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Mismatching Amodal Redundancy Inhibits Operant Learning in 5-month-old Infants

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Abstract

The current study examined the functional role redundant amodal information plays in an operant learning task in 5-month-old human infants. Prior studies have suggested that both simple and complex learning processes (discrimination, associative conditioning) are facilitated when amodal information is presented redundantly across sensory modalities. These studies, however, did not test whether the amodal information had to be similar across modalities for facilitation to occur. The current study examined how both matching and mismatching redundant amodal information about the shape of an object would influence learning of an operant response in human infants. Infants learned an operant kick response to move a mobile of cylinders while either holding a cylinder, a rectangular cube, or no object. Kick rate served as the dependent measure. The results showed that infants given mismatching redundant amodal information (e.g., viewed cylinders while holding a rectangular cube) showed inhibited operant learning. These results extend the Intersensory Redundancy Hypothesis by demonstrating that amodal redundancy can function in some instances to inhibit complex learning processes.

Keywords

Amodal redundancy; Operant learning; Inhibition; Multisensory processing; Shape; Human infants

1. Introduction

The adult human perceptual world is multisensory in nature--we use multiple sensory systems to perceive objects and events that we experience. What may be less obvious to the causal perceiver is the underlying complexity of the interactions among sensory systems requiring integration at both neural and behavioral levels in order for us to perceive a unified and coherent perceptual world. One example of this complexity is the integration of sensory systems through the processing of amodal information. "Amodal information is information that is not specific to a particular sense modality, but is common or redundant across multiple senses" (Bahrack, 2010, p. 124). For example, rhythm is information that can be processed by both the visual and auditory systems. Modal information, in contrast, is information that is specific to an individual sensory system; for example, color is processed

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only by the visual system. Developmental psychologists have demonstrated that processing global amodal information such as temporal and/or spatial synchrony plays a critical role in helping infants learn which modal information belongs together (i.e., that the sight and sound of a clock ticking represents a single object) and thereby provides the beginnings of structure and organization for our perceptual world (Bahrick & Pickens, 1994; Gibson, 1969, 1983; Lewkowicz, 2000; Spelke, 1979). Understanding the development of the relationship between amodal and modal information is an important step in understanding the ability of humans to integrate sensory/perceptual information from multiple sources to perceive a unified perceptual world.

One theory attempting to understand the developmental relationship between amodal and modal information is the Intersensory Redundancy Hypothesis (Bahrick, 2010; Bahrick & Lickliter, 2000, 2002). According to Bahrick (2010), the Intersensory Redundancy Hypothesis (IRH) “provides a framework for understanding how and under what conditions attention is allocated to amodal versus modality-specific aspects of stimulation” (p. 127). At the heart of the IRH is the prediction that amodal information will become highly salient and will be detected more easily by infants when that information is presented redundantly and synchronously across two or more sensory modalities. The increased salience of the amodal information, in turn, allows for stronger discrimination between different forms of the amodal information. For example, the IRH predicts that infants would detect a rhythmic pattern easier if it is simultaneously presented both visually and aurally as opposed to a visual-only or auditory-only presentation. This enhanced detection of rhythmic information then allows the infants to discriminate easier between two different rhythms as long as the synchronous and redundant bimodal presentation is maintained. This enhanced detection/discrimination of amodal information under conditions of bimodal synchronous presentation is termed “intersensory facilitation” (Bahrick, 2010, p. 129).

Intersensory facilitation in human infants has been demonstrated for several types of amodal information (tempo, serial order of objects, object number). Using an infant-controlled habituation of looking time procedure, Bahrick, Flom, and Lickliter (2002) demonstrated that 3-month-old infants discriminated a change in the tempo of a hammer striking a surface only when infants could both see and hear the hammer strikes. Lewkowicz (2004, 2008) demonstrated that 4-month-old infants detected changes in the serial order of three moving shapes only when these changes were specified both visually and aurally. Jordan, Suanda, and Brannon (2008) showed that discrimination of object number was facilitated within a synchronous bimodal presentation: 6-month-old infants showed discrimination of the number of balls bouncing (8 vs. 12) when the visual movement of the balls dropping was paired with an auditory impact. This discrimination was not evident in the absence of the auditory impact and was not evident when nonsynchronous auditory information (classical music) was presented with the visual information. All three examples show that redundant presentation of amodal information can influence discrimination processes.

