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Intrasensory Redundancy Facilitates Infant Detection of Tempo: Extending Predictions of the Intersensory Redundancy Hypothesis

Lorraine E. Bahrick and Robert Lickliter
Department of Psychology
Florida International University

Irina Castellanos
Department of Otolaryngology Head and Neck Surgery
Indiana University School of Medicine

James Torrence Todd
Department of Psychology
Florida International University

Research has demonstrated that intersensory redundancy (stimulation synchronized across multiple senses) is highly salient and facilitates processing of amodal properties in multimodal events, bootstrapping early perceptual development. The present study is the first to extend this central principle of the intersensory redundancy hypothesis (IRH) to certain types of intrasensory redundancy (stimulation synchronized within a single sense). Infants were habituated to videos of a toy hammer tapping silently (unimodal control), depicting intersensory redundancy (synchronized with a soundtrack) or intrasensory redundancy (synchronized with another visual event; light flashing or bat tapping). In Experiment 1, 2-month-olds showed both intersensory and intrasensory facilitation (with respect to the unimodal control) for

Correspondence should be sent to Lorraine Bahrick, Department of Psychology, Florida International University, Miami, FL 33199. E-mail: bahrick@fiu.edu.

detecting a change in tempo. However, intrasensory facilitation was found when the hammer was synchronized with the light flashing (different motion) but not with the bat tapping (same motion). Experiment 2 tested 3-month-olds using a somewhat easier tempo contrast. Results supported a similarity hypothesis: intrasensory redundancy between two dissimilar events was more effective than that between two similar events for promoting processing of amodal properties. These findings extend the IRH and indicate that in addition to intersensory redundancy, intrasensory redundancy between two synchronized dissimilar visual events is also effective in promoting perceptual processing of amodal event properties.

Young infants face several fundamental challenges in making sense of the dynamic world of constantly changing stimulation to all of their senses. How do they determine which patterns of stimulation belong together and constitute unitary events, such as the face and voice of a person speaking, and which are unrelated? And how do they learn to selectively attend to stimulation that is relevant to their needs and actions and ignore the vast array of stimulation that is irrelevant? Proper intersensory coordination provides a critical basis for meeting these challenges and is a foundation for the typical development of attention, perception, learning, and memory (Bahrick & Lickliter, 2014; Bremner, Lewkowicz, & Spence, 2012).

Convergent evidence across human and nonhuman animal infants highlights the importance of infant sensitivity to a critical type of information for promoting proper intersensory coordination and economical attention allocation, "redundant amodal information" (Bahrick & Lickliter, 2012; Bahrick & Pickens, 1994; Lickliter & Bahrick, 2004). The environment provides two types of information to our sensory systems about the properties of objects and events, information that is redundant and information that is nonredundant across the senses. Properties of events that are *redundantly specified* across more than one sense modality are termed *amodal* properties. These properties, such as synchrony, rhythm, and tempo of action, are not tied to a particular sense but are detectable across two or more senses. For example, the sights and sounds of a ball bouncing share temporal synchrony, rhythm, and tempo. When the same temporal information is simultaneously detected in two modalities (intersensory redundancy), the invariant amodal information becomes attentionally salient. It specifies the unitary nature of the audible and visible stimulation, separating it from other events that do not share its structure (Bahrick, 2004; Bahrick & Lickliter, 2002, 2012; Gibson, 1969; Lewkowicz, 2000).

Young infants are adept at detecting amodal information, including tempo, rhythm, and duration uniting audible and visible stimulation in speech and object events, as well as affect and prosody in audiovisual speech (see Bahrick, 2010; Bahrick & Lickliter, 2012; Lewkowicz, 2000). Detection of amodal relations allows intersensory development to proceed veridically, without an initial knowledge base to direct selectivity. This guides and organizes perceptual development by promoting detection of unitary multimodal events prior to processing more specific details of those events (Bahrick, 1992, 2001; Bahrick, Hernandez-Reif, & Flom, 2005; Gogate & Bahrick, 1998; Hernandez-Reif & Bahrick, 2001). Thus, defining the conditions that facilitate versus attenuate selective attention and perception of amodal properties is central to developmental theory and to understanding how perception functions in natural, multimodal learning contexts.

To provide an organizing conceptual framework for this effort, we proposed the intersensory redundancy hypothesis (IRH, Bahrick & Lickliter, 2000, 2002, 2012, 2014; Bahrick, Lickliter, & Flom, 2004). The IRH is a model of selective attention which synthesizes knowledge gained from behavioral research on animal and human intersensory development with findings from the neural level of analysis to address attentional processes underlying early intersensory development. *Intersensory redundancy* refers to the spatially coordinated and temporally synchronous presentation of the same amodal information across two or more senses. The IRH attempts to explain how the detection of redundant amodal information can guide selective attention, perception, and learning during infancy and how this process is intercoordinated with perception of nonredundant and modality-specific information (information specific to a single sense such as color, pattern, pitch, or timbre).

A fundamental prediction of the IRH is that amodal properties of events are most salient and receive processing priority when they are detected in synchronous multimodal stimulation (providing intersensory redundancy), as contrasted with when the same amodal properties are detected in unimodal stimulation (where no intersensory redundancy is available). This is termed *intersensory facilitation*. A variety of studies with both human and animal infants have demonstrated intersensory facilitation. For example, human infants detect the rhythm and tempo of an object tapping across redundantly presented (synchronized) sights and sounds of impacts, but not in unimodal stimulation (sights or sounds alone) or when the patterns are presented asynchronously across visual and acoustic stimulation (Bahrick, Flom, & Lickliter, 2002; Bahrick & Lickliter, 2000). Further, infants detect amodal properties such as rhythm and tempo developmentally earlier in redundant audiovisual synchronous stimulation than in unimodal stimulation (Bahrick & Lickliter, 2004). These principles of the IRH have enhanced our understanding of the emergence and maintenance of a variety of attentional, perceptual, and cognitive skills in infancy, including the development of affect discrimination (Flom & Bahrick, 2007), face discrimination (Bahrick, Krogh-Jespersen, Argumosa, & Lopez, 2014; Bahrick, Lickliter, & Castellanos, 2013a; Bahrick & Newell, 2008), rhythm and tempo discrimination (Bahrick & Lickliter, 2000, 2004; Bahrick et al., 2002), numerical discrimination (Farzin, Charles, & Rivera, 2009; Jordan, Suanda, & Brannon, 2008), sequence detection (Lewkowicz, 2004), abstract rule learning (Frank, Slemmer, Marcus, & Johnson, 2009), operant learning (Kraebel, 2012), and word comprehension and segmentation (Gogate & Bahrick, 2001; Gogate, Walker-Andrews, & Bahrick, 2001; Hollich, Newman, & Jusczyk, 2005). Together, these studies demonstrate intersensory facilitation of amodal properties across early development. That is, intersensory redundancy promotes enhanced and earlier detection of a variety of amodal properties as compared with detection of the same amodal properties in unimodal stimulation. The advantages of intersensory redundancy for detection of amodal properties also appear to extend to older infants, children, and adults (Bahrick, Krogh-Jespersen, Naclerio, & Lau, 2011; Bahrick, Todd, & Martin, 2013b).

