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Redundant Amodal Properties Facilitate Operant Learning in 3-Month-Old Infants

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Abstract

The current study examined the role redundant amodal properties play in an operant learning task in 3-month-old human infants. Prior studies have suggested that the presence of redundant amodal information facilitates detection and discrimination of amodal properties and potentially functions to influence general learning processes such as associative conditioning. The current study examined how human infants use redundant amodal information (visual and haptic) about the shape of an object to influence learning of an operant response. Infants learned to kick 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 matching redundant amodal properties (e.g., viewed cylinders while holding a cylinder) showed facilitated operant learning whereas infants given mismatching redundant amodal properties showed inhibited operant learning. These results support and extend the Intersensory Redundancy Hypothesis by demonstrating that amodal redundancy influences complex learning processes such as operant conditioning.

Keywords

amodal redundancy; operant learning; facilitation; inhibition; multisensory processing; shape; human infants

1. Introduction

The human perceptual world includes both modality-specific information (information that is specific to individual sensory systems; for example, color is processed only by the visual system) and amodal information. Amodal information is typically defined as information that is not specific to an individual sensory system (Bahrick, 2010, p. 124) and it can either be information provided by an object or it can be an inherent part (i.e. property) of an object. For example, a ball audibly striking a surface provides information, such as rhythm, that can be presented redundantly in several modalities (visual, auditory), and is hence amodal in nature. Note, however, that rhythm itself (and other forms of temporal information such as duration and tempo) is not an amodal property of the ball--a ball does not have an inherent rhythm. A ball does, however, have other properties that are amodal in nature, such as shape and size. Shape is a property that is amodal in nature (can be processed by multiple

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modalities) and is an inherent part of the object. Thus, an object, like a ball, can contain inherent amodal properties (shape, size) and can provide amodal information (temporal information such as rhythm). Amodal properties and amodal information share the commonality that they can be processed redundantly in multiple sensory modalities.

Modal information and amodal information (including amodal properties) can be presented within multimodal and unimodal contexts, and both present the perceiver with a vast array of information requiring proficiency in multisensory processing in order to perceive a unified and coherent perceptual world. Although modality-specific processing has long been studied, recent studies have begun looking more closely at the organizing role amodal information (and amodal object properties) plays in various developmental processes. For example, Bahrnick (2010) described the importance of amodal information in social development and Lewkowicz and Ghazanfar (2009) recently outlined the developmental role of amodal information in perceptual tuning processes.

The potential importance of amodal information for developmental processes was demonstrated early on, with numerous studies showing that infants readily detect amodal information and properties. Infants detect synchrony between the visual and acoustic impacts of objects striking against a surface (Bahrnick, 1983; Spelke, 1979; 1981). Infants detect the rate of action uniting sights and sounds (Spelke, 1979; Lewkowicz, 1994). Infants are sensitive to the common rhythm and duration uniting flashing lights with tones (Lewkowicz, 1986). Infants are sensitive to correlated motion/sounds produced by puppets (Mendelson & Ferland, 1982). Infants can match faces and voices on the basis of voice-lip synchrony, affective expressions, speech sounds, and gender (for a review see Bahrnick & Pickens, 1994). In addition, amodal processing is not confined to human infants. Infant rats have shown sensitivity to amodal dimensions, such as stimulus intensity (Kraebel & Spear, 2000; Kraebel, Vizvary, & Spear, 1998).

Researchers have also begun to show that detection of amodal information is facilitated when such information is presented simultaneously across two or more senses, a situation known as intersensory redundancy (Bahrnick & Lickliter, 2000; 2002). In these situations, infants show discrimination between two forms of amodal information (for example, discriminating one tempo from another tempo) when two important conditions are met: The amodal information is presented across two or more sensory modalities (i.e., bimodal or multimodal presentation) and that presentation is temporally/spatially synchronous. The facilitating effect of intersensory redundancy can be seen for various types of amodal information. For example, Bahrnick, Flom, and Lickliter (2002) showed that 3-month-old infants discriminate a change in tempo of a hammer striking a surface only during synchronous auditory and visual presentation. Four-month-old infants detected changes in the serial order of three moving shapes only when these changes were specified by both audible and visible attributes (Lewkowicz, 2004; 2008). Jordan, Suanda, and Brannon (2008) showed that discrimination of the abstract amodal information of number was facilitated only within a synchronous bimodal presentation: Six-month-old infants showed discrimination between 8 and 12 ball bounces when the visual movement of the ball 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.

