), and can facilitate perceptual learning of arbitrary relations such as those between speech sounds and the objects to which they refer (Gogate & Bahrick 1998; Hernandez-Reif & Bahrick, 2001).

Recently, Bahrick and Lickliter (2000) proposed and provided evidence for an ''intersensory redundancy hypothesis'' to describe how the detection of amodal and modality-specific information influences early perceptual development. Intersensory redundancy refers to the concurrent, spatially co-located presentation of the same information across two or more sensory systems (e.g., rate, rhythm, duration, intensity). For auditory–visual stimulation, it also entails temporal synchrony between the two sources of stimulation. This hypothesis holds that in early development, information presented redundantly to two or more senses simultaneously selectively recruits infants' attention and promotes their perceptual learning of amodal stimulus properties more effectively than does the same information presented to one sense modality alone. In contrast, when information is presented to one sense modality (e.g., visually), it selectively recruits attention to modality-specific properties more effectively than to amodal properties. Since most events are multimodal and perceived through several senses simultaneously, this attentional selectivity gives an early developmental advantage to perceiving and learning on the basis of amodal properties prior to the learning on the basis of modality-specific properties. This should be especially true when the properties to be perceived are difficult for the infant to discriminate, are relatively novel, or both.

According to the intersensory redundancy hypothesis, amodal properties such as rhythm, tempo, intensity, or duration should at first be more easily perceived when they are presented bimodally (i.e., audiovisually) than when they are presented unimodally (visually or acoustically) because the intersensory redundancy serves to highlight the amodal properties of stimulation. Bahrick and Lickliter (2000) tested this prediction with 5-month-old infants using the amodal property of rhythm. They habituated infants to a hammer tapping out a complex rhythm under bimodal (synchronized vs. nonsynchronized audiovisual) or unimodal (acoustic or visual) presentation conditions. Infants then were presented with a novel rhythm to assess whether they could discriminate it from the familiar rhythm. Results indicated that only infants who received the synchronized bimodal presentation showed significant visual recovery (an increase in attention relative to the habituated level) to the new rhythm whereas those who received either unimodal visual, unimodal auditory, or bimodal nonsynchronized presentations did not. Thus, only infants who received synchronous bimodal audiovisual stimulation showed evidence of discriminating the amodal property of rhythm. These results support the first prediction of the intersensory redundancy hypothesis.

Further studies with young infants also have supported the second prediction of the intersensory redundancy hypothesis. Namely, under conditions of unimodal stimulation, infants' attention is more likely to be recruited toward modality-specific stimulus properties (pitch, orientation, timbre, color, pattern), facilitating discrimination and learning of these properties to a greater extent than under conditions of bimodal stimulation. For example, Bahrick, Lickliter, and Flom (2000) habituated 5-month-old infants to videos of a hammer tapping in one of two spatial orientations (upward vs. downward). Discrimination of orientation was evident under unimodal visual exposure, but not following bimodal audiovisual exposure. These two studies suggest that detection of amodal properties can be facilitated by intersensory redundancy and attenuated under unimodal exposure. It should be emphasized, however, that the advantage of bimodal stimulation for perceiving amodal properties is most evident when the information to be perceived is relatively difficult or first learned by infants or adult perceivers. Once the information is easily perceived, it also is detectable in unimodal stimulation, and the advantage of bimodal, redundant stimulation may no longer be apparent.

Comparative studies with precocial avian embryos have found a similar pattern of results (Lickliter, Bahrick, & Honeycutt, 2002). Bobwhite quail embryos showed significantly enhanced perceptual learning when amodal information (i.e., rate, rhythm, and duration) available in a maternal call was presented audiovisually and in a temporally coordinated manner (redundantly) as compared with embryos receiving unimodal auditory stimulation. In fact, embryos learned the maternal call four times faster when intersensory redundancy was provided by synchronizing a flashing light with temporal properties of the call. Asynchronous, bimodal presentations did not foster prenatal perceptual learning and, in fact, appeared to interfere with learning. These findings indicate that embryos also are more sensitive to amodal properties such as rate, rhythm, and duration when stimulation is presented redundantly across two sensory modalities as compared with one sensory modality presented alone.