Although the importance of intersensory redundancy for unifying information across the senses and bootstrapping perceptual and cognitive development has been well documented, the basis for the attentional salience of intersensory redundancy remains poorly understood. How does synchrony/redundancy across the senses promote attention to amodal properties? Does redundancy create a perceptual "pop out" effect when different sensory signals overlap? Do some forms of redundancy promote detection of amodal properties more effectively than others?

Neural findings provide some evidence for mechanisms underlying the attentional salience of intersensory redundancy. Human infants show heightened attention and deeper processing of redundant than nonredundant stimulation according to measures of event-related potential. Five-month-olds showed a greater amplitude Nc component (associated with attentional salience) and a greater reduction in the late positive slow wave across blocks (associated with depth of processing and recognition memory) during synchronous than asynchronous face–voice stimulation (Reynolds, Bahrick, Lickliter, & Guy, 2014; see also Hyde, Jones, Flom, & Porter, 2011). Animal and human studies have found evidence of multisensory neurons and a *superadditive effect* across the senses. That is, simultaneous and congruent sensory stimulation to two sense modalities elicits neural activation that is greater than the sum of the neural activation for each sense alone (Calvert, Campbell, & Brammer, 2000; Stein & Meredith, 1993).

To date, research has focused on *intersensory* redundancy—that is, redundancy across the senses—for highlighting amodal properties.

However, in natural events, examples of *intrasensory* redundancy—that is, redundancy within a single sense—also abound. For example, several musical instruments playing or two individuals speaking in unison provide auditory redundancy, and several dancers moving together provide visual redundancy. Might redundancy *within a sense* also promote attention to amodal properties of events? Do the facilitating effects of redundancy for highlighting amodal properties extend to intrasensory redundancy as well? If intrasensory redundancy is effective, are some types more effective than others?

The present research addresses these critical and unexplored questions. Specifically, in Experiment 1, we asked whether intrasensory redundancy could enhance attention and perceptual processing of amodal properties of stimulation in a manner similar to intersensory redundancy. Intersensory redundancy was depicted by a toy hammer tapping in synchrony with its percussive sound. Intrasensory redundancy was created by synchronizing a video of the hammer with a light flashing or a toy bat tapping, creating two types of intrasensory visual redundancy, different objects undergoing similar motions (both continuous up/down) versus different objects undergoing different motions (discrete on/off versus continuous up/down). We explored whether 2-month-old infants would (1) show enhanced detection of the amodal property of tempo when it was redundantly specified *within* or *across* sense modalities, as compared with when the amodal property was unimodally presented and (2) whether one type of intrasensory redundancy might be more effective than another. Results revealed intrasensory facilitation for the synchronized objects undergoing different motions (hammer/light) but not for the synchronized objects undergoing the same motions (hammer/bat). Experiment 2 explored a similarity hypothesis as a possible basis for differences in the effectiveness of the two examples of intrasensory redundancy in somewhat older infants and an easier task.

EXPERIMENT 1: INTRASENSORY FACILITATION IN 2-MONTH-OLD INFANTS

The present experiment assessed the effects of intersensory redundancy and intrasensory redundancy on infants' perception of tempo. Although prior research has demonstrated intersensory facilitation of tempo in 3-month-old infants (Bahrick & Lickliter, 2004; Bahrick et al., 2002), no studies have assessed tempo discrimination in audiovisual events in infants as young as 2 months. Further, no studies have assessed intrasensory facilitation nor compared intrasensory with intersensory processing. Would intrasensory redundancy also facilitate processing of redundantly specified tempo and, if so, to what extent relative to intersensory redundancy? Consistent with Gibson's (1969) invariant detection view, perceivers detect patterns of stimulation that are amodal and common across differing forms of sensory stimulation, both within and across sense modalities. Thus, if intrasensory redundancy is also effective in highlighting amodal properties of events, we expected to find evidence that two patterns of synchronous visual stimulation would lead to enhanced detection of the amodal property of tempo (relative to unimodal visual stimulation), similar to the enhancement observed for synchronous patterns of audiovisual stimulation. We also reasoned that enhanced detection of amodal properties may be more evident under some conditions of intrasensory redundancy than others. As a first step in exploring this possibility, we created two types of intrasensory redundancy, one depicting visual events that were very dissimilar (toy hammer tapping with a light flashing) and another depicting visual events that were more similar (toy hammer tapping with bat tapping).

Method

Participants

Sixty-four 2-month-old infants (35 females and 29 males) with a mean age of 71.16 days (*SD* = 3.15) participated. All the infants had a gestational age of at least 39 weeks. Fifty infants were Hispanic, 10 were Caucasian, 3 were multiracial, and 1 was of Asian origin. Thirty-nine additional infants participated, but their data were excluded from analyses due to failure to habituate (*n* = 9), equipment failure (*n* = 7), falling asleep (*n* = 6), fussiness (*n* = 6), experimenter error (*n* = 5), external interference (*n* = 1), visual recovery exceeding 3 *SD*s from the group mean (*n* = 1), and failure to pass the fatigue criterion (*n* = 4; see the Procedures section for details). When broken down by condition, the number of infants whose data were excluded was intersensory audiovisual (*n* = 8), intrasensory different movement (*n* = 10), intrasensory same movement (*n* = 8), and unimodal visual control (*n* = 13).

Stimulus events

All events depicted versions of a red toy hammer tapping one of two-four-beat rhythms (rhythm 1 versus 2) at one of two tempos (159 versus 198 beats per minute; bpm) against an off-white wooden surface set against a black background. Rhythms and tempos were modeled after those of Bahrick et al. (2002) and Bahrick and Lickliter (2000) with two half beat, one whole beat, and another half beat note (rhythm 1) or the reverse (rhythm 2). The tempos of 159 bpm and 198 bpm were selected based on pilot data to yield somewhat difficult tempo contrasts that we expected would be discriminable to 2-month-old infants with the help of intersensory audiovisual redundancy, but not in the unimodal visual control condition.

Stimulus events depicting different versions of the videotaped toy red hammer tapping a four-beat rhythm at a particular tempo were created for each of the four conditions (intersensory audiovisual, intrasensory different movement, intrasensory same movement, unisensory visual control; see Figure 1). All events were created by an experimenter (a trained musician) who listened to a computer-generated recording of the rhythm/tempo through an earpiece and tapped the toy hammer in time with the recording. (1) For the intersensory audiovisual redundancy condition (hammer/sound), the red toy hammer depicted continuous up and down movements and could be seen and heard tapping in synchrony against a surface, creating naturalistic percussive sounds. The same video patterns depicting the toy red hammer tapping were used in the remaining three conditions, but without a soundtrack accompaniment. (2) In the intrasensory different movement (hammer/light) visual redundancy condition, the continuous up and down movements of the red toy hammer were synchronized with the discrete (on/off) flashing of a yellow light. The light was illuminated (via a simple circuit connecting the light with a plate under the surface where the hammer struck) each time the hammer touched the surface for a duration

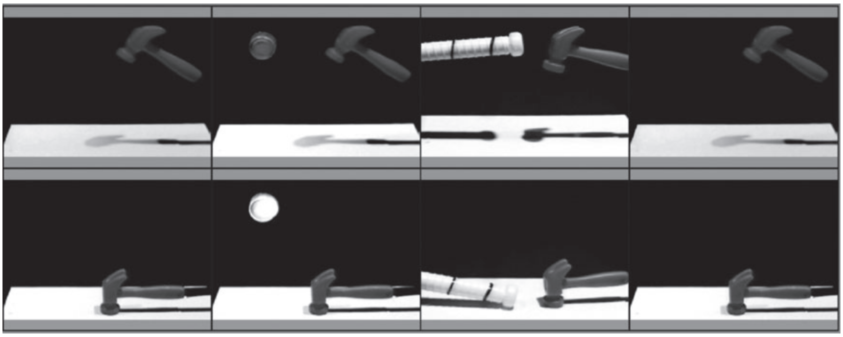

Figure 1 Static images of the stimulus events.

of approximately 160 ms (SD = 19.5) for the half beats and 273 ms (SD = 16.5) for the whole beat during each cycle of the rhythm. (3) In the intrasensory same movement (hammer/bat) visual redundancy condition, the continuous up and down movements of the red toy hammer were synchronized with the continuous up and down movements of a yellow bat with blue stripes. This was created by the experimenter who held the toy hammer in one hand and the bat in the other hand and struck them simultaneously and in synchrony. (4) In the unimodal visual baseline control (hammer only) condition, the video of the red toy hammer was shown tapping silently with no accompanying sound or visual event. A control display depicting a green and white plastic turtle with spinning arms, which created a whirring sound, was also used as a warm up and final event, as in prior studies (Bahrick & Lickliter, 2000, 2004; Bahrick et al., 2002).

Apparatus

Infants sat in a standard infant seat facing a color television monitor (Sony KV-20520) approximately 55 cm away. Black curtains surrounded the television monitor to obscure extraneous stimuli and two 7-cm apertures allowed trained observers to view the infants' visual fixations. Observers, unaware of the infants' condition, depressed buttons on a joystick corresponding to the length of the infants' visual fixations. The joystick was connected to a computer, which collected the data on line. The observations of the primary observer controlled the video presentations, and those of the secondary observer were recorded for later calculation of interobserver reliability. To prevent extraneous noise from distracting the infants and to reduce the time needed for switching tapes from one trial to the next, we used four Panasonic video decks (DS545 and AG7750) to play the events.

Procedure

Infants were tested in an infant-controlled habituation procedure (with procedures identical to Bahrick & Lickliter, 2000, 2004), to determine whether they could detect a change in tempo following intersensory audiovisual redundancy (n = 16), intrasensory (different movement) visual redundancy (n = 16), intrasensory (same movement) visual redundancy (n = 16), or unisensory visual, no redundancy control (n = 16) exposure to a rhythmic sequence. Infants in the intersensory condition received synchronized audible and visible presentations of the hammer events for habituation and test. Infants in the intrasensory and unimodal control conditions received silent visual presentations of the hammer events for habituation and test. The tempos (slow; 159 bpm versus fast; 198 bpm) and rhythms (1 versus 2) of the events were counterbalanced such that half of the infants in each condition received rhythm 1 and half received rhythm 2. Half of the infants within each of these groups received the slow tempo for habituation and the fast one for test, and half received the opposite arrangement.

The infant-controlled habituation procedure (see Bahrick & Lickliter, 2000, 2004; Bahrick et al., 2002) began with a control trial depicting the toy turtle and continued with 6 mandatory habituation trials, to a maximum of 20 habituation trials. Trials began when infants visually fixated on the monitor and terminated when infants made a single look away for 1 s or when 45 s had elapsed. Additional trials of the same event were presented until infants reached the habituation criterion: a decrease of 50% or greater in visual fixation on two consecutive trials, relative to their fixation level on the first two trials of the habituation procedure (baseline). Once the habituation 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 (see Bertenthal, Haith, & Campos, 1983). If the infant's posthabituation fixation level exceeded that of their habituation criterion, they were considered not to have habituated. In this case, additional habituation trials were presented until they reached the habituation criterion again and then test trials were presented (see Vaillant-Molina & Bahrick, 2012). Eight infants (intersensory, $n = 3$; intrasensory different movement, $n = 2$; intrasensory same movement, $n = 2$; unimodal control, $n = 1$) received additional habituation trials prior to their test trials. Following the two no-change posthabituation trials, infants received two infant-control test trials depicting the familiar rhythmic event but at a novel tempo to assess discrimination of the tempo change. A final control trial depicting a toy turtle ended the testing session. Visual recovery, the difference in visual fixation on the two test trials depicting the novel tempo relative to that of the two posthabituation trials depicting the familiar tempo, served as the measure of tempo discrimination.

To make certain that infants were not overly fatigued, their visual fixations to the initial and final control trials depicting the toy turtle were compared. Infants were judged as fatigued ($n = 4$) if their visual fixation to the final control trial was less than 20% of their fixation level to the initial control trial (for details, see Bahrick, Lickliter, & Flom, 2006; Bahrick, Lickliter, Castellanos, & Vaillant-Molina, 2010). Overall, infants in the sample showed high levels of interest in the final control trial with respect to the initial control trial ($M = 1.33$; $SD = .90$). In addition, as a basis for establishing interobserver reliability, two observers monitored approximately 42% ($n = 27$) of the infants and a Pearson product-moment correlation between the scores of the two observers was calculated. The mean correlation between the two observers was .99 ($SD = .02$).

Results

Visual recovery to the change in tempo served as the primary dependent variable. Infants' visual recovery to the change in tempo as a function of stimulus condition (intersensory redundancy, intrasensory different movement, intrasensory same movement, unimodal visual control) is depicted in Figure 2.

To determine under which conditions infants showed evidence of discriminating the change in tempo, single-sample *t*-tests on mean visual recovery scores against the chance value of zero were conducted (with

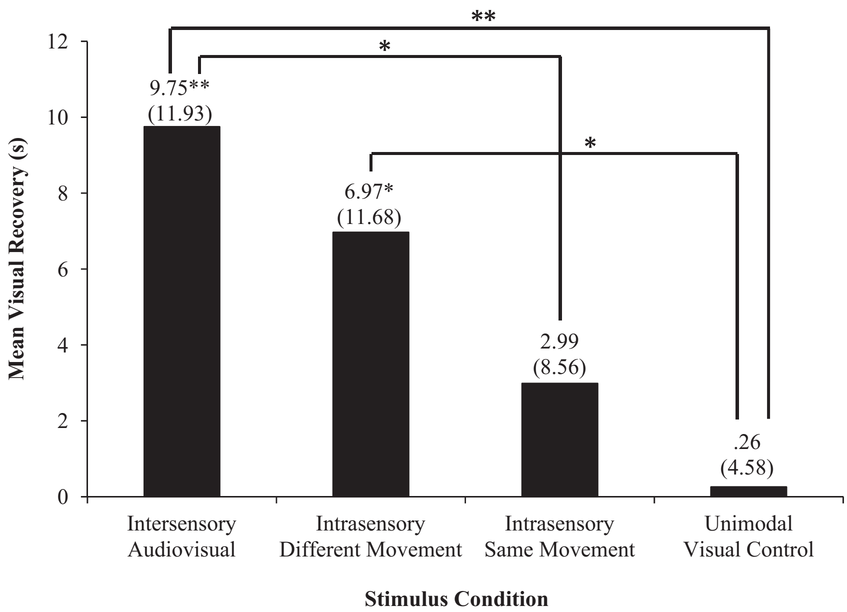

Figure 2 Experiment 1: Mean visual recovery (and *SD*) to tempo contrasts of high difficulty (198 versus 159 bpm) as a function of condition in 2-month-old infants ($N = 64$). $^{**}p < .01$; $^{*}p < .05$.

all tests two-tailed). Results indicate that infants in the intersensory audiovisual and intrasensory different movement conditions demonstrated significant visual recovery to the change in tempo ($t(15) = 3.27$, $p = .005$, *Cohen's* $d = .82$; $t(15) = 2.39$, $p = .03$, $d = .60$, respectively) indicating tempo discrimination. In contrast, in the intrasensory same movement condition, where redundancy was conveyed through two objects, both moving continuously, infants failed to show significant visual recovery to the change in tempo, $t(15) = 1.40$, $p = .18$, $d = .35$. Similarly, in the unimodal visual baseline condition, where redundancy was not available, infants also failed to show visual recovery to the change in tempo, $t(15) = .22$, $p = .83$, $d = .06$.

To address our primary research question, under what conditions did infants show facilitation of tempo discrimination with respect to the unimodal control group, we conducted a one-way analysis of variance (ANOVA) on visual recovery scores with condition (intersensory redundancy, intrasensory different movement, intrasensory same movement, unimodal visual control) as the between-subjects factor. Results revealed a main effect of condition, $F(3, 60) = 3.03$, $p = .04$, $\eta_p^2 = .13$. Planned pairwise comparisons indicated that infants in the intersensory audiovisual and intrasensory different movement conditions demonstrated significantly greater visual recovery to the change in tempo than infants in the unimodal visual control condition ($p = .007$, $p = .05$, respectively). These results provide evidence for both intersensory and intrasensory facilitation. Also, infants in the intersensory audiovisual condition showed greater visual recovery to the change in tempo than infants in the intrasensory same movement condition ($p = .05$), suggesting that intersensory redundancy provides better information for tempo than some forms of intrasensory redundancy. Furthermore, results indicated a significant linear decrease across condition, $F(1, 60) = 9.05$, $p = .004$, with visual recovery scores decreasing monotonically, from intersensory audiovisual → intrasensory different movement → intrasensory same movement → unimodal visual control.

Secondary analyses were performed to examine any potential differences in tempo discrimination as a function of the tempo or rhythm of the stimulus events. A two-way ANOVA was conducted on visual recovery with condition, habituation tempo (159 bpm versus 198 bpm), and rhythm (1 versus 2) as between-subjects factors. No main effects of tempo or rhythm or interactions between these variables and condition were found (*p*s > .06), indicating that visual recovery did not differ as a function of which tempo or rhythm infants received during habituation.

Secondary analyses were also performed on each of the four habituation variables (see Table 1) to assess whether infants showed differences in habituation patterns as a function of condition. Results indicate a significant main effect of condition for the number of trials infants needed in order to habituate, $F(3, 60) = 3.63$, $p = .02$, $\eta_p^2 = .15$, with infants in the intrasensory same movement visual redundancy (hammer/bat) condition requiring significantly more trials to habituate than infants in the intrasensory different movement (hammer/light) and unisensory visual control conditions ($p = .004$, $p = .02$, respectively). Results also indicate a main effect of condition for processing time, $F(3, 60) = 3.41$, $p = .02$, $\eta_p^2 = .13$, with infants in the intersensory redundancy and intrasensory same movement condition spending more overall time looking to the events than infants in the intrasensory different movement condition ($p = .01$, $p = .02$, respectively) and with infants in the intersensory redundancy condition spending more overall time looking to the event than infants in the unisensory visual control ($p = .04$). To determine whether these results impacted the main findings, separate analyses of variance were conducted with processing time and number of trials to habituation as covariates. Results indicated that neither processing time nor number of trials to habituation was significant covariates ($F(1, 59) = .00$, $p = .97$, $\eta_p^2 = .00$; $F(1, 59) = .01$, $p = .94$, $\eta_p^2 = .00$, respectively) and the main effect of condition was still significant ($F(3, 59) = 2.94$, $p = .04$, $\eta_p^2 = .13$; $F(3, 59) = 2.98$, $p = .04$, $\eta_p^2 = .13$, respectively) even when processing time was held constant.

TABLE 1

Experiment 1, 2-month-olds: Means and Standard Deviations For Visual Fixation in Seconds for Baseline (First Two Habituation Trials), Number of Habituation Trials, Posthabituation (Two No-Change Trials Following Habituation Reflecting Final Interest Level), Processing Time (Total Number of Seconds Fixating the Habituation Events), and Test Trials as a Function of Condition

Condition	*Baseline*	*Trials to Habituation*	*Posthabituation*	*Processing Time*	*Test*
Intersensory Audiovisual	35.49 (11.30)	10.44 (4.35)	9.70 (6.84)	272.55 (150.73)	19.45 (11.78)
Intrasensory Different Movement	29.91 (13.08)	8.00 (2.22)	5.90 (5.08)	171.67 (80.78)	12.88 (12.23)
Intrasensory Same Movement	30.89 (9.96)	11.56 (2.87)	7.44 (4.88)	263.25 (115.79)	10.42 (7.90)
Unimodal Visual Control	29.97 (11.14)	8.75 (3.71)	9.00 (4.55)	188.03 (83.59)	9.25 (6.13)

Discussion

Our results replicate previous findings of intersensory facilitation (Bahrick & Lickliter, 2000, 2004; Bahrick et al., 2002) and demonstrate greater detection of a change in an amodal temporal property (tempo) in synchronous audiovisual stimulation than in unimodal visual stimulation. Further, they extend prior findings of intersensory facilitation of tempo discrimination in 3-month-old infants (Bahrick et al., 2002) to infants of 2 months of age and to a more difficult tempo contrast (159 versus 198 bpm) than that given to 3-month-olds in the prior study (110 versus 240 bpm).

More importantly, these results also provide the first evidence of intrasensory facilitation of sensitivity to amodal properties. Two-month-old infants who received intrasensory visual redundancy between the continuous movements of a toy hammer tapping and the discrete flashing of a synchronized light (intrasensory different movement condition) showed significantly greater detection of a change in the tempo of the toy hammer tapping than infants who received unimodal visual stimulation. In contrast, results revealed no evidence of intrasensory facilitation when two visual events differed only in visual appearance but depicted the same type of motion (the hammer and bat both undergoing synchronous, continuous up/down movements). These findings indicate that, similar to redundancy across the senses, some types of redundancy within a sense modality (but not other types) are also effective in recruiting infants' selective attention and promoting perceptual processing of amodal properties of stimulation, and they do so more effectively than unimodal stimulation. This facilitation of attention to amodal properties appears to be evident particularly when two patterns of synchronous visual stimulation are relatively dissimilar, in this case, differing in appearance and the type of motion. Facilitation was not evident for synchronized events of high similarity, two objects differing in appearance (yellow bat versus red hammer) but depicting the same continuous up and down movements. Such synchronous stimulation between different objects moving in similar ways is a common occurrence in the environment, including dancers coordinating movements, people speaking or singing in unison, or musicians playing a concert. Dissimilar and synchronous movements are also evident. In bumper-to-bumper traffic, one can see the onset/offset of brake lights synchronized with the stop and start of each vehicle's movement. Dancers and musicians also provide rich examples of dissimilar movements synchronized across time. Different instruments require different types of motion (bowing, plucking, striking, etc.), and choreography typically depicts coordination between the same and different dance movements to achieve different effects. Results also revealed greater intersensory facilitation for tempo discrimination (audiovisual hammer) relative to intrasensory discrimination in the same movement condition. If replicable, taken together with the other conditions, this finding would suggest that detection of amodal properties of stimulation is also facilitated in intersensory stimulation with respect to some types of intrasensory stimulation.

Further, results of this comparison also address the potential confound of amount of stimulation typically inherent in studies comparing intersensory conditions (which provide two streams of stimulation) with unisensory conditions (which provide only a single stream of stimulation). In prior studies (Bahrick & Lickliter, 2000; Bahrick et al., 2002), an asynchronous control condition was included (providing two streams of stimulation identical to that of the synchronous condition) and results demonstrated greater discrimination under synchronous than asynchronous conditions. In the present experiment, both the intersensory (hammer with soundtrack) and intrasensory (hammer with bat or light) events provide two streams of stimulation, holding relatively constant the amount of stimulation across conditions. Nevertheless, results revealed greater discrimination following intersensory than intrasensory (same movement) stimulation but not intrasensory (different movement) stimulation. Thus, some types of synchronous intrasensory stimulation appear to be more effective than others in promoting perceptual processing of amodal temporal properties.

The findings also revealed that tempo discriminability (visual recovery) decreased monotonically across conditions. Although the conditions can be conceptualized in terms of providing qualitatively different types of stimulation (e.g., different motion types in the two intrasensory conditions), they can also be characterized as ordered in terms of degree of similarity (number of dimensions that differ) between the two synchronized events. Infants showed the greatest sensitivity to the tempo of the hammer tapping when the continuous movements were synchronized with the natural, discrete impact sounds (different modalities, different types of motion), somewhat less sensitivity when the continuous movements were synchronized with the discrete flashing of the light (same modalities, different types of motion), even less when the continuous movements were synchronized with the continuous movements of another object (same modalities, same types of motion), and least when there was no accompanying synchronous stimulation. These findings raise the possibility of a “similarity hypothesis” relating effects of redundancy on attentional salience and discriminability, where the salience and discriminability of amodal properties is negatively related to the degree or type of similarity between two patterns of synchronous stimulation. Further research will be needed to explore this similarity effect and its possible role in inter/intrasensory facilitation.

Experiment 2 was conducted as a first step in this direction. By testing older infants in an easier tempo discrimination task, we sought to replicate evidence of intrasensory facilitation and learn more about the similarity effect—that discriminability of amodal properties varies as a function of similarity between two synchronous patterns of stimulation. Each event depicted the continuously moving hammer tapping along with a second type of synchronous stimulation (auditory, low visual similarity, high visual similarity). We expected that tempo discrimination would decrease systematically as a function of similarity (with intersensory > intrasensory different movement > intrasensory same movement) as in Experiment 1. Further, only the type of stimulation (and not the number of streams of stimulation) varied across conditions, eliminating this potential confound. Given that age and task difficulty interact with intersensory facilitation (Bahrick et al., 2010), by making the task easier and testing somewhat older infants, we hoped to avoid possible floor effects and bring out differences in tempo discriminability between the two intrasensory conditions to learn more about the role of similarity.

EXPERIMENT 2: INTRASENSORY FACILITATION IN 3-MONTH-OLD INFANTS IN AN EASIER TASK

Experiment 2 explored the role of similarity between two patterns of synchronous stimulation on tempo discrimination in conditions similar to those of Experiment 1 (audiovisual hammer, hammer/light, hammer/bat), however, with older infants and an easier tempo discrimination task. We tested 3-month-olds in the tempo discrimination task used by Bahrick et al. (2002). This task was identical to that of Experiment 1 except the tempo contrast was more extreme (110 versus 240 bpm rather than 159 versus 198 bpm). This also allowed us to extend our findings of intrasensory facilitation across tasks of different difficulty as well as to infants who were somewhat more experienced.

Method

Participants

Forty-eight 3-month-old infants (21 females, 27 males) with a mean age of 90.52 days ($SD = 3.34$) and a gestation period of at least 39 weeks participated. Thirty-nine were Hispanic, 7 were Caucasian, 1 was African American, and 1 was of Asian origin. Thirteen additional infants participated, but their data were excluded from analyses due to failure to habituate (n = 1), equipment failure (n = 1), fussiness (n = 4), experimenter error (n = 3), failure to meet the fatigue (n = 2) criteria (see the Procedures section for details), external interference (n = 1), and a 3 *SD* outlier (n = 1). These included infants from (n = 2) the intersensory audiovisual condition, (n = 6) intrasensory different movement/low similarity, and (n = 5) intrasensory same movement/high similarity.

Stimulus events

We created new videos of the three events, audiovisual hammer, the hammer/light, and hammer/bat, each depicting the tempo contrast of 110 versus 240 bpm for each of the two-four-beat rhythms.

Apparatus and procedure

The apparatus and procedures were identical to those of Experiment 1. All infants passed the habituation and posthabituation criteria, and thus, none received re-habituation trials. Two observers monitored approximately 31% (n = 15) of the infants, and a Pearson product-moment correlation between the two observers averaged .95 (*SD* = .09).

Results and Discussion

To determine under what conditions infants were able to discriminate a change in tempo, single-sample t-tests on the mean visual recovery scores against the chance value of zero were conducted (see Figure 3). Results confirmed our predictions and indicate that infants in the intersensory audiovisual redundancy, intrasensory different movement (low similarity) visual redundancy, and intrasensory same movement (high similarity) visual redundancy conditions demonstrated significant visual recovery to the change in tempo ($t(15) = 4.36$, $p = .001$, $d = 1.09$; $t(15) = 3.41$, $p = .004$, $d = .85$; $t(15) = 3.76$, $p = .002$, $d = .94$, respectively). These findings indicate that infants who received intersensory redundancy as well as both types of intrasensory redundancy (low and high similarity) showed significant discrimination of the change in tempo. The findings of the intersensory and intrasensory different movement (low similarity) conditions replicate those of Experiment 1. In addition, the finding of tempo discrimination for infants in the intrasensory same movement (high similarity) condition emerged when the task was made easier and somewhat older infants were tested.

To compare infants' tempo discrimination across conditions in Experiment 2, a one-way ANOVA was conducted on visual recovery with condi-

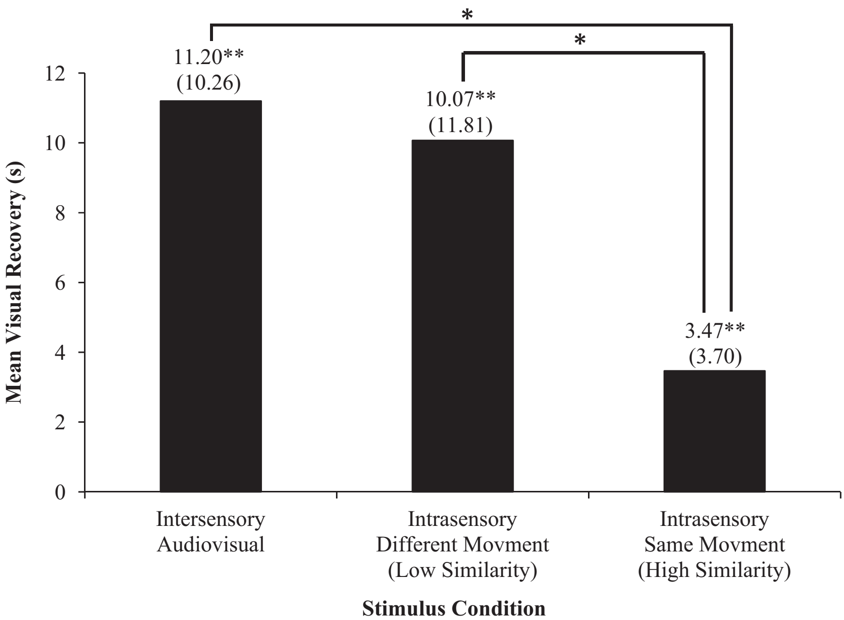

Figure 3 Experiment 2: Mean visual recovery (and *SD*) to tempo contrasts of low difficulty (240 versus 110 bpm) as a function of condition in 3-month-old infants ($N = 48$). **$p < .01$; *$p < .05$.

tion (intersensory audiovisual, intrasensory different movement, intrasensory same movement) as the between-subjects factor. Results revealed a main effect of condition, $F(2, 45) = 3.24$, $p = .049$, $\eta_p^2 = .13$. Planned pairwise comparisons indicated that infants in the intersensory audiovisual condition showed significantly greater visual recovery to the change in tempo than infants in the intrasensory same movement (high similarity) condition ($p = .02$). This replicates findings of intersensory facilitation of Experiment 1, demonstrating that intersensory redundancy is more effective than some types of intrasensory redundancy (high visual similarity) in promoting attention and processing of amodal properties. Moreover, infants in the intrasensory different movement (low similarity) condition also demonstrated significantly greater visual recovery to the change in tempo than infants in the intrasensory same movement (high similarity) condition ($p = .05$), unlike 2-month-olds in Experiment 1. Thus, when somewhat older infants were tested in an easier task, performance in the intrasensory different movement (low similarity condition), but not performance in the same movement (high similarity condition) improved. These findings indicate that different types of intrasensory redundancy are differentially effective in promoting attention to amodal properties of events. Further, as in Experiment 1, results also indicated a significant linear decrease across conditions, $F(1, 45) = 5.54$, $p = .02$, with visual recovery scores decreasing monotonically as a function of degree of similarity, providing converging evidence for a similarity effect.

Secondary analyses examined the roles of the tempo and rhythm of the stimulus events. A two-way ANOVA was conducted on visual recovery with condition, habituation tempo (110 versus 240 bpm), and rhythm (1 versus 2) as between-subjects factors. No main effects of tempo or rhythm or interactions between these variables and condition were found (ps > .10), indicating that visual recovery did not differ as a function of which tempo or rhythm infants received.

Secondary analyses were also performed to assess whether infants showed differences in habituation patterns as a function of condition (see Table 2). ANOVAs were conducted with condition as the between-subjects factor for each of the four habituation measures: mean baseline looking, mean number of habituation trials, mean posthabituation looking, and mean total processing time. Results revealed no significant differences across condition for mean baseline looking, mean number of habituation trials, mean posthabituation looking, and mean total processing time (all ps > .14). Unlike 2-month-olds in Experiment 1, 3-month-olds did not look longer to the intersensory than the intrasensory events during habituation.

GENERAL DISCUSSION

Intersensory redundancy has been shown to promote perceptual, cognitive, and social development by guiding infant attention to amodal properties, specific features of events that unite different streams of sensory stimulation (Bremner et al., 2012). According to the intersensory redundancy hypothesis (IRH; Bahrick & Lickliter, 2000, 2012, 2014), detection of amodal properties is facilitated when they are redundantly specified in multimodal synchronous stimulation compared with the same amodal properties in unimodal stimulation. However, it was not known whether redundancy *within a sense* was also effective at guiding infant attention to amodal properties. Here we report the first evidence of intrasensory facilitation in infants.

Across two experiments, we probed the effectiveness of intrasensory and intersensory redundancy for detecting the amodal property of tempo of action. Infants were habituated with videos of a red toy hammer tapping at a particular tempo under various redundancy conditions and were

TABLE 2

Experiment 2, 3-month-olds: Means and Standard Deviations for Visual Fixation in Seconds for Baseline (First Two Habituation Trials), Number of Habituation Trials, Posthabituation (Two No-Change Trials Following Habituation Reflecting Final Interest Level), Processing Time (Total Number of Seconds Fixating the Habituation Events), and Test Trials as a Function of Condition

Condition	*Baseline*	*Trials to Habituation*	*Posthabituation*	*Processing Time*	*Test*
Intersensory Audiovisual	35.68 (12.81)	7.75 (2.75)	7.02 (5.17)	189.59 (158.25)	18.22 (10.63)
Intrasensory Different Movement (Low Similarity)	34.59 (17.51)	9.63 (4.38)	10.23 (8.09)	266.26 (220.71)	20.30 (12.89)
Intrasensory Same Movement (High Similarity)	35.11 (17.46)	7.50 (2.31)	8.83 (5.89)	198.93 (160.25)	12.31 (5.29)

Note: Intrasensory low similarity depicts the hammer tapping in synchrony with the light flashing and intrasensory high similarity depicts the hammer tapping in synchrony with the bat tapping, similar to the different and same movement conditions of Experiment 1.

then tested with the hammer tapping at a novel tempo. In both studies, infants demonstrated intersensory facilitation as well as intrasensory facilitation for certain types of visual redundancy.

In Experiment 1, 2-month-old infants viewed the hammer tapping under one of four redundancy conditions, intersensory (hammer tapping synchronized with impact sounds), intrasensory different movement (continuous up/down motions of hammer synchronized with discrete on/off flashing light), intrasensory same movement (continuous up/down motions of hammer synchronized with continuous up/down motions of bat tapping), and a visual control condition (no redundancy, hammer alone tapping silently). Results demonstrated tempo discrimination differed as a function of redundancy condition. There was greater detection of tempo changes in the intersensory as well as the intrasensory different movement conditions compared with the unimodal control demonstrating both intersensory and intrasensory facilitation for tempo. Further, intersensory discrimination of tempo was greater than intrasensory discrimination in the same movement condition and tempo discrimination decreased monotonically across conditions. These findings extended evidence of intersensory facilitation for detection of tempo to infants of 2 months and provided the first evidence of intrasensory facilitation for certain types of visual stimulation. Infants showed enhanced discrimination of the amodal property of tempo for two synchronized visual events when they depicted different types of motion (discrete on/off versus continuous up/down) but not when both visual events depicted the same type of motion (continuous up/down).

Results also are consistent with a similarity hypothesis regarding the effectiveness of stimulation for promoting processing of amodal properties. As the similarity of the two patterns of synchronous stimulation (in terms of number of shared dimensions; modality and type of motion) increased, discrimination of tempo decreased (intersensory discrimination > intrasensory different movement > intrasensory same movement > unimodal control). Consistent with Gibson's (1969) invariant detection view, we hypothesized that greater differences across two patterns of redundant stimulation (i.e., in number of dimensions or type of stimulation) would lead to better detection of the amodal properties that were shared across the two patterns of synchronous stimulation. Similarity was thus defined by the number of shared dimensions (modality—auditory versus visual; type of motion—continuous up/down versus discrete on/off) between the two synchronous/redundant streams of stimulation. Thus, the intersensory condition was considered the least similar (different modality; different type of motion); the intrasensory hammer/light condition, a low similarity intrasensory condition (same modality; different type of motion); and the intrasensory hammer-bat condition, the high similarity intrasensory condition (same modality; same type of motion).

Given the novelty of our findings of intrasensory facilitation, Experiment 2 was conducted to replicate and extend evidence of intrasensory facilitation and to further explore the role of inter/intrasensory similarity in facilitating attention to amodal properties. We tested 3-month-olds using an easier tempo discrimination task to assess generalization of intrasensory facilitation across age and task difficulty. We reasoned that given the interaction of task difficulty with intersensory facilitation (Bahrick et al., 2010), an easier task may bring out differences in tempo discriminability between the three conditions and reduce any possible floor effects. Thus, if the two types of intrasensory redundancy were in fact differentially salient as a function of similarity, significant differences in tempo discrimination between these conditions should become evident.

Infants received the three redundancy conditions of Experiment 1 (intersensory, intrasensory different movement, intrasensory same movement) with an easier tempo contrast (110 versus 240 bpm rather than 159 versus 198 bpm). Results of Experiment 2 replicated and extended those of Experiment 1. The predicted difference between tempo discrimination in the intrasensory same and different movement conditions became evident. Infants showed greater detection of tempo changes for events depicting different movements (low similarity intrasensory redundancy) than events depicting the same type of movement (high similarity intrasensory redundancy). Evidence of both intersensory and intrasensory facilitation were again found, this time with greater tempo discrimination for intersensory and intrasensory different movement events with respect to the intrasensory same movement events. Results also confirmed those of Experiment 1, revealing that tempo discrimination decreased monotonically as a function of similarity (intersensory > intrasensory different movement > intrasensory same movement).

A number of important conclusions emerged from findings across the two experiments. In both experiments, infants showed evidence of intrasensory facilitation for amodal tempo information, similar to the facilitation observed for events synchronized across the senses. Two- and 3-month-old infants appear capable of detecting tempo changes not only when the tempo is redundantly specified across modalities, but also when it is redundantly specified within a sense modality, as long as the two streams of visual stimulation are sufficiently different from one another. In the present studies, the two redundant visual events differed in a number of ways including their types of motion as well as visual appearance. Intrasensory facilitation was found when continuous up/down motions of a toy hammer were synchronized with discrete on/off flashing of a light, but not when they were synchronized with continuous up/down motions of a yellow bat. Evidence of intrasensory facilitation of tempo perception was also replicated across two studies, in Experiment 1 with 2-month-olds in comparison with a unimodal visual control condition (hammer alone) using a somewhat difficult tempo contrast and in Experiment 2 with 3-month-olds in comparison with the high similarity intrasensory condition (hammer/bat) and using an easier tempo discrimination task.

Second, findings indicate that some types of synchronous intrasensory events appear to be more effective than others in promoting attention and perceptual processing of amodal temporal properties. Synchronous stimulation across visual patterns that are more different (different motion and appearance, low similarity) appears to be more effective than synchronous patterns that are more similar (e.g., same motion but different appearance, high similarity). In Experiment 1, discrimination of tempo in different motion/low similarity intrasensory condition (hammer with light), but not the same motion/high similarity condition (hammer with bat), was significantly greater than in the unimodal visual condition (hammer alone). In Experiment 2, discrimination of tempo in the different motion/low similarity condition was significantly greater than in the same motion/high similarity intrasensory condition. Thus, not only is intrasensory redundancy effective in promoting attention to amodal properties, but it appears that visual patterns that differ more are more effective. These novel findings have important implications for theories of attention as well as for applications in educational settings and deserve further study. For example, teachers could promote attention and enhance learning by matching learning tasks to learning contexts. Teaching amodal attributes (e.g., rhythm and tempo) would best be accomplished using intersensory redundancy or intrasensory redundancy across stimuli that differ along multiple dimensions. In contrast, teaching attributes that are modality specific (e.g., pitch, color) would be facilitated by avoiding intersensory and intrasensory redundancy.

It is worth-noting that the intrasensory facilitation described here differs from and complements the facilitation from multiple correlated cues within the same modality, such as infant perception of quantity (Baker, Mahamane, & Jordan, 2014), surface area (Cordes & Brannon, 2008), ordinality (Suanda, Tompson, & Brannon, 2008), and spatial patterns (Kirkham, Slemmer, Richardson, & Johnson, 2007). Intrasensory redundancy (like intersensory redundancy) entails synchrony between two streams of stimulation and facilitates attention and processing of amodal properties (aspects of time, space, and/or intensity change) which are identical and detectable in both streams of stimulation. In contrast, multiple correlated cues covary (e.g., concurrent increases in size and number of elements enhance discrimination of quantity; Baker et al., 2014). They need not entail synchrony across different patterns of stimulation, may be evident in dynamic or in static stimuli, and specify different attributes of objects or events in each type/stream of stimulation.

Although the present findings demonstrate evidence of intrasensory facilitation for visual events depicting different types of motion (low similarity events), they do not reveal whether or to what extent intersensory redundancy is superior to this type of intrasensory redundancy for facilitating attention and perceptual procession of amodal information. Although visual recovery to tempo changes in the context of intersensory redundancy in experiments 1 and 2 was greater than that of intrasensory redundancy, the difference with respect to the different movement/low similarity intrasensory condition did not reach significance. This difference, however, may have been limited by ceiling effects. Thus, the relative effectiveness of intersensory redundancy versus redundancy depicted by dissimilar visual events is not known and remains a fruitful topic for future research.

Third, results of Experiment 1 also extend findings of intersensory facilitation of tempo discrimination from infants of 3 months of age (Bahrick et al., 2002) to younger infants of 2 months and to a more difficult tempo discrimination task (159 versus 198 bpm; prior study 110 versus 240 bpm). The present study found that 2-month-olds detected these fine-grained tempo changes not only in redundant audiovisual stimulation, but also in dissimilar redundant visual stimulation (two streams of dissimilar visual stimulation; continuous up/down hammer motions synchronized with discrete on/off flashing light). This highlights the excellent temporal resolution skills of young infants. Two-month-olds demonstrated sensitivity to a tempo increase of as little as 25% in otherwise identical rapidly occurring rhythmic patterns. Discriminating such small tempo differences has been shown for simple isochronous tones in unimodal auditory sequences (Baruch & Drake, 1997), but not for complex rhythmic patterns, nor in redundant visual or audiovisual sequences. Detecting tempo information is central to a host of more complex skills, from discerning communicative intent and affect, to contingency perception and intercoordinating with a social partner.

Fourth, findings across experiments 1 and 2 extend predictions of the IRH to redundancy within a sense modality. A new prediction, *intrasensory facilitation*, paralleling that of intersensory facilitation, is suggested by the data and provides a starting point for future research to refine; that is, detection of amodal properties of events is facilitated by dissimilar but redundant (synchronized) stimulation within a sense modality as compared with the same amodal properties in unimodal, nonredundant stimulation.

The facilitating effects of intersensory redundancy for detecting amodal properties promote attention to unitary multimodal events (as opposed to patterns of stimulation that share no amodal structure and do not belong together). This provides a meaningful basis for further processing of the multimodal event and focuses attention on amodal properties (e.g., synchrony, rhythm, tempo, intensity), properties that bootstrap early perceptual, cognitive, and social development (Bahrick, 2010; Bahrick & Lickliter, 2002, 2012). Importantly, the present findings suggest that some types of intrasensory redundancy may also serve to promote perceptual processing of amodal information, unitize stimulation from synchronous events within a sense modality, and therefore bootstrap early perceptual, cognitive, and social development.

Several alternative explanations for the observed pattern of findings were also considered and discounted. For example, 2-month-olds' perception of differences between conditions on the basis of causal relations (different causal structure in the hammer–sound and hammer–light condition compared with the hammer–bat condition) seemed implausible given the complexity of our tasks and how young the infants were. Prior findings demonstrate the importance of using simple launching events and multiple cues to support causal reasoning, even at 6 months and older (Cohen & Amsel, 1998; Leslie, 1982, 1984). Also unlikely was the possibility that infants discriminated tempo based solely on the second source of information (light, sound, or bat). Prior research with infants has demonstrated the ineffectiveness of the sound alone or the sound presented asynchronously for tempo discrimination (Bahrick et al., 2002), and the current findings indicate that some sorts of synchrony promote better detection of tempo than others at 2 months. Future research should address the basis for the observed facilitation effects. Whether facilitation of tempo discrimination in the hammer–light condition is particular to presenting two objects depicting different types of movement and to what extent complexity or overall similarity between the two patterns of synchronous stimulation plays a role are not known.

We propose a similarity hypothesis relating effects of redundancy and attentional salience as an explanation of the pattern of findings across the two experiments. The data suggest that as similarity between two patterns of synchronous stimulation decreases (in terms of number of dimensions of stimulation), the effectiveness of redundancy for highlighting amodal properties increases. There was a significant linear decrease in discriminability of tempo from intersensory to intrasensory low similarity, to intrasensory high similarity, and to unimodal visual control conditions across studies. These data are consistent with an invariant detection view of perceptual development (Gibson, 1969). In particular, they suggest that attentional salience is greatest for patterns of convergence (amodal properties) across streams of stimulation that are most different from one another. Such patterns may create a particularly strong perceptual pop out for infants against a background of changing stimulation. Our findings provide preliminary evidence for a similarity hypothesis relating effects of redundancy on attentional salience and discriminability where the salience and discriminability of amodal properties is negatively related to the degree or type of similarity between two patterns of synchronous stimulation.

Similarity continua could be defined by perceptual similarity, in terms of number of dimensions of stimulation differing across the two synchronous events (as in the present studies), or by activation of the same, different, or overlapping neural pathways. For example, the effectiveness of the intersensory audiovisual events may stem from providing stimulation synchronized across different neural areas (auditory and visual cortex). Likewise, the dissimilar visual patterns presented to infants in the intrasensory low similarity condition (hammer tapping in synchrony with a flashing light) may each activate somewhat different neural pathways. In the classic "dorsal–ventral" processing framework of the visual system (see Haxby et al., 2001; Milner & Goodale, 2008; Mishkin & Ungerleider, 1982), the occipital–temporal–frontal ventral stream preferentially processes information about form and color. In contrast, the occipital–parietal–frontal dorsal stream preferentially processes information about movement, and the spatial location of an object. Thus, detection of the light flashing, which has impoverished information about form, may preferentially activate the dorsal "where/how" pathway responsive to moving stimuli. Because it has a familiar form, detection of continuous motion of the hammer tapping may also recruit additional regions of the ventral "what" pathway. In contrast, perceiving two visual objects, both undergoing the same type of continuous motion (intrasensory high similarity condition), would likely result in two streams of stimulation, both activating the same pathways. Thus, it is possible that intrasensory facilitation, like intersensory facilitation, would be most likely to be observed when detection of two patterns of stimulation relies on synchronous activation of *different* neural pathways but not when it relies on activation of the *same* neural pathways. These intriguing questions can be addressed by future research. Particularly promising are recent studies using measures of event-related potentials (ERPs) with infants and children. Given that intersensory redundancy promotes ERP responses indicative of attentional salience in young infants (Reynolds et al., 2014), it seems important to assess whether similar evidence might be found for intrasensory redundancy.

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