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Music in Motion: Associations Between Musical Pitch and Visuospatial Direction in Infants and Adults

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Music in Motion: Associations Between Musical Pitch and Visuospatial Direction in Infants and Adults

by

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Dedication

This dissertation is dedicated to my family and to my fiancé, Nathaniel Baca, for their love and support.

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Music in Motion: Associations Between Musical Pitch and Visuospatial Direction in Infants and Adults

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Although many researchers investigate the senses separately, most people have a coherent conscious experience of the world that is not divided into separate perceptions of vision, hearing, or other senses. The brain integrates the information received from our senses into a unified representation of the world around us. Previous research has demonstrated that what people perceive with one sense can influence their perception of stimuli with the other senses (Roffler & Butler, 1968; Marks, 2000). The current set of studies was designed to illuminate the associations between musical pitch and visuospatial motion.

The first two experiments with infants revealed that 11-month-old infants are sensitive to associations between ascending and descending musical pitch and the direction of an object's motion. Additionally, two more experiments with infants revealed that infants of the same age do not show the associations of rightward motion with ascending pitch and leftward motion with descending pitch that adults have demonstrated in some experiments (Eitan & Granot, 2006).

The fifth experiment tested the influence of ascending and descending musical stimuli on making a visuospatial motion to a target location. Adult subjects demonstrated faster reaction times when using a trackball to move a cursor to a target location on a computer screen when the direction of the target was congruent with the musical stimulus to which they were listening. The effect was stronger for vertical target locations than for horizontal target locations.

The results of these studies indicate that both infants and adults are sensitive to associations between musical pitch and visuospatial motion in the vertical plane, and adults may also make associations between musical pitch and visuospatial motion in the horizontal plane.

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Introduction

Review of intersensory perception and cross-modal matching studies in adults

Although many researchers investigate the senses separately, most people have a coherent conscious experience of the world that is not divided into separate perceptions of vision, hearing, or other senses. The brain integrates the information received from our senses into a unified representation of the world around us. Recent research in neuroimaging has identified areas of the brain that may be responsible for this task, including the superior colliculus in the midbrain and cortical structures such as the superior temporal gyrus and auditory and visual association areas (Stein & Meredith, 1993; Afifi & Bergman, 2005).

In addition to the integration of sensory information that is accomplished by the brain, much information in our environment reaches us through multiple senses. Multimodal information provides greater perceptual accuracy than does unimodal information (Gibson, 1979). We can often use information received by one sense to clarify ambiguous information received from another sense; for example, it is easier to understand unclear speech if one can see the speaker's mouth moving. Likewise, most adults are bothered by asynchrony of certain auditory and visual components, such as watching a foreign film in which the actors' mouth movements are speaking a language different from the one that has been dubbed over on the sound track to which one is listening.

These links between the senses shape our perception of the stimuli we encounter. For example, the visual system and the auditory system often work in concert to accurately perceive stimuli in the environment. Adults are very sensitive to auditory and visual synchrony; most can detect an asynchrony of 65-112 ms in an objects' motion and a concurrent sound (Lewkowicz, 1996). However, some associations between auditory and visual perception are less obvious than the ability to perceive temporal synchrony. Research has demonstrated that many adults perceive synesthetic associations between auditory characteristics such as pitch and volume and visual characteristics such as color and brightness (Marks, 1974, 1987). Amodal intensity matches could explain these associations, but they are nonetheless consistently reported in the literature and indicate commonality between auditory and visual processing.

Evidence from other studies suggests that associations between the auditory system and the visual system may in part serve to guide the visual "where" system. Researchers have argued that the auditory system has both a "what" and a "where" system, and that the auditory "where" system functions to inform the visual "where" system (Kubovy & Van Valkenburg, 2001). They propose that although the auditory "where" system is more malleable than the visual "where" system, the auditory "where" system serves visual localization.

Sound localization is associated with visual orienting. Directional discrimination of sound seems to be an innate ability that is tied to visual orientation from birth; even newborns turn their heads in the direction of a sound in order to locate the source of the sound (Clifton, 1992). In one study, researchers placed a toy cricket next to either the right or left ear of an infant just three minutes after birth (Wertheimer, 1961). On most trials in which the infant moved her eyes, the movement was in the direction of the cricket. This indicates that infants are able to use auditory signals to locate an object in space immediately after birth.

Auditory localization can be influenced by simultaneous visual stimuli and by the act of visual orientation. Bertleson and Aschersleben (1998) found that subjects who were asked to report the source of a sound as either on the left or the right of a median sagittal plane showed shifts of the reported localization in the direction of an off-center simultaneous light flash. Spence and Driver (1997) asked subjects to judge the elevation of peripheral auditory or visual targets in a square array of four audio speakers following uninformative cues on either side with an intermediate elevation. They found that subjects gave more accurate localizations of the targets in either modality when preceded by an uninformative auditory cue on the side of the target (the auditory cue did not indicate elevation). However, visual cues facilitated judgments of visual targets, but not auditory targets. Thus, in this experiment, auditory cueing facilitated visual localization, but the visual cueing did not facilitate auditory localization. This suggests a one-way cross-modal dependence in orientation in which auditory events influence visual perception, but visual events do not influence auditory perception in the same way.