Amodal redundancy not only influences detection/discrimination processes but it also appears to play a role in facilitating learning and memory processes. In an extensive series of studies, Spear et al. demonstrated facilitated associative learning in infant rats under conditions of amodal redundancy. Infant rats expressed stronger learning when conditioned with a multimodal compound stimulus than with a single element stimulus (see Lewkowicz & Kraebel, 2004 and Spear & McKinzie, 1994 for reviews), and although specific amodal dimensions were not directly tested, Spear and colleagues speculated that redundant amodal information provided by the multimodal stimuli was likely mediating the learning effects. As for facilitated memory performance, Lickliter, Bahrick and Honeycutt, (2002, 2004) demonstrated that bobwhite quail chicks showed a postnatal preference for a familiar rhythmic pattern of a maternal call much earlier, and remembered the preference longer, if

the chicks had received prenatal exposure to the pattern of the call in a synchronous bimodal presentation (light flashing in time with the call). Thus, in young animals, conditions (redundant, synchronous presentation of amodal information across two or more sensory systems) that produce intersensory facilitation (enhanced detection/discrimination of that amodal information) seem to likewise enhance learning (Spear & McKinzie, 1994) and memory (Lickliter et al., 2002, 2004) performance.

Kraebel (2012) questioned whether similar facilitative learning and memory effects due to amodal redundancy would be observed in human infants. Would conditions of amodal redundancy produce facilitated learning in a standard learning paradigm such as operant learning? To test this, Kraebel trained 3-month-old infants to kick (operant response) for reinforcement (movement, sound) from a toy mobile comprised of colorful cylinders. Object shape served as the amodal unifier and it was presented redundantly through the sense of touch and through the sense of sight. That is, infants learned to kick to make a mobile move while holding an object whose shape matched the shape of the mobile's objects. Thus, infants in the experimental group learned the operant behavior of kicking while holding a cylinder and looking at cylinders on a mobile. Infants in this group received matching amodal information about shape while learning an operant task (e.g., view cylinders, hold a cylinder). Control infants did not hold any object while learning the operant task; thus, the amodal information was presented non-redundantly in only a single modality (only view cylinders). Kraebel found that infants who held a cylinder while learning to make a mobile of cylinders move showed the strongest expression of operant learning at test.

The findings of Kraebel (2012) demonstrated that matching amodal redundancy facilitated the expression of operant learning in 3-month-old infants. Similar to the works (described above) of Lickliter and of Spear, Kraebel's results demonstrate that amodal redundancy can influence more complex learning processes, such as learning an association between a behavior and a reinforcing consequence.

The purpose of the current study is to determine if similar results would be observed with older infants (5-month-olds). According to the Intersensory Redundancy Hypothesis (IRH), as infants get older, the necessity of amodal redundancy for detection/discrimination of amodal information decreases. That is, older infants are able to discriminate amodal information in both multimodal and unimodal presentations, whereas younger infants can do so only when the information is presented redundantly across two or more senses. Kraebel's (2012) results followed this pattern in that the 3-month-olds showed facilitated operant learning only when the amodal shape information was presented both haptically and visually (in comparison to control infants who viewed the cylinders on the mobile but did not hold an object). The IRH would predict equivalent levels of learning between these two groups for older infants. The results of Kraebel, however, also revealed a unique finding. A second control group of infants received shape information redundantly but the information was incongruent: these infants learned to kick to make the mobile of cylinders move while holding a rectangular cube (e.g., a brick-shaped object). These infants expressed inhibited learning in comparison to infants who received only visual shape information. Tests of the IRH have not included this type of control group. Thus, the IRH does not directly address how mismatching amodal information might influence detection/discrimination processes or its subsequent influence on learning and memory processes at either younger or older ages. Inclusion of this type of control group, however, can help to determine which aspects of the amodal redundancy are critical for eliciting facilitated learning and/or preventing inhibited learning.