The facilitating effect of intersensory redundancy on amodal information is not confined to human infants, nor does its role appear to be limited to simpler processes such as detection and discrimination. Using bobwhite quail chicks, Lickliter and colleagues demonstrated that prenatal exposure to the particular rhythmic pattern of a maternal quail call in a synchronous bimodal presentation (light flashing in time with the call) facilitated how early the chicks

would show a postnatal preference for the familiar patterned call vs. a novel patterned call and bimodal synchronous presentation extended the memory for this preference (Lickliter, Bahrick & Honeycutt, 2002; 2004).

Finally, in examining ontogenetic differences in learning using a rodent model, Spear and colleagues (see Lewkowicz & Kraebel, 2004 and Spear & McKinzie, 1994 for reviews) conducted a series of studies that demonstrated facilitated associative learning in infant rats under conditions of intersensory redundancy. They demonstrated stronger aversive conditioning given prior conditioning to a bimodal stimulus than a unimodal stimulus. Similar facilitative effects were found in other associative learning procedures such as sensory conditioning and second order conditioning (Spear & McKinzie, 1994). Although they did not specifically use the term intersensory redundancy, its two primary conditions of multimodal and synchronous presentation were met in these studies, and although specific amodal dimensions were not directly tested, Spear and colleagues proposed that unifying amodal information was likely mediating the learning effects. What is most interesting about this series of studies is that the presumed presence of redundant amodal information appears to have facilitated general learning processes. That is, in the studies with human infants and bobwhite quail, it was the detection of the amodal information itself that was facilitated under conditions of amodal redundancy. In the studies with infant rats, it was the learning of an association between a stimulus and an aversive event that was facilitated under conditions of (apparent) amodal redundancy. Thus, the presence of amodal redundancy appears to have a functional role in learning processes: When required to learn an association between a stimulus and an aversive event, infant rats learned that association better under conditions of multimodal amodal redundancy than under conditions of unimodal presentation. Adult rats did not show this pattern of facilitation. Thus, detection of amodal information itself is facilitated when it is presented redundantly across two or more sensory modalities, and this redundant amodal information also appears to influence the ability of young animals to express stronger associative learning.

To summarize, human infants can detect amodal information (and amodal properties) and this detection is facilitated by redundant, multimodal presentation. Data from the animal literature suggests that infant rats show facilitated associative learning in the presence of redundant, amodal information. Combined, these data suggest that human infants should likewise detect and use amodal information (and amodal properties) in more complex learning procedures and that detection of these correspondences should facilitate general learning processes. The primary goal of this study is to test this hypothesis.

The goal of the current study is to examine how detection of redundant amodal information functions within complex learning processes in human infants. The mobile conjugate reinforcement procedure is commonly used to assess operant learning in human infants (Rovee-Collier & Gerhardstein, 1997; Rovee & Rovee, 1969; Sullivan, Rovee-Collier, & Tynes, 1979). Infants, in this procedure, learn operant kicking for visual and auditory reinforcement (from a toy mobile) and they are learning more than just a behavioral response; they are learning to make specific objects move. Infants readily detect changes in color (Gerhardstein, Renner, & Rovee-Collier, 1999), size (Gerhardstein, Adler, & Rovee-Collier, 2000), and shape (Kraebel, West, & Gerhardstein, 2007) of the mobile's objects. In other words, aspects of the objects processed visually (i.e., color, size, shape) function to influence learning and memory of the operant response. The issue addressed by the present investigation is whether amodal properties will function in a similar manner. If infants process an amodal aspect of the objects displayed on the mobile while learning the operant response, will that information facilitate responding at test?