The purpose of the present experiment was to examine whether the predictions of the intersensory redundancy hypothesis extend to a different amodal property, tempo of action, as well as to younger infants. We asked whether 3-month-olds could detect a change in the tempo of an event more easily following bimodal, audiovisual familiarization than following unimodal auditory or unimodal visual familiarization. We chose the amodal property of tempo because virtually no previous research bears on predictions of the intersensory redundancy hypothesis and tempo is one of the most basic amodal properties shared by visual and acoustic stimulation from single, unitary events. Common tempo unites the movements and sounds of most audible and visible events, including speech and the motions of social and nonsocial objects. Perception of tempo is essential for communication and social interaction, as it conveys information about affect, intent, emphasis, and meaning (e.g., Bullowa, 1979; Jaffee, Beebe, Feldstein, Crown, & Jasnow, 2001; Stern, 1985; Trevarthan, 1993; Walker-Andrews, 1997). Infant-directed communication differs from adult-directed communication along a number of temporal dimensions, including tempo and rhythm, and infants discriminate and attend selectively to infant-directed speech, singing, and signing (e.g., Cooper & Aslin, 1990; Fernald, 1985; Jaffee, et al., 2001; Koester, Papousek, & Papousek, 1989; Masatka, 1996; Trainor, Clark, Huntley, & Adams, 1997).

Despite the importance of tempo perception for communication and social development, few studies have investigated infants' sensitivity to tempo or rate of occurrence in multimodal, complex events. Most studies of tempo perception have examined infants' ability to detect tempo in unimodal presentations and/or with stimuli that are isochronous (even-metered) with little or no rhythmic complexity or object motion, unlike the stimulation available in most social and communicative interactions. This research has shown that infants discriminate simple differences in tempos presented in unimodal auditory stimulation (e.g., Baruch & Drake, 1997; Trehub & Thorpe, 1989), unimodal visual stimulation (e.g., Balaban & Dannemiller, 1992; Gardner & Karmel, 1995; Lewkowicz, 1985a), and bimodal audiovisual stimulation (e.g., Lewkowicz 1988a, 1988b, 1992) within the first months of life. Some research also has investigated discrimination of tempos in more naturalistic, complex, bimodal stimulation. Pickens and Bahrick (1995, 1997) found that 7-month-olds could use tempo differences to discriminate changes in complex rhythmic patterns displayed by moving, audible objects, and could categorize these rhythmic patterns on the basis of tempo.

Infants also have shown intersensory matching on the basis of tempo. That is, when hearing the soundtrack to an event of a particular tempo, infants have demonstrated enhanced visual exploration to the one of two visible events that matched its tempo. For example, 4-month-old infants matched auditory and visual stimulation from complex, moving objects on the basis of tempo (Spelke, 1979). However, other studies of intersensory matching have yielded mixed results, with some failing to find evidence of intersensory perception of sounds matching the tempo of isochronous moving objects (Lewkowicz, 1992, 1994) or isochronous flashing lights (Humphrey & Tees, 1980; Lewkowicz, 1985b), at least prior to 6 to 10 months of age (see Lewkowicz, 2000, for a review). Given the differences in stimulus modality, complexity, and procedures, it is difficult to compare and draw firm conclusions from results across studies. Consequently, research is needed to clarify when and under what conditions sensitivity to tempo and the ability to match movement and sound on the basis of tempo emerges. Further, no studies to date have compared infants' discrimination of changes in tempo in unimodal versus bimodal stimulation, and as a result, the effects of intersensory redundancy have not been evaluated. A few studies of multimodal tempo perception have included some unimodal conditions (e.g., Lewkowicz, 1988a, 1988b, 1992), but have not been designed to ask whether tempo discrimination is facilitated in bimodal as compared with unimodal stimulation, and relevant comparisons are not possible.

Given that tempo is an important and prevalent type of amodal stimulation and one that is among the earliest detected (Lewkowicz, 2000), in this study we evaluated the intersensory redundancy hypothesis by asking whether infants' discrimination of tempo would be facilitated in the context of bimodal as compared with unimodal stimulation, similar to the facilitation found for 5-month-olds with the amodal property of rhythm (Bahrick & Lickliter, 2000). Further, infants as young as 4 to 7 months have previously shown sensitivity to tempo in relatively complex, bimodal, naturalistic stimulation (Pickens & Bahrick, 1995, 1997; Spelke, 1979). Thus, younger, 3-month-old infants were selected for this study because we wanted to choose a task that was known to be difficult for young infants under bimodal conditions and then test whether detection of the same information was easier or more difficult when presented unimodally. We expected that sensitivity to a change in tempo would be facilitated under bimodal presentations (Experiment 1) and attenuated under unimodal presentations (Experiment 2), supporting the intersensory redundancy hypothesis.

EXPERIMENT 1: DISCRIMINATION OF TEMPO IN REDUNDANT, BIMODAL STIMULATION

In this experiment, we investigated whether 3-month-olds are able to perceive a change in tempo given redundant, bimodal (auditory and visual) information, using procedures and stimuli similar to those of Bahrick & Lickliter (2000). Infants in this experiment were bimodally habituated to a videotaped event that consisted of a hammer tapping out one of two rhythms at one of two tempos on a wooden surface (stimuli taken from Pickens & Bahrick, 1995, 1997). Following habituation, each infant received two test trials that depicted a change in tempo.