1.1. Purpose

The purpose of the current study was to assess how the presence of matching and mismatching amodal information (shape) might influence (e.g., facilitate/inhibit) expression of an operant response (kicking makes a toy mobile move) in 5-month-old infants. Three groups of infants were tested. One group of infants held a cylinder while learning to kick to make a mobile of cylinders move (group Amodal Match). Another group of infants did not hold any object during operant learning (group Amodal None) and a third group (Amodal Mismatch) of infants held a rectangular cube while learning to kick to make a mobile of cylinders move. These three groups replicate the groups tested in Kraebel (2012) in which facilitated learning (Amodal Match expressed stronger learning than Amodal None) and inhibited learning (Amodal Mismatch expressed weaker learning than Amodal None) were found in 3-month-old infants. For older infants in the current study, based on the IRH, equivalent expression of learning is predicted between groups Amodal Match and Amodal None. It is not clear, however, how the older infants will respond to the presence of mismatching amodal information. This control group represents a unique test of the IRH and will help clarify the components of amodal redundancy that are influential to learning and memory processes.

2. Methods

2.1. Participants

Thirty-six 5-month-old infants (23 females, 13 males; M age = 163.94 days, $SE = 1.74$) participated. Infants were randomly assigned, as they became available, to one of three groups, with a final sample size of 12 infants per group. Fifteen infants were tested but not included in the final sample due to: technical problems ($n = 3$), engaging in rolling behavior ($n = 2$), refusal to hold the object ($n = 1$), parental/sibling interference ($n = 2$) and failure to meet the learning criterion (Amodal None: $n = 1$, Amodal Match: $n = 3$; Amodal Mismatch: $n = 3$). To meet the learning criterion, infants must kick 1.5 times higher than their baseline rate of kicking for two out of three consecutive min during the acquisition or test periods (Greco, Hayne, & Rovee-Collier, 1990). Five additional infants (Amodal None: $n = 2$, Amodal Match: $n = 2$; Amodal Mismatch: $n = 1$) were excluded because they failed to complete the experimental session due to fussiness. Fussiness was typically due to a change or disruption in the infant's sleep-wake schedule and was manifested by crying, inattentiveness, or sleepiness.

Ethnicity, from parental report, was as follows: 75% Caucasian, and 25% did not select an ethnic category. Mean parental educational attainment was 15.54 years ($SE = .20$; reported for 97% of the sample). Mean socioeconomic status (Nakao & Treas, 1992) was 57.70 ($SE = 2.33$, range = 30.93 to 74.77, reported for 81% of the sample). Two parents of the sample reported "stay at home mom" and two parents reported "student." These were not factored into the calculation of socioeconomic status.

Infants were recruited through a market database and through local birth announcements. Some infants were recruited through participation in a prior study of operant learning at 3 months of age. Studies have shown that without reminder treatments infants forget the operant procedure within two weeks (Hill, Borovsky, & Rovee-Collier, 1988; Sullivan, Rovee-Collier, & Tynes, 1979). Parental consent was obtained for all infants, and parents were given a certificate of appreciation as well as a summary of the study's results.

2.2. Apparatus

A computerized apparatus was used to record kicking and to provide auditory and visual reinforcement. The set-up consisted of two commercially available microphone stands and a

standard lap-top computer. One microphone stand supported the kick-detecting device (described below), and the other stand supported the mobile and the housing for a motor and speaker. See Kraebel (2012) and Kraebel, Fable, and Gerhardstein (2004) for a picture of the standard set-up and for a full description of the apparatus.

The kick-detecting device consisted of a commercially available cordless mouse connected to a retractable dog leash, which was mounted securely to a microphone stand. To detect kicks, a ribbon was looped around the infant's foot, and the other end was attached, without slack, to the retractable dog leash. The infant's kicks pulled on the leash and turned a nylon cylinder (inside the leash housing) that was attached via a VCR belt to the y-axis wheel mechanism of the cordless mouse (the ball was removed from the mouse). A computer program monitored the mouse movements; if the mouse moved 400 pixels (in one direction) within 1 s, then a kick was recorded. A pause of at least one second or a reverse mouse movement of at least 200 pixels was required to initiate a test for a subsequent kick. Each recorded kick caused the computer to send a signal to a small electric motor attached to a metal bar from which the mobile was suspended (the motor unit and mobile were mounted on a second microphone stand). Each motorized pull of the metal bar caused the mobile to swing. The objects on the training mobile were allowed to rotate freely about the axis of the line suspending them from the mobile (testing occurred during a static period of non-reinforcement). With each kick recorded, the computer also played a 1 s segment of Sesame Street songs (Rubber Duckie and the Elmo song), presented through a small stereo speaker located directly above the suspended mobile. Subsequent kicks within the 1 s interval caused the volume of the audio reinforcement to increase, up to a maximum of three (approximately equal) steps above the minimum volume. The volume faded at the same rate if no kicks were detected. Kraebel et al. (2004) demonstrated that the computerized apparatus is a sensitive and reliable measure of the basic learning and memory effects consistently observed in the traditional (non-computerized) set-up (Rovee & Rovee, 1969).