Object shape served as the redundant amodal property in the current study. Object shape has been shown to be processed both visually and haptically by infants (Rose, 1994; Streri, 1993). Infants as young as two months can process shape through the sense of touch alone (Lederman & Klatzky, 1990; Streri, 1993; Streri, Lhote, & Dutilleul, 2000) and can transfer shape information between haptic and visual modalities (Meltzoff & Borton, 1979; Rose, 1994; Streri & Molina, 1994). Thus, amodal object shape will provide the correspondence between what is seen and what is held during the mobile reinforcement procedure.

Specifically, one could ask whether infants given matching visual and haptic shape information (i.e., viewing cylinders on a mobile while holding a cylinder) would show better learning of the operant task than those not given haptic information (viewing cylinders on a mobile while holding nothing) or those given mismatching tactile and visual information (viewing cylinders on a mobile while holding a rectangular cube). Evidence of facilitated learning in infants given matching information (view and hold matching shape information) would suggest that infants not only detect but also use the redundant amodal properties available to them.

1.1. Purpose

The purpose of the current study was to determine if the presence of a matching amodal property (shape) would facilitate expression of an operant response (kicking makes a toy mobile move). 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). One 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 (i.e., a brick-shaped object) while learning to kick to make a mobile of cylinders move. It was predicted that infants who received matching amodal properties (hold a cylinder while learning to kick to make a mobile of cylinders move) would have higher kick rates at test than infants who did not hold an object. The group of infants who received mismatching amodal properties (hold a brick while learning to kick to make a mobile of cylinders move) served as a control for potential differences in sensory arousal due to holding an object while learning.

2. Methods

2.1. Participants

Thirty-six 3-month-old infants (16 females, 20 males; M age = 96.14 days, $SE = 1.62$) participated. Infants were randomly assigned, as they became available, to one of three groups, with a final sample size of 12 infants per group. Five additional infants were tested but not included in the final sample due to: technical problems ($n = 1$), parental interference ($n = 1$) and failure to meet the learning criterion (Amodal None: $n = 1$, Amodal Match: $n = 2$, Amodal Mismatch: $n = 0$). To meet the learning criterion, infants must kick 1.5 times higher than their baseline rate of kicking for 2 out of 3 consecutive min during the acquisition period (Greco, Hayne, & Rovee-Collier, 1990). An additional five infants were excluded because they failed to complete the experimental session due to fussiness (typically due to changes in sleep-wake cycles).

Ethnicity, from parental report, was as follows: 92% Caucasian, 6% African-American, and 3% did not select an ethnic category. Mean parental educational attainment was 15.14 years ($SE = .27$; reported for 97% of the sample). Mean socioeconomic status (Nakao & Treas, 1992) was 53.22 ($SE = 2.83$, range = 30.93 to 102.0, reported for 89% of the sample). Three percent of the sample reported “student” and were not factored into the calculation of socioeconomic status.

2.2. Apparatus

A computerized apparatus was used to record kicking and to provide auditory and visual reinforcement. The set-up consisted of a standard lap-top computer and two commercially-available microphone stands. 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. Infants were tested supine on the floor with the stand containing the kick-detecting device positioned near their feet and the stand supporting the mobile positioned near their head (see Figure 1). Kraebel, Fable, and Gerhardstein (2004) provide 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. Thus, each kick caused immediate movement of the mobile. There was no discernible delay between a registered kick and movement of the mobile. The objects on the 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 a Sesame Street 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 (see Figure 2a) consisted of 5 cylinders (each painted a different color and each hanging at a different angle so that shape was the unifying feature). Each cylinder measured 8×1.5 cm and were made of wood. The cylinders were lightly sanded, primed, and painted. They were attached using standard fishing line to a round, white Plexiglas shield. The shield measured 40 cm in diameter and served to block the infants' view of the housing unit for the motor and speaker, as well as to provide a uniform visual background against which the infants viewed the cylinders. The cylinders were suspended approximately 30 cm above the infant. At that viewing distance, the objects subtended 3 (width) to 15 (length) degrees of visual angle. Kraebel and Gerhardstein (2006) demonstrated that 3-month-old infants could visually discriminate similar-sized objects at a similar viewing distance.

Two different objects provided the haptic experience: A cylinder and a brick-shaped object (i.e., a rectangular cube), see Figure 2b. Both objects had been lightly sanded, primed, painted white, and given a coat of varnish. The cylinder and brick measured 8×1.5 cm (e.g., the same measurements as the mobile's objects). Prior studies have shown that infants can haptically discriminate between round objects and objects with hard lines and angles, such

as squares and cubes (Streri, 1993). A padded shield with an arm opening (see Figure 3) was used to ensure that infants did not explore the held objects visually or orally. Infants could hold the object and move their arms relatively freely but they could not bring the object to their mouth or to their eyes. The arm shield measured 63 cm long and 20 cm high. The aperture measured 10×8 cm.

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. All infants were tested on the floor, lying either on carpeting or blankets depending on the parent's preference.

All infants were given one experimental session. The session began with the infant lying on its back directly under the mobile. A satin ribbon was looped around the infant's right ankle (the left ankle was used if the parents indicated that the infant was stronger on that side) and the other end of the ribbon was attached to the kick-detecting device. The first 3 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 9-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 3-min test period during which kicking did not activate movement of the mobile nor the music. Thus, the experimental session was 15 min long and began with 3 min of nonreinforcement, followed by 9 min of visual and auditory reinforcement, and ended with 3 min of nonreinforcement. These time periods replicate those used by Rovee-Collier and colleagues (standardized by Sullivan et al. 1979). 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 music did not play.

The object that provided the haptic experience was only presented during the 9-min acquisition period, starting at approximately the end of the first minute (to allow the infant to make some kicks to activate the mobile without the potential distraction of the object). The object was presented to the infant's right hand in such a way that fingers and thumb encircled the object. If the object was dropped, it was placed immediately back in the infant's hand. If the infant was holding the object during the last minute of the acquisition phase, the experimenter removed the object before the start of the test phase. If the object was voluntarily dropped within the last minute of the acquisition phase, it was not reintroduced. Prior to the start of the session, the parent/care giver was asked if the infant brought held objects intentionally to their mouth or eyes. If the parent indicated that their infant regularly engaged in this behavior, then the padded arm shield was used to prevent visual and/or oral exploration of the objects. The majority of the infants, however, did not require the arm shield and simply held the object in their hand with their arm extended out from their side. They made no attempts to look at the hand-held object but instead were visually focused on the mobile. The level of haptic exploration of the objects was minimal, and limited to how long the objects were held and how often they were dropped. Infants did not explore the objects in terms of moving them within their grasp or differentially moving their fingers around the objects.

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 three min of the session (a baseline measure of kicking), and the last three 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.

Note, Rovee-Collier and colleagues refer to kick rates during the last three minutes of a session as a measure of the “final level of learning and retention after zero delay” (e.g., Hartshorn et al., 1998, p. 66). Thus, kick rates during the “test” in the current study can be described as indicative of either learning or memory (with zero delay) processes. When Rovee-Collier and colleagues make assessments of memory and retention, these assessments are typically based on kick rates (converted to ratios) that occur during the first three minutes of a subsequent session (e.g., a session that occurs after a delay period). The current study will maintain the conventions established by Rovee-Collier and refer to kick rates at “test” as a measure of learning, recognizing that these differences could also be described as differences in memory with a zero delay.

3. Results

If the presence of matching amodal information facilitated expression of operant learning, it was expected that infants in group Amodal Match would show a higher 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 confirmed these predictions. There was a significant $\text{Group} \times \text{Phase}$ interaction, $F(2,33) = 5.12, p = .01$. Planned comparisons of this interaction revealed that, although there were no differences in baseline kicking among the three groups, there were significant differences among the three groups at test (see Figure 4). As predicted, kick rate was significantly higher for Amodal Match than Amodal None, showing facilitation. In addition, and interestingly, infants' kick rate in Amodal Mismatch was significantly lower than in Amodal None, $p = .048$, suggesting an inhibitory effect due to mismatching amodal information. Kick rates increased from baseline to test for all three groups, indicating that infants in all three groups showed evidence of learning (including group Amodal Mismatch), but the strength of the expression of learning at test varied as function of the matching/mismatching amodal information provided during acquisition.

The expression of facilitated and inhibited learning was only evident during the test phase. A $3(\text{Group}) \times 9(\text{Minute})$ ANOVA on kicking during the 9-min acquisition period revealed only a significant main effect of minute, $F(8, 264) = 3.58, p = .0005$; kicking increased across the acquisition period for all three groups equally. Thus, holding the objects during this period did not influence kick rates. See Figure 5. In addition, there were no differences among the groups in the number of minutes to meet the learning criterion (e.g., the requirement that infants kick 1.5 times higher than their baseline rate of kicking for 2 out of 3 consecutive min during the acquisition period). A one-way ANOVA revealed a non-significant main effect of group, $F(2, 33) = 1.16, p = .32$; infants reached criterion, on average, in 5.1 minutes ($SE = .49$).

Infants' holding behavior of the two objects was assessed during the acquisition period. An independent t -test showed a statistically significant difference in total holding time across the 9 minutes, $t(22) = 2.05, p = .05$, (M holding time for cylinder = 315 s, $SE = 17.72$; M holding time for brick = 252 s, $SE = 24.61$). Although infants held the cylinder, on average, about 63 s longer than the brick, infants held both objects well above the 90 s required for

infants to detect shape haptically (Streri, 1987). An independent *t*-test on number of times the objects were dropped was not significant; $t(22) = .83$ $p = .41$, but the pattern of dropping the brick more often ($M = 3.8$ drops, $SE = .50$) than the cylinder ($M = 3.25$ drops, $SE = .43$) likely contributed to the decreased holding time for the brick. Pilot data on infants' holding behavior of the two objects did not reveal any differences between them. These pilot data, however, assessed only haptic exploration of the objects; that is, the infants were not engaged in looking at, or kicking to make move, a mobile of cylinders. Given infants' disposition to process redundant amodal information (Bahrick et al. 2002; Jordan et al. 2008; Lewkowicz, 2004; 2008) it is possible that holding time is increased in a context of matching amodal information (facilitation) and decreased in a context of mismatching amodal information (inhibition).

4. Discussion

The results of the current study revealed that infants given matching amodal properties while learning an operant response (e.g., hold a cylinder while learning to kick to make a mobile of cylinders move) expressed facilitated operant learning at test in comparison to control infants who did not hold any object while learning the same operant behavior. In addition, infants given mismatching amodal properties (e.g., hold a brick while learning to kick to make a mobile of cylinders move) expressed inhibited learning at test in comparison to the control infants.

It is important to note that the observed facilitation and inhibition of learning is for expression of the operant response (e.g. that kicking makes the mobile move), and not for the discrimination/perceptual learning of amodal shape. Prior studies with human infants have shown that discrimination/perceptual learning of the amodal information itself is enhanced when that information is presented redundantly across two sensory systems. The current study extends these findings by demonstrating that learning that occurs in the presence of, or towards, redundant (and matching) amodal information is facilitated.

The observed facilitation of operant learning at test could be a result of the redundant amodal properties increasing the salience of the reinforcement (a moving, audible mobile of objects). The mobile itself provides additional visual information, such as the color, size, orientation, and shape of its objects. If a characteristic (i.e., shape) of the mobile's objects is made more salient, this might increase the perceived saliency of the reinforcement, and thus lead to stronger expression of learning. The Intersensory Redundancy Hypothesis (IRH) proposed by Bahrick and Lickliter (2000; 2002; Bahrick, Lickliter & Flom, 2004) supports this possibility. The IRH states that providing amodal information redundantly across two or more sensory modalities makes the amodal information more salient to the infant. This increase in salience in turn guides what the infant perceives and learns about the event. In the current study, infants processed amodal shape both visually and haptically. According to the IRH, this would make the shape of the mobile's objects more salient to the infants, and the increased attention to shape may have increased the perceived intensity of the reinforcement.

Spear and colleagues (Kucharski & Spear, 1984; 1985; Mellon, Kraemer, & Spear, 1991; Spear & McKinzie, 1994) suggested a similar explanation for their findings of increased associative learning in infant rats using compound stimuli. Stronger aversive conditioning was found in infant rats who had been conditioned to a compound stimulus in comparison to those who had been conditioned to a single element stimulus. Adult rats, under similar conditions, typically show stronger conditioning to the single stimulus. To explain this unusual ontogenetic difference in learning Spear and colleagues proposed that younger animals might be more predisposed to process compound stimuli based on amodal

information. Thus, a compound stimulus might have been perceived by the infant rats as a more salient conditioned stimulus because it was encoded as a single “more intense” stimulus or as a single “more novel” stimulus. The increase in stimulus saliency then presumably produced stronger aversive learning.

Another possible underlying mechanism for the facilitated operant learning is that the redundant amodal information could be recruiting infants’ attention to the operant relationship itself - that kicking makes the mobile move - perhaps via general arousal mechanisms. That is, a multisensory context with redundant amodal information might increase attention to the amodal information as well as to other aspects of the learning environment (e.g., the operant behavior, the reinforcement, the relationship between these two, the context, the relationship between the context and reinforcement, etc). The IRH does not support this idea because 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). It seems unlikely then that attentional resources would be directed to other aspects of the learning environment. The current study, however, suggests that amodal redundancy may have a wider impact on attentional resources because the data on object holding showed that infants held *both* objects for relatively long periods of time (for almost 5 min on average within the 9 min acquisition period). This is in contrast to the standard 30–60 s holding times found in most studies of tactile habituation to a held object (e.g., Streri & Spelke, 1988). The long holding times might reflect increased attention to the amodal property of shape but they might also be indicative of general arousal since holding time was high for both the cylinder and brick.

It is difficult to distinguish between these two potential mechanisms--to do so would require providing amodal redundancy to the infant that is not a part of the reinforcement. If, however, intersensory redundancy of amodal information/properties does function to enhance general arousal levels, then presumably other types of learning that do not require direct reinforcement might also show facilitative effects. In relation to the IRH and the potential functional role that matching amodal properties might play in learning processes, the current study provides some additional points (discussed below) to consider.

The current study demonstrated that facilitated operant learning only occurred when the amodal redundancy matched across the two sensory systems. When the amodal properties were presented across two sensory modalities but did not match (infants held a brick while looking at cylinders), inhibition (in comparison to the control group) was expressed. The incongruity between what the infants saw and what they felt clearly had some significance for the infant, otherwise infants in the Amodal Mismatch group would have behaved similar to those in Amodal None. Tests of the IRH have not included this type of control group, thus, the IRH does not directly address how mismatching information might influence processing of amodal information. There have, however, been control groups in which the temporal synchrony of the amodal information was mismatched (Bahrick & Lickliter, 2000) to determine whether bimodal stimulation enhanced processing of amodal information simply because there was more overall stimulation than with a unimodal presentation or if synchrony was critical to the detection of amodal information when temporal information was tested (i.e., rate, rhythm, tempo). The results indicated that synchrony was critical for the detection of amodal temporal information. Infants given asynchronous presentations of a hammer’s movement and the sound of its impacts did not show discrimination of tempo in bimodal presentation. Thus, the mismatch in synchrony inhibited discrimination of tempo; this is similar to the current study’s finding of inhibition in group Amodal Mismatch. Asynchronous presentation of matching amodal information, however, is not identical to synchronous presentation of mismatching amodal information and future studies will need to be done to determine which aspects of the amodal redundancy are critical for eliciting

facilitative learning and/or preventing inhibited learning. Synchrony clearly plays a role (Lickliter et al. 2002; Mellon et al. 1991) but synchrony may not be a necessary condition with all types of amodal information. The current study did not provide perfect synchronization of the visual and tactile shape information. Infants dropped the object on average about 3 times during the acquisition period. In addition, infants did not hold the object during the baseline period, nor during the first few minutes of the acquisition period. Perfect synchronization may not be necessary for facilitation when the amodal information is not temporal in nature.

The current study also observed differential expression of the facilitative/inhibitive effects: Facilitation and inhibition were observed during the test period, but not during acquisition. Differential expression of learning has been emphasized as an important feature of any theory of learning (Spear, Miller, & Jagielo, 1990). The absence/presence of expressed learning, however, is not random; Spear et al. pointed to a behavior-systems approach (Timberlake, 1983; 1993) to understand differences in expression of conditioned learning and stressed the importance of understanding the overall organization and structure of a system of behavior to understand discontinuities in responding. Such organization and structure have already been noted in infantile processing of amodal information. For example, Lewkowicz (2000) demonstrated a response hierarchy for temporal amodal information with infants responding to more basic temporal parameters before responding to more complicated temporal parameters, thus, infants respond first to synchrony, then duration, then tempo, and finally rhythm. Gogate and Bahrick (1998) have noted that amodal relations provide the basis for later learning of arbitrary intermodal relations. The IRH has demonstrated the presence of salience hierarchies between amodal and modal information, with amodal information more salient in bimodal presentation and modal information more salient under unimodal presentation. Understanding the factors that control expression of processes such as facilitation and inhibition due to amodal redundancy is an important next step to understanding the functional role that amodal information plays in learning and memory. The differential expression of facilitation/inhibition at test but not during acquisition in the current study may reflect the role of exploration in learning processes. The operant task involves a strong exploratory component with infants kicking to directly control the mobile--the immediate act of exploration may have prevented the expression of differences in learning during acquisition.

A final point of interest is the finding that the facilitation and inhibition occurred in the absence of the redundant amodal properties. That is, the facilitation and inhibition occurred during a period (test) when the infants were not physically holding the objects. Thus, the patterns of facilitated/inhibited kicking cannot be explained by either arousal-based increases or distraction-based decreases from the immediate sensations produced by holding an object. It also demonstrates that the effect of amodal redundancy is strong enough to withstand generalization decrement. (e.g., decreases in learned responding at test due to differences in stimulus conditions between acquisition and test). In the current study, infants were trained to kick for reinforcement from a mobile that included amodal shape information from both tactile and visual sources, yet they were tested for responding to only the visual mobile. Despite these differences in stimulus conditions, facilitated and inhibited learned were expressed. Such "immunity" to generalization decrement was also observed in Spear and colleagues' conditioning studies and in Lickliter's work with bobwhite quail (Kucharski & Spear, 1984; 1985; Lickliter et al. 2002; 2004; Mellon et al. 1991; Spear & McKinzie, 1994). In both cases, bimodal stimuli were presented during acquisition but responsivity was assessed to a unimodal stimulus. Combined, these findings suggest that the presence of amodal redundancy is itself not a necessary condition for expression of its influence over behavior.

5. Conclusion

The current study highlights the functional role that amodal redundancy plays in learning processes in young infants. The results support and extend the Intersensory Redundancy Hypothesis (Bahrick & Lickliter, 2000; 2002) by demonstrating that the presence of matching amodal properties can facilitate the expression of an operant response and that mismatching amodal properties can inhibit expression of an operant response. The results also hint at the potential strength of amodal redundancy in learning processes: the facilitative/inhibitive effects were observed despite less than perfect synchrony between the amodal dimensions, despite changes in stimulus conditions between training and test, and despite the fact that the amodal redundancy was not present at test when the effects were expressed. 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.

Highlights

The functional role of amodal redundancy in an operant learning task was examined.
 Infants given matching amodal redundancy expressed facilitated operant learning.
 Infants given mismatching amodal redundancy expressed inhibited operant learning.

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Figure 1.
An infant engages with the mobile apparatus. The left tripod supports the mobile and the housing for the motor and speaker. The right tripod supports the kick-detecting device.

Figure 2.

A side view of the objects on the mobile. Each cylinder was painted a different color and hung at a different angle so that object shape (cylindrical) was the unifying feature. The dimensions (8×1.5 cm) of the held objects were identical to the objects on the mobile.

Figure 3.
A padded shield allowed arm movement while preventing visual and/or oral exploration of the held object.

Figure 4.

Infants' mean kick rate during the baseline and test phases as a function of the 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 cuboid during acquisition).

Figure 5. 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 cuboid).