However, in a similar experiment, Rorden and Driver (1999) seated subjects in front of the same square array of speakers and asked them to identify whether a sound came from one of the top speakers (above their head) or one of the bottom speakers (below their head). Before the sound played, subjects were given a cue instructing them to shift their eyes to the left or to the right. Reaction times for correct top/bottom decisions were shorter when the sound originated from the same side to which the subjects were instructed to shift their eyes. This suggests that visual orientation facilitates localization of the source of auditory event. This seems contradictory to the previous experiment, but there is an important difference between the two. In the first experiment, subjects were not instructed to shift their eyes toward the visual cue; they only noted it with their peripheral vision. In the second experiment, however, subjects engaged in visual orientation. Thus, in order for visual events to influence auditory perception, it seems necessary that a person actually shift his eyes in the direction of the visual event. It is not sufficient to see an object or visual event with the peripheral vision; only the act of visual localization, accompanied by eye movement, influences auditory perception. These studies provide evidence that auditory and visual perception are closely tied, and that both systems can aid localization of objects and events. Though the relationships between the auditory and visual localization systems may not be exactly parallel in their influence over each other, both systems work together to create a coherent, multi-modal perception of one's environment.

Review of intersensory perception and cross-modal matching studies in infants

Infant perception studies have established that infants can recognize with one sense a stimulus perceived with a different sense (Gottfried, Rose, & Bridger, 1977; Spelke, 1976). This ability is known as cross-modal matching, and it has been demonstrated across the auditory, visual, and tactile modalities. In many cases, such intersensory perceptual abilities help infants locate objects in space.

In one experiment, each infant viewed his mother in the next room through a window directly in front of him, but heard his mother's voice coming through a speaker that was placed in the same room as the infant, but 90 degrees to the right or left of where the mother stood. Infants recognized the spatial discrepancy and showed emotional distress at the inconsistency (Aronson & Rosenbloom, 1971). This indicates that the infants perceived the relationship between normally correlated auditory and visual stimulation (Schiffman, 2001). Another study used a preferential-looking paradigm to test whether 5-month-old infants could match an auditory and a visual stimulus (Walker-Andrews & Lennon, 1985). Infants watched two videos side by side: one of an approaching automobile, and one of an automobile driving away. While watching the videos, infants listened to a sound track of an automobile that either increased in intensity (as an approaching automobile) or decreased in intensity (as an automobile driving away). The infants looked longer at the video that matched the auditory sound track that was playing during in each trial, indicating that they are able to match the auditory stimuli with the videos of the moving automobiles.

Several studies indicate that infants are also able to perceive audio-visual temporal synchrony, or the movement of objects that are synchronized with auditory events. Infants as young as 2 months of age are able to integrate concurrent auditory and visual inputs on the basis of temporal synchrony (Bahrick, 1987, 1992; Lewkowicz, 1986, 1992a, 1992b). Lewkowicz (1992b) used a preferential looking paradigm to examine whether infants would look at the video that matched an auditory stimulus while viewing two videos side by side, only one of which matched the auditory stimulus. He found that infants prefer to look at the object that is moving in synchrony with the auditory stimulus. Research using habituation has revealed that after viewing a habituation sequence in which a disk bounced at the same time that a sound played, infants dishabituated to asynchronous test trials in which the sound occurred 350 ms before or 450 ms after the disk bounced (Lewkowicz, 1996). Though this threshold is much longer than the threshold in adults, who can perceive an asynchrony 65 ms before or 112 ms after the movement of the object, infants are sensitive to temporal synchrony.

Wagner et al. (1981) investigated infants' ability to make "metaphorical" matches, or matches that are based on abstract resemblances across modalities instead of physical similarity. Metaphorical matches are those underlying synesthetic metaphors, such as associating bright colors with loud tones and dull colors with quiet tones. The researchers conducting this study tested infants aged 6 to 14 months of age (mean of 11 months) on 8 sets of matches, each consisting of a pair of visual stimuli and a corresponding pair of auditory stimuli. For example, a bright pink and black checkerboard and a gray and white checkerboard were paired with a loud tone and a quiet tone. For each trial, infants were presented with an auditory stimulus, and then shown the pair of visual stimuli while the auditory stimulus continued. Looking times were recorded to determine whether infants were able to "match" the appropriate auditory and visual stimuli. The data revealed that of the 8 sets of stimuli tested, infants showed a significant preference for the matching audio-visual pairs on 3 sets. Infants looked longer at a broken line when listening to a pulsing tone and a continuous line when listening to a continuous tone, as well as a jagged circle when listening to the pulsing tone and a smooth circle when listening to the continuous tone. This demonstrates that infants can make audiovisual matches between stimuli that are "smooth" and "jagged." In addition, infants looked longer at an upward-pointing arrow when listening to an ascending tone and a downward-pointing arrow when listening to a descending tone. This indicates that infants may be able to match certain static visual events with dynamic auditory events, and that infants may be sensitive to the phenomenon known as spatial verticality. However, this study used static visual images, not dynamic moving objects that were synchronized with the auditory stimuli, and the experimental design was not rigorous. Thus, further investigation using dynamic visual stimuli that are synchronized with the auditory stimuli is necessary to clarify infants' abilities to associate auditory and visual stimuli.

Review of cross-modal matching and sensory integration theories

One of the classic demonstrations of young infants' perceptual and cognitive abilities involves a task in which very young infants are given a pacifier to suck on that is either smooth (like a normal pacifier) or bumpy. The infant is then shown two pictures, one of a smooth pacifier and one of a bumpy pacifier, and is assumed to look at the one that matches the pacifier in his mouth. Even infants under one month of age are able to "match" the pacifiers (Meltzoff & Borton, 1979). Similarly, other