2.3. Stimuli

The mobile consisted of 5 cylinders (each of a different color and each hanging at a different angle so that shape was the unifying feature). Each cylinder measured 8 cm × 3.5 cm and were made of foam. The cylinders were attached to a white, round Plexiglas shield (40 cm in diameter) using standard fishing line. The shield blocked the infants' view of the housing unit of the motor and speaker and provided a uniform background against which the infants viewed the cylinders. The cylinders were suspended approximately 30 cm above the infant.

Two different wooden objects (see inset of Fig. 1) provided the haptic experience: a cylinder and a rectangular cube. Both objects were lightly sanded but left unpainted and unvarnished because of potential oral exploration of the objects. The objects were cleaned with infant disinfectant wipes between participants. The cylinder and rectangular cube measured 8 cm × 2.5 cm. The held objects were slightly smaller than the mobile's objects so that the infants could maintain a good grasp on the object. Prior studies have shown that infants as young as two months can haptically discriminate between round objects and objects with hard lines and angles, such as squares and cubes (Streri, 1993).

A pilot study, in which infants were first haptically habituated to the cylinder and then presented with the rectangular cube (object order was counterbalanced), showed no differences between the objects in initial exploration time, the number of trials to habituate, or the increase in holding time to the test object. The pilot study suggested that infants treated the cylinder and rectangular cube equivalently and were able to discriminate between the two objects using only their sense of touch.

2.4. Procedure

All infants were trained and tested at home in the presence of their parent/caregiver(s) and a trained experimenter. Infants were tested at a time of day, chosen by the parent, when they were considered to be active and ready to play. Infants were tested on the floor, lying on their back, either on carpeting or blankets. The mobile was positioned above the infants' head, allowing the infant to look directly up at the mobile. An U-shaped nursing pillow (known commercially as a "boppy") was used for those infants who showed signs of rolling from their back to their stomach. The boppy prevented the rolling behavior while still allowing the infant to kick freely. Because the boppy positioned the infant in a reclined position (head forward, resting on the back of the boppy), the mobile was positioned slightly in front of the infant's face, so that the infant could view the mobile without having to force their head back to look up (see Fig. 1).

All infants were given one experimental session. The infant was positioned under the mobile and a satin ribbon (attached to the kick-detecting device) was looped around the infant's right ankle. The first 2 min of the session served as a baseline measure of the infant's kicking rate. During this period, the mobile remained stationary and silent. Infants were then given a 6-min acquisition period. During this period, each time the infant kicked, the mobile swayed (visual reinforcement) and Sesame Street songs were played (auditory reinforcement). The session ended with a 2-min extinction period during which kicking did not activate movement of the mobile nor the music. Thus, the experimental session was 10 min long and began with 2 min of nonreinforcement, followed by 6 min of visual and auditory reinforcement, and ended with 2 min of nonreinforcement. These time periods replicate those used previously with older infants in the mobile reinforcement procedure (Hill et al., 1988). During reinforcement periods, kicking produced mobile movement and sound. During nonreinforcement periods, the infant could still kick but the mobile did not move and the sound did not play.