Participants

Sixteen 3-month-old infants participated. There were 5 females and 11 males, with a mean age of 89 days, ($SD = 2.8$). Two infants were Caucasian, and 14 were of Hispanic descent. Eleven additional infants (41%) participated, but were excluded from the analyses due to fussiness ($n = 1$), experimenter error ($n = 2$), falling asleep ($n = 2$), failure to habituate ($n = 1$) or failure to meet the habituation ($n = 1$), or fatigue ($n = 4$) criteria (see Procedure for details). This participant attrition rate is typical for habituation procedures with 3-month-olds, whose attentive periods and state are unpredictable. The infants were primarily from middle-class homes, and the parents had at least a high-school education. All infants had a gestation period of at least 38 weeks.

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 and tempo (see Pickens & Bahrick, 1995, 1997, for details). The natural sounds could be heard. The events depicted two distinctive rhythms each played at two different tempos. The rhythms were irregular in structure and differed in terms of the arrangement of their elements. Each rhythm contained a repeating pattern of a four-beat measure with four impacts alternating with a four-beat measure of rests. The two rhythms were: Rhythm 1 = X O XX X, and Rhythm 2 = XX O X X (where X represents a whole-beat impact, XX represents two half-beat impacts, and O represents a whole-beat rest). Each rhythm was presented at one of two tempos (not taking into account the four-beat measures of rests), 110 bpm (1.8 Hz) or 240 bpm (4 Hz). A control display consisted of a green and white toy turtle whose arms spun, making a whirring sound.

Apparatus

Infants sat in a standard infant seat facing a 19-in. (Panasonic BT-S1900N) video monitor at a distance of approximately 55 cm. The infant seat and monitor were surrounded by black curtains and black poster board. 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 infants' visual fixations. A small set of bells inside plastic balls was positioned near the video monitor and was used to attract the infants' attention toward the monitor 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 using a Panasonic (VHS NV-A500) edit controller connected to three Panasonic video decks (AG 6300 and AG 7750). These three video decks and edit controller also were used during the experiment to present the audiovisual events and enabled us to switch between the habituation, test, and control events while reducing extraneous noise and time that would have resulted from changing displays using one or two video decks. All auditory information was presented from a speaker located just beneath the video monitor at a level of approximately 65 dB (A scale, fast response) as measured from the infant seat.

A trained observer, unaware of the infant's condition and unable to see the test event, monitored infants' visual fixations by pressing and holding a button that indicated the infant was visually fixating on the display. The button box was connected to a computer that recorded and computed the duration of infants' visual fixations to the video displays and signaled a second experimenter regarding when to commence and terminate each trial. A record of the infants' visual fixations was created on-line. The observations of the primary observer controlled the audiovisual presentations, and those of the secondary observer were recorded for later calculation of inter-observer reliability.

Procedure

Infants were tested in our laboratory at Florida International University. Testing began when the infant was judged to be in a quiet, alert state. A parent was present in the testing room with the child throughout the procedure, but not visible to the infant.

Infants were tested to determine whether they could detect a change in tempo following bimodal exposure to a rhythmic sequence in an infant-controlled habituation procedure (see Horowitz, 1975; Horowitz, Paden, Bhana, & Self, 1972). In this procedure, the infants control the length of each trial by their looking behavior. Each trial lasts until the infant looks away for 1.5 s. Additional trials of the same event are presented until the infant's visual fixation level decreases, to a preset habituation criterion, in relation to his or her initial fixation level. Discrimination is inferred when the visual fixation time during the test trials (depicting a new event) shows a significant increase relative to that of the habituated level of the familiar event (visual recovery). Sixteen infants were randomly assigned to one of two tempo conditions (fast vs. slow) for habituation, and within each of these conditions, infants received one of two complex rhythms ($n = 4$ per condition; same rhythms used by Bahrick & Lickliter, 2000). Infants received bimodal, audible and visible displays during habituation and test. The habituation sequence was initiated with an initial control trial (turtle). Four mandatory habituation trials then were presented, and the habituation criterion was met when the infants showed a decrement of 50% or greater on two consecutive trials, relative to their fixation level on the first two trials (baseline). Once the criterion was met, two no-change posthabituation trials were presented. These two additional habituation trials were presented to establish a more conservative habituation criterion by reducing the possibility of chance habituation and taking into account spontaneous regression toward the mean (see Bertenthal, Haith, & Campos, 1983). Following the two no-change posthabituation trials each infant received, two test trials presented the same rhythmic event but at the novel tempo to assess the infant's ability to discriminate a change in tempo. Then, the final control trial (turtle) was presented. Each trial began when the infant visually fixated the monitor and was terminated when the infant looked away for at least 1.5 s (or if 60 s of looking was accumulated). Infants were considered unable to habituate if they failed to reach the habituation criterion within 20 trials. The data of 1 infant were rejected for this reason.

The infants' data were examined to ascertain whether two criteria had been met, one to identify fatigue and the other to ensure that infants who reached the habituation criterion had, in fact, habituated (see Bahrick, 1992, 1994; Bahrick & Lickliter, 2000). To make certain that infants were not overly fatigued and unable to show visual recovery, their visual fixation to the toy turtle on the final control trial was compared with that of the initial control trial. A visual fixation to the toy turtle on the final trial that was at least 35% of the initial fixation level to the turtle was set as a minimum criteria for inclusion. The data of 4 infants were rejected for failure to meet this criterion. The remaining infants showed substantial visual fixation on the final control trial ($Mdn = 96\%$ of the fixation level on the initial control trial). In addition, to evaluate whether infants had, in fact, habituated to the events, we compared infants' mean posthabituation fixation level with their mean initial fixation level (baseline). The data of any infant whose posthabituation fixation level exceeded their baseline fixation level were excluded ($n = 1$).

A secondary observer monitored the visual attention of 8 infants (50% of the sample) for assessing interobserver reliability. Length of visual fixation was calculated for each trial for each infant and each observer. A Pearson product–moment correlation was computed between the observations of the primary and secondary observers and averaged .95 ($SD = .06$).

Results and Discussion

The primary dependent variable used as the index of discrimination was visual recovery to a change in tempo. Visual recovery, a difference score, was computed for each infant by subtracting the mean number of seconds looking during the two no-change posthabituation trials from the mean number of seconds looking during the two test trials. Figure 1 presents infants' mean visual fixation as a function of trial type (baseline, posthabituation, and test), and Figure 2 (first bar) presents infants' mean visual recovery scores.

To examine whether 3-month-olds were able to discriminate a change in tempo, we conducted a single-sample *t* test on infants' mean visual recovery score against the chance value of zero (see Figure 2). The results were significant, $t(15) = 2.30$, $p = .036$ (all tests two-tailed), and indicate that 3-month-old infants were able to discriminate between the two tempos under conditions of bimodal habituation and testing. In other words, infants receiving redundant (synchronized auditory and visual) rhythmic sequences during habituation showed significant visual recovery to a change in tempo.

In addition, we examined the data at the individual subject level to ascertain whether the significant visual

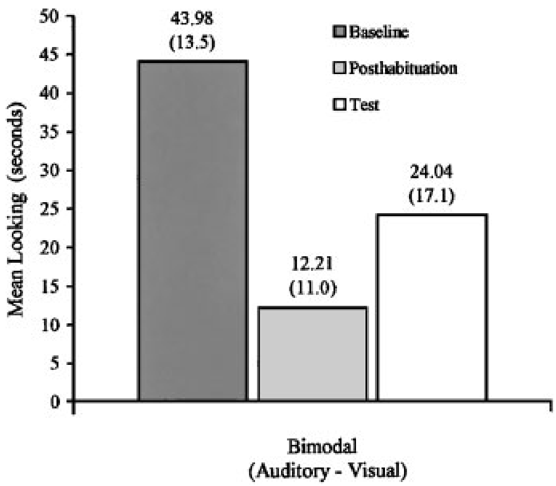

FIGURE 1 Experiment 1: Mean visual fixation (and *SD*s) as a function of trial type (baseline, posthabituation, and test) during redundant audiovisual presentation of tempo. Baseline is the mean visual fixation during the first two habituation trials, reflecting initial interest level. Posthabituation is the mean visual fixation during the two no-change trials just after the habituation criterion was met, reflecting final interest level in the habituation event. Test is the mean visual fixation during the two tempo change trials.

recovery was a result of the group as a whole or was primarily carried by a few infants who had particularly high visual recovery scores. Recovery scores were classified as positive or negative, and a binomial

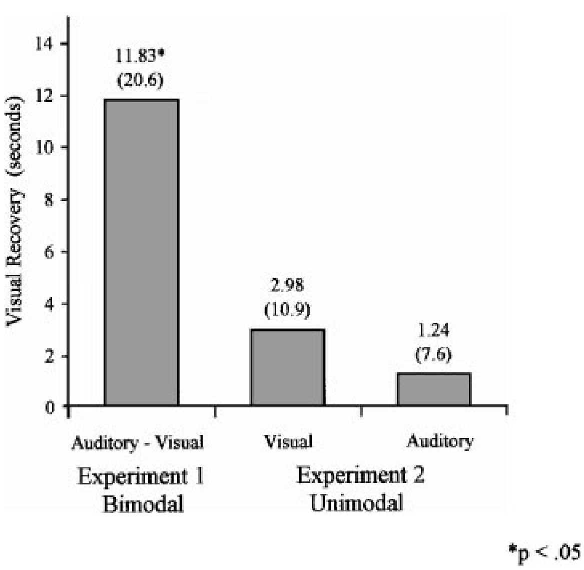

FIGURE 2 Experiments 1 and 2: Mean visual recovery (and *SD*s) to a change in tempo following redundant bimodal stimulation (Experiment 1) versus Unimodal visual or unimodal auditory stimulation (Experiment 2). Visual recovery is a difference score between visual fixation during the test trials and visual fixation during the posthabituation trials.

test was conducted to assess whether the number of infants who showed positive visual recovery scores was significantly greater than chance (.50). Thirteen of the 16 infants showed positive recovery scores ($p = .021$), indicating that discrimination was robust and not carried by a few infants.

Secondary analyses also were performed to assess whether infants showed any stimulus preferences. A two-way analysis of variance was performed on the visual recovery scores with stimulus rhythm (Rhythm 1 vs. Rhythm 2) as one main factor and tempo of habituation (fast vs. slow) as the other factor. Results indicated no significant effect of rhythm, $F(1, 12) = .033$, $p > .1$, tempo, $F(1, 12) = 3.11$, $p > .1$, or interaction, $F(1, 12) = 1.4$, $p > .1$.

These results demonstrate that 3-month-old infants are capable of discriminating between two tempos when presented bimodally (synchronized audible and visual presentations) during habituation and test. This is the first study to demonstrate that infants as young as 3 months can discriminate complex, naturalistic, bimodal events on the basis of tempo alone.

However, it is not known whether 3-month-old infants also can discriminate these changes in tempo when presented to only one sensory modality. According to the intersensory redundancy hypothesis, infants should be better able to discriminate the change in tempo under bimodal exposure than under unimodal exposure when they are first learning to perceive tempo information or when the tempos are difficult to perceive. Experiment 2 tested this prediction by assessing discrimination of tempo under unimodal visual (silent films of the hammer tapping) or unimodal auditory (the sound track of the hammer tapping) habituation conditions and then assessing visual recovery to a change in tempo.

EXPERIMENT 2: DISCRIMINATION OF TEMPO IN UNIMODAL STIMULATION

The present experiment was identical to Experiment 1, with the exception that 3-month-olds received either unimodal auditory or unimodal visual exposure to the events played at one of the two tempos. In the unimodal visual condition, infants received silent films of the hammer tapping during habituation and test. In the unimodal auditory condition, infants received the soundtracks from the hammer tapping along with a still image of a hammer. Consistent with predictions of the intersensory redundancy hypothesis, we expected that infants' discrimination of tempo would be attenuated under the unimodal auditory and visual conditions.

Participants

Thirty-two 3-month-olds participated. There were 18 females and 14 males, with a mean age of 91 days ($SD = 4.9$). Six infants were of Caucasian descent, 22 were Hispanic, 3 were African American, and 1 was American Indian. Fourteen additional infants (30%) participated, but were excluded from the analyses due to fussiness ($n = 5$), experimenter error ($n = 2$), equipment failure ($n = 1$), failure to pass the fatigue criterion ($n = 5$), and 1 infant was excluded due to a visual impairment. As in the prior sample, the infants were primarily from middle-class homes, the parents had at least a high school education, and all infants had a gestation period of at least 38 weeks.

Apparatus and Stimuli

The apparatus and stimuli were identical to those of Experiment 1, with the exception that the tempo events were presented to only one sensory modality during habituation and testing. In the unimodal visual condition, the video portions of the events of Experiment 1 were used, and in the unimodal auditory condition, the audio portions of the events of Experiment 1 were used. In addition, two still images of the hammer were used during habituation and testing in the auditory condition by filming one frame of the video depicting the hammer in an upward position and another in a downward position of its trajectory.

Procedure

Infants were randomly assigned to one of the two conditions: unimodal auditory or unimodal visual ($n = 16$ each). Within each unimodal condition infants were randomly assigned to one of the two rhythms and one of the two tempos for habituation. The same tempos and rhythms were used as in Experiment 1.

The habituation and testing procedures also were identical to those of Experiment 1, with the exception that the stimuli were unimodal. In the unimodal visual condition, the films were played silently throughout habituation and testing. In the unimodal auditory condition, the soundtrack of the hammer tapping was played while a static image of the hammer remained visible on the monitor throughout habituation and testing. Looking directed toward the still hammer was used as a measure of attention to the soundtrack (see Bahrick & Lickliter, 2000; Walker-Andrews & Grolnick, 1983; Walker-Andrews & Lennon, 1991).

As in Experiment 1, we examined the data to ensure that the habituation and fatigue criteria had been met. The data of 5 infants were rejected for fatigue and none for failure to habituate. A secondary observer monitored the visual attention of 6 infants (19%) for assessing interobserver reliability. The Pearson product–moment correlation between the observations of the two observers averaged .92 ($SD = .07$).

Results and Discussion

Figure 3 displays infants' mean visual fixation as a function of trial type (baseline, posthabituation, and test), and Figure 2 presents infants' mean visual recovery for the unimodal visual and auditory conditions along with visual recovery of the bimodal condition of Experiment 1. To determine whether infants showed discrimination of the tempo changes in Experiment 2, single sample *t* tests were performed on the visual recovery scores against the chance value of 0 for the unimodal auditory and visual conditions. In contrast to the results of Experiment 1, infants who received unimodal visual and unimodal auditory exposure to tempo information during habituation failed to show significant visual recovery to a change in tempo, $t(15) = 1.1$, $p > .1$; $t(15) = .65$, $p > .1$, respectively. These results suggest that infants did not discriminate between the two tempos following unimodal visual exposure.

Secondary analyses were performed to determine whether infants showed any evidence of stimulus

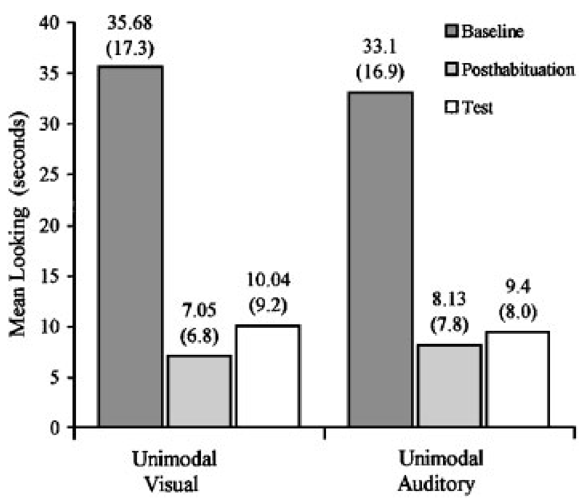

FIGURE 3 Experiment 2: Mean visual fixation (and *SD*s) as a function of trial type (baseline, posthabituation, and test) during unimodal visual and unimodal auditory presentation of tempo. Baseline is the mean visual fixation during the first two habituation trials, reflecting initial interest level. Posthabituation is the mean visual fixation during the two no-change trials just after the habituation criterion was met, reflecting final interest level in the habituation event. Test is the mean visual fixation during the two tempo change trials.

preferences. A three-way analysis of variance was performed on the visual recovery scores with condition (unimodal visual, unimodal auditory), stimulus rhythm (Rhythm 1 vs. Rhythm 2), and tempo of habituation (fast vs. slow) as between subject factors. Results indicated no significant effect of any of the factors or interactions ($ps > .1$). Thus, infants did not show greater visual recovery in the auditory as compared to the visual condition, for one rhythm over the other, or for one tempo over the other.

To further evaluate the primary research question, we asked whether infants showed better discrimination of tempo under bimodal as compared with unimodal habituation conditions by comparing infants' performance across Experiments 1 and 2 on the main dependent variable, visual recovery (see Figure 2). Given no differences between the unimodal visual and auditory conditions on any of the habituation variables, performance across the two unimodal conditions was collapsed. A one-way analysis of variance was conducted with experiment (bimodal vs. unimodal) as the main factor on visual recovery scores. Results indicated a significant difference between infants' visual recovery following a change in tempo after bimodal exposure in Experiment 1 as compared with unimodal exposure in Experiment 2, $F(1, 46) = 5.14$, $p = .028$. These findings provide additional support for the intersensory redundancy hypothesis and indicate that at 3 months, discrimination of amodal tempo is significantly greater following bimodal as compared with unimodal processing.

Secondary analyses also were conducted across Experiments 1 and 2 to determine whether infants differed in their patterns of habituation to the unimodal auditory, visual, and bimodal stimuli, and if so, whether the differences qualified the main findings. Analyses assessed whether infants differed in initial interest level (mean baseline looking), mean number of trials to habituation, total processing time (defined as the mean number of seconds to habituation), or final interest level (mean posthabituation looking) in the stimulus events. One-way analyses of variance were conducted on each of the four measures of habituation with condition (bimodal, unimodal visual, unimodal auditory) as the main factor. Results indicated no main effects of condition ($ps > .1$), indicating that infants in the three conditions did not differ significantly in initial interest, processing time, or final interest in the stimuli. We also examined whether infants' level of fatigue (ability to show visual recovery to a control trial) differed across conditions of Experiments 1 and 2 by evaluating their visual recovery to the final control trial (turtle) with respect to their posthabituation fixation level to the hammer event. A one-way analysis of variance with condition (bimodal, unimodal visual, unimodal auditory) revealed no significant difference in recovery to the control stimulus across conditions, $F(1, 45) = 1.74$, $p > .1$. Thus, infants did not become differentially bored or fatigued across conditions during the course of the experiments. In fact, visual recovery to the final control trial was highly significant in all three conditions, bimodal, unimodal visual, and unimodal auditory habituation, according to single sample t tests against the chance value of 0 ($ps < .00001$). These analyses suggest that infants in Experiments 1 and 2 showed similar patterns of visual fixation prior to test, indicating comparable levels of initial interest, habituation, and fatigue, and no differences were found that could qualify the main results. Three-month-old infants discriminate bimodal events on the basis of differences in tempo, but show no evidence of discrimination when the unimodal components of these events are presented.

GENERAL DISCUSSION

The results of this study indicate that amodal stimulus properties such as tempo are more salient and readily perceived by young infants when they are presented bimodally than when they are presented unimodally. This replicates and extends the generalizability of the results found by Bahrick and Lickliter (2000) with 5-month-olds' perception of the amodal property of rhythm, to younger, 3-month-old infants, and to the amodal property of tempo. In the present study, 3-month-old infants discriminated between two different tempos when they were presented bimodally (Experiment 1), but not when they were presented unimodally (Experiment 2). In fact, their discrimination of the amodal tempos was significantly greater under the bimodal as compared with the unimodal presentations. It appears that when infants first learn to differentiate amodal information, differentiation of the amodal property is facilitated by redundant, bimodal stimulation. Because most events are multimodal, this facilitation can promote earlier processing, learning, and memory for stimulus properties specified in more than one sensory modality. Conversely, when multimodal stimulation is not available, attention is likely to be more broadly focused on a variety of stimulus properties that are unique to individual sensory modalities. Consequently, amodal properties then will be less attended (Experiment 2). The results of this study thus extend the generalizability of the intersensory redundancy hypothesis (Bahrick & Lickliter, 2000) to younger infants and to additional amodal properties.

In addition, the findings of this study demonstrate that infants as young as 3 months are capable of perceiving the tempo of a complex, naturalistic, bimodal event. Perception of tempo is critical for perceiving the unity of sounds and objects, for effective communication and social interaction, for perceiving meaning, affect, and emphasis, and for the mutual regulation of the rhythmic structure of dialogue (Bahrick & Pickens, 1994; Bullowa, 1979; Jaffee et al., 2001; Stern, 1985; Trevarthan, 1993; Walker-Andrews, 1997). To our knowledge, this is the first study that has demonstrated that infants as young as 3 months discriminate tempo in naturalistic events, apart from other temporal properties such as rhythm or synchrony that typically covary with tempo.

The present findings are congruent with other studies of human infants documenting the salience of multimodal stimulation in the months following birth. For example, studies have demonstrated that infants discriminate changes in amodal properties such as rhythm, rate, synchrony, and duration when the changes occur in both the visual and auditory modalities concurrently and synchronously (e.g., Gogate & Bahrick, 1998; Kuhl & Meltzoff, 1984; Lewkowicz, 1988a, 1988b, 1992, 1996; Pickens & Bahrick, 1995, 1997; Spelke, 1979; Spelke et al., 1983). When changes in these amodal properties occur in only one modality, discrimination is not consistently observed (Balaban & Dannemiller, 1992; Lewkowicz, 1988b, 1996). Further, Bahrick (1988, 1992, 1994, 2000) provided evidence regarding the fundamental role of bimodally specified information for guiding and organizing early perceptual learning and development. In these studies, amodal redundant information was found to provide the basis for intersensory learning about which sounds and objects belonged together. It also buffered the infant from learning incongruent or arbitrary intersensory relationships. Further, the ability to detect amodal relations was found to precede and provide the basis for the detection of arbitrary, modality-specific relations (Bahrick, 1992, 1994, 2000; Gogate & Bahrick, 1998; Hernandez-Reif & Bahrick, 2001).

Comparative research has provided additional support for the view that bimodal stimulation is functionally distinct from unimodal stimulation, even during the prenatal period (Gottlieb, 1993; Lickliter, Lewkowicz, & Columbus, 1996; Sleigh, Columbus, & Lickliter, 1998). Work with precocial birds has shown different developmental consequences of bimodal versus unimodal exposure to the same information. For example, consistent with the intersensory redundancy hypothesis, recent evidence from bobwhite quail indicates that embryos learn an individual maternal call prenatally four times faster when it is presented concurrently and synchronously with patterned light than when the call is presented unimodally (Lickliter et al., 2002). Redundant, bimodal information appears to facilitate attentional selectivity and perceptual learning even during the prenatal period.

Indeed, attentional selectivity for bimodally specified information will likely be most pronounced during early perceptual development, when the information to be perceived is relatively difficult or novel. Once the information is easily discriminated or familiar to the young organism, the advantage of redundant bimodal stimulation likely will diminish. For example, converging evidence from a number of studies demonstrates that young infants are adept perceivers of amodal information in unimodal stimulation (e.g., Chang & Trehub, 1977; Demany, McKenzie, & Vurpillot, 1977; Mendelson, 1986; Morrongiello, 1984, 1988). Studies also have documented infants' perception of amodal information in unimodal stimulation using cross-modal transfer procedures (see Rose & Ruff, 1987, for a review) as well as procedures that involve the successive presentation of audible and visible components of an event (e.g., Bahrick, 1983; Spelke et al., 1983). However, comparisons of infants' abilities to detect amodal properties in bimodal versus unimodal contexts with comparable stimuli and procedures, and with measures of sufficient sensitivity to detect differences, have not been made, and thus it is not yet clear whether the advantage of intersensory redundancy persists across development. Future research must explore this issue.

In our view, intersensory redundancy *initially* guides perceptual learning by capturing and directing infants' attention toward those properties of an event that are redundantly specified. With experience in a given domain, infants' attention becomes more flexible and efficient such that they can perceive multiple properties of an event under varying conditions. In this case, they may first process amodal properties and then quickly move on to explore other properties of stimulation in a given encounter. Future research in needed to examine when and under what conditions older infants are able to discriminate a change in amodal information (e.g., tempo or rhythm) with unimodal versus bimodal stimulation as well as when and under what conditions older infants are capable of detecting changes in unimodal properties (e.g., color, orientation, or pitch) with bimodal versus unimodal stimulation.

The intersensory redundancy hypothesis emphasizes that it is the redundancy of amodal stimulation in multimodal objects and events that recruits infants' attention and initiates perceptual processing of amodal information. Given that the infant's environment is primarily multimodal, this redundancy has important implications for perception, learning, and memory across development in a variety of domains including cognitive, social, and communicative development. The availability of intersensory redundancy creates initial conditions in which amodal information can guide and scaffold development. Adults instinctively scaffold infant attention and learning by providing rich sources of intersensory redundancy when interacting with infants. For example, adults use infant-directed speech with exaggerated prosody, including amodal tempo, rhythm, duration, and intensity shifts in speech (Ferguson, 1964; Fernald, 1985; Papousek, Papousek, & Bornstein, 1985). This speech occurs along with synchronized movements of the mouth, face, and body, given that speech is an inherently multimodal event, and thus provides a rich source of intersensory redundancy. Adult–infant communication is temporally patterned, mutually regulated, and coordinated across modalities (Gogate, Bahrick, & Watson, 2000; Jaffee et al., 2001; Koester, Papousek, & Papousek, 1989; Zukow-Goldring, 1997). Further research is needed to evaluate the importance of "multimodal motherese" (Gogate & Bahrick, 1998), and the importance of intersensory redundancy in adult–infant communication for social and linguistic development. As a case in point, when mothers teach infants novel verbal labels for objects and events, they provide intersensory redundancy across sound and gesture by synchronizing their speech sounds with motions of the object (Gogate, Bahrick, & Watson, 2000). In fact, early learning of speech sound–object relations has been found to be facilitated by this intersensory redundancy and impaired when redundancy is lacking (Gogate & Bahrick, 1998). There are a host of intuitive parental behaviors which provide exaggerated intersensory redundancy for the infant and which can support learning about objects, events, language, social interaction, and the self. Given the rich source of intersensory redundancy in the infants' social, communicative, and cognitive environment, paired with the salience of this redundancy for infant attention, intersensory redundancy is likely to have a powerful organizing influence across early development.

NOTES

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