In Kraebel (2012), the object was presented throughout the acquisition period for as long as the infants would hold it (3-month-olds held the object, on average, for approximately 5 min in a 9-min acquisition period) and holding the object did not interfere with kick rates. In addition, 3-month-olds rarely attempted to explore the held object orally or visually (and for those who did, an arm shield was used successfully to prevent this extra sensory exploration). Pilot data demonstrated that 5-month-old infants were distracted from kicking while holding an object and attempts to prevent oral and visual exploration of the held object were unsuccessful. Thus, in the current study, the object was presented during the acquisition period for only 90 s and the infants were not prevented from orally or visually exploring the object. The 90 s holding period started at approximately 1.5 min into the acquisition phase. This allowed the infants to make some kicks to activate the mobile prior to holding the object. The majority of infants brought the object immediately to their mouth and mouthed the object throughout the 90 s while looking at the mobile. After 90 s, the object was removed from the infants' hands. Streri (1987) demonstrated that 90 s is sufficient time for infants as young as two months to process the shape of an object haptically.

2.5. Design and analysis

To assess differences in learning among the three groups of infants, the mean number of kicks per min was calculated during two time periods: the first 2 min of the session (a baseline measure of kicking), and the last 2 min of the session (a test of learning). Note that measures of kick rate during baseline and at test occurred during periods of nonreinforcement (e.g., the mobile did not move or play music) and no object was held during these two phases, thus eliminating arousal-based explanations for any observed

increases in kick rate at test. A mixed factor ANOVA was used to analyze the data: Group (Amodal Match, Amodal None, Amodal Mismatch) served as the between-subject factor and Phase (baseline, test) served as the within-subject factor. Within each group, significant increases in kick rate from baseline to test indicated learning. Across groups, significant differences in kick rate at test (above or below the control group's kick rate) indicated facilitated or inhibited learning.

3. Results

It was predicted that the 5-month-old infants in the current study would express equivalent levels of learning at test in the bimodal (Amodal Match) and unimodal (Amodal None) presentations. This finding would be in contrast to 3-month-olds (Kraebel, 2012) who expressed facilitated operant learning with a matching bimodal presentation. If mismatching amodal information inhibited learning (as was observed in 3-month-olds), then it was expected that infants in group Amodal Mismatch would show a lower rate of kicking at test than infants in group Amodal None. A $3(\text{Group}) \times 2(\text{Phase: baseline, test})$ ANOVA on kick rate revealed a significant interaction between Group and Phase, $F(2, 33) = 5.05$, $p = .012$. Planned comparisons of this interaction revealed that there were no differences in baseline kicking among the three groups, so any differences in kick rates at test were not due to initial differences in kick rate prior to learning. As predicted, there were no differences in kick rates at test between Amodal Match and Amodal None: the 5-month-old infants did not express facilitated operant learning (see Fig. 2). With regard to inhibited learning, as predicted, kick rates at test were significantly lower for Amodal Mismatch compared to Amodal None ($p < .0001$). Thus, similar to 3-month-olds (Kraebel, 2012), 5-month-olds expressed inhibited learning under mismatching amodal conditions.

This pattern of expression of inhibition but not facilitation was also observed during the acquisition period. A $3(\text{Group}) \times 6(\text{Minute})$ ANOVA on kicking during the 6-min acquisition period revealed a significant main effect of group, $F(2, 33) = 4.80$, $p = .015$; infants in Amodal Mismatch kicked significantly less during acquisition than infants in Amodal None and Amodal Match (see Fig. 3). In addition, as was observed during the test period, there were no differences in responding between Amodal Match and Amodal None during acquisition. It is important to note that infants in Amodal Mismatch did express learning of the operant response. The $\text{Group} \times \text{Minute}$ analysis on kicking during acquisition revealed a significant main effect of minute, $F(5, 165) = 5.26$, $p < .001$; kicking increased across minutes for all three groups. Note, the $\text{Group} \times \text{Minute}$ interaction was not significant, $F(10, 165) = .87$, $p = .56$; response patterns across acquisition did not differ among the three groups. Likewise, planned comparisons of the significant $\text{Group} \times \text{Phase}$ interaction revealed that all 3 groups significantly increased their test kick rates above baseline levels.

Characterization of learning was also examined in the current study by assessing group differences in meeting a pre-established learning criterion. As standardized by Rovee-Collier (Greco et al., 1990), infants must kick 1.5 times above their baseline rates during acquisition. In the current study this criterion was extended to include the test phase. Pilot data had indicated that kick levels were momentarily suppressed after infants held the brick-shaped object (this suppression can be observed in Fig. 3, min 3). Since 5-month-olds can quickly become bored with the operant task, it was decided to maintain the traditional 6-min acquisition period but extend the learning criterion into the test phase. This modification was used for all three groups and was set in place prior to the start of the experiment. Only one infant in Amodal None required this additional time, whereas 3 infants required it in Amodal Match and 4 infants required it in Amodal Mismatch. A one-way ANOVA on the number of minutes to reach criterion revealed a significant main effect of Group, $F(2, 33) = 3.63$, $p = .036$.

037. Planned comparisons revealed infants in Amodal Mismatch were slower to reach criterion than Amodal None ($p = .01$). Infants in Amodal Match met the criterion, on average, in 4.8 min ($SE = .52$) and did not differ significantly from Amodal None ($M = 3.8$ min, $SE = .59$) or Amodal Mismatch ($M = 5.9$ min, $SE = .52$). This pattern of results supports the group differences observed during acquisition and test: infants in Amodal Mismatch learned the operant task but their level of learning was inhibited in comparison to infants in Amodal None and Amodal Match. Note, to ensure that the results of the current study were not altered by the inclusion of the 8 infants who met the criterion during the test phase, the two overall ANOVAs were rerun without these infants: the Group $\times$ Phase interaction was still significant, $F(2, 25) = 4.6$, $p = .02$, and although the main effect from the Group $\times$ Minute ANOVA was not significant at the .05 level, $F(2, 25) = 2.52$, $p = .10$, the direction of the differences among the groups matched what was observed in the original analysis. Thus, extending the criterion into the test phase did not alter the general pattern of results.

Overall, the results of the current study demonstrate that infants who experienced mismatching amodal information during acquisition (group Amodal Mismatch) learned the operant relationship between kicking and making the mobile move. The expression of this learning, however, was inhibited during acquisition and test when examined in comparison to the levels expressed by infants who experienced either matching amodal information (group Amodal Match) or experienced only modal information (group Amodal None).

4. Discussion

The current study assessed whether the presence of matching and mismatching amodal information (shape) might influence (e.g., facilitate/inhibit) expression of an operant response (kicking makes a toy mobile move) in 5-month-old infants. The results revealed that infants given mismatching amodal properties while learning an operant response (e.g., hold a rectangular cube while learning to kick to make a mobile of cylinders move) expressed inhibited operant learning at test in comparison to control infants who did not hold any object while learning the same operant behavior and in comparison to infants given matching amodal properties (e.g., hold a cylinder while learning to kick to make a mobile of cylinders move). In addition, unlike 3-month-old infants who express facilitated learning under conditions of matching amodal information (Kraebel, 2012), the older infants in the current study did not express facilitation under similar conditions.

The results of the current study are supported in part by the Intersensory Redundancy Hypothesis (Bahrick, 2010; Bahrick & Lickliter, 2000; 2002). According to the IRH, as infants get older they are more likely to process amodal information under both bimodal and unimodal conditions. Thus, the IRH would have predicted equivalent responding between groups Amodal Match and Amodal None and this result was observed in the current study. Interestingly, it was the presence of mismatching amodal information that exhibited the greatest influence over the 5-month-olds' kick rates, with infants in group Amodal Mismatch expressing inhibited learning. As discussed below, this group represents a unique test of the IRH and may help us understand the role amodal information plays in learning and memory processes.

For infants in Amodal Mismatch, the incongruity between what they saw and what they felt clearly had some significance, otherwise infants in Amodal Mismatch would have behaved similar to those in Amodal None. Previous tests of the IRH have not included this type of control group, thus, the IRH does not directly address how mismatching amodal information might influence processing of that amodal information itself nor does it address how the presence of mismatching information might influence other learning processes. There have,

however, been control groups in which the temporal synchrony of amodal information was mismatched (e.g., Bahrick & Lickliter, 2000; Jordan et al., 2008). These asynchronous control groups tested whether bimodal stimulation enhanced processing of amodal information simply because there was more overall stimulation (compared to unimodal presentations) or whether the synchronous presentation itself was critical to the detection of amodal information. The results indicated that synchrony was critical for the detection of amodal information. For example, infants given asynchronous presentations of a hammer's rhythmic movement and the sound of its impacts did not show discrimination of tempo in a bimodal presentation (Bahrick & Lickliter, 2000). Thus, the mismatch in synchrony inhibited discrimination of tempo; this is similar to the current study's finding of inhibition in expression of learning in group Amodal Mismatch. Asynchronous presentation of matching amodal information, however, is not identical to synchronous presentation of mismatching amodal information. Although synchrony clearly plays a role in the processing of multimodal information (see also Lickliter et al., 2002; Mellon et al., 1991), synchrony may not be a necessary condition with all types of amodal information (particularly those not temporal in nature). For example, it would be interesting to examine the effects of redundant amodal information presented sequentially. The observation of inhibition in the current study also shows that the facilitation effects observed in other studies were not due to simply providing any type of amodal information redundantly. Exposure to multiple aspects of a singular amodal dimension (e.g., such as the exposure to two different shapes in the current study) is not sufficient to induce facilitation and indeed, the results of the current study suggest that this type of exposure impedes learning.

The finding of inhibition in the current study raises some interesting questions about the nature of the amodal information and how it influences behavior. It must be remembered, however, that infants in group Amodal Mismatch did show learning of the operant relationship: they met the learning criterion, their kicking increased across acquisition, and their kick rates increased between baseline and test. The expression of this learning was simply inhibited (i.e., lower) in comparison to the levels expressed by Amodal None and Amodal Match.

Several possibilities might explain the observed inhibition. First, the infants might have found the incongruency between what they felt (via both oral and tactile exploration) and what they saw distracting and thus, did not pay attention to other aspects of the learning situation, such as the relationship between kicking and reinforcement. The IRH does suggest a role for attentional mechanisms to explain facilitation effects (i.e., intersensory facilitation). The IRH suggests that the limited attentional resources of infants are drawn to amodal information/properties at the expense of attention to modality-specific properties (Bahrick, Lickliter, & Flom, 2006; Flom & Bahrick, 2010), at least in instances of matching synchronous amodal information. It is possible that mismatching amodal properties recruit similar levels of attentional resources but at the expense of learning about the operant relationship.

Another possible underlying mechanism for the inhibited operant learning is that infants may be responding to perceived stimulus change. Previous studies have demonstrated that changing aspects of the mobile's components between acquisition and test normally produces a decrease in responding (Bhatt & Rovee-Collier, 1997; Gerhardstein, Adler, & Rovee-Collier, 2000). If the infants perceive the held object as a component of the reinforcing stimulus, then removing the object might be perceived as altering the reinforcing stimulus. Given that the infants only held the object for 90 s, it seems unlikely, however, that the stimulus change alone can account completely for the inhibited responding throughout the remaining 3 min of acquisition and the 2 min of test. Plus, such inhibited responding did not occur for the infants who held the cylinder (group Amodal Match). These

infants likewise experienced a stimulus change and yet their kicking remained at the same levels as infants who did not hold an object. One could perhaps argue that removing a mismatched component represents a greater stimulus change than a matched component, but an explanation of decreased responding based solely on stimulus change could not explain the expression of facilitated learning. Kraebel (2012) showed that 3-month-old infants given matching amodal information expressed facilitated operant learning at test. The younger infants experienced a similar stimulus change as the 5-month-olds (e.g., they held an object during acquisition but not during test) and yet their kick rates at test increased significantly above their own baseline levels and in comparison to control infants.

A third possibility is that exposure to amodal incongruency somehow disrupted learning about the operant relationship between kicking and the mobile's movement. Disruption of learning due to prior experience with a component of a learning event has been observed in other traditional learning paradigms. For example, in classical conditioning procedures, exposure to the conditioned stimulus (CS) prior to standard CS-US pairings typically results in slower acquisition of the conditioned response (e.g., latent inhibition; Rudy & Cheattle, 1979). Likewise, numerous studies have demonstrated that retention of new learning can often be inhibited by the prior establishment of related memories (e.g., proactive inhibition, Bower & Hilgard, 1981). In the current study, perhaps the brief exposure to the incongruency worked to produce inhibited responding by altering the value of the reinforcement. In operant learning, the strength of the learned response is a function of the perceived value of the reinforcement. If the presence of matching redundant amodal information is functionally significant enough to infants that it facilitates learning and memory processes (Bahrack et al., 2002; Jordan et al., 2008; Lewkowicz, 2004, 2008; Lickliter et al., 2002, 2004; Spear & McKinzie, 1994), then perhaps the presence of mismatching amodal information is functionally significant enough to disrupt operant learning by decreasing the reinforcement value (perhaps by being perceived as punishing or simply due to decreasing attention). The possibility of mismatching information altering the value of the reinforcement is intriguing because it does provide for an underlying mechanism for both facilitation and inhibition effects. Kraebel (2012) suggested that the matching amodal information increased the value of the reinforcement and this, in turn, led to facilitated expression of the operant response.

There were some procedural differences between the current study and Kraebel (2012) and these differences might explain why the current study did not observe differential expression of the inhibitive effects between the acquisition and test periods. This is in contrast to the younger infants who showed inhibition (and facilitation) during test but not during acquisition. Kraebel (2012) suggested that the strong exploratory component of operant procedures might have prevented the expression of differences in learning during acquisition. The older infants, however, held the object for only 90 s at the beginning of the acquisition phase. This might have allowed for expression of differences in learning (in this case, inhibition) among the groups. In addition, unlike the 3-month-olds, the older infants were allowed to mouth the objects, so they received both tactile and oral amodal information about the shape of the object. The increased sensory processing of the amodal information might have disrupted attention to the operant relationship, increased the perceived stimulus change, or altered the perceived value of the reinforcement to such an extent that the inhibition was observed during both the acquisition and test phase. It is also interesting to note that, in both the current study and in Kraebel (2012), the facilitative and inhibitive effects are strong enough for their expression to occur in the actual absence of amodal redundancy. That is, these effects were observed during the test phase when the infants were not physically holding the objects.

5. Conclusion

The current study highlights the functional role that amodal redundancy plays in learning processes in young infants. The results support the Intersensory Redundancy Hypothesis (Bahrick & Lickliter, 2000, 2002) by demonstrating that older infants are able to process amodal properties in both unimodal and bimodal presentations. The results extend the IRH by demonstrating that mismatched amodal information produces inhibited learning and suggest that factors other than mere redundancy are critical in controlling behavior in learning situations. The results also hint at the potential strength of amodal redundancy in learning processes: the inhibitive effects were observed when the actual amodal redundancy was not present. Researchers have begun demonstrating the importance of amodal information for various developmental processes, such as perceptual tuning (Lewkowicz & Ghazanfar, 2009) and its role in social development and autism (Bahrick, 2010). Understanding the functional role of amodal redundancy in basic learning and memory processes will add to our understanding of how an infant perceives and learns about a multisensory world and how this might differ during normal vs. atypical development.

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Highlights

The functional role of amodal redundancy in an operant learning task was examined.

Infants given mismatching amodal redundancy expressed inhibited operant learning.

Infants given matching amodal redundancy did not express facilitated operant learning.

Figure 1.

The computerized apparatus consists of two tripods: one which supports the mobile and one which supports the kick-detecting device. The tripod supporting the kick-detecting device was positioned near the infant's feet. For infants tested lying on their backs, the mobile was positioned directly above the infant's head [see Kraebel (2012) and Kraebel et al., (2004) for a depiction of the apparatus in this arrangement]. Infants who showed indications of rolling behavior were tested in an infant nursing pillow (as shown above) and the tripod supporting the mobile was positioned in front of the infant.

Inset: During acquisition, infants in Amodal Match held a cylinder and infants in Amodal Mismatch held a rectangular cube. The objects were wooden, unpainted, and measured 8 cm $\times$ 2.5 cm.

Figure 2.

Infants' mean kick rate during the baseline and test phases as a function of the 90 s of amodal redundancy present during the acquisition phase: Amodal None (infants did not hold an object during acquisition), Amodal Match (infants viewed cylinders and held a cylinder during acquisition) or Amodal Mismatch (infants viewed cylinders and held a rectangular cube during acquisition).

Figure 3.

Infants' mean kick totals during the acquisition phase as a function of amodal redundancy: Amodal None (infants did not hold an object), Amodal Match (infants viewed cylinders and held a cylinder) or Amodal Mismatch (infants viewed cylinders and held a rectangular cube). The 90 s holding period (during which the infants in Amodal Match and Amodal Mismatch held their respective objects) started approximately 1.5 min into the acquisition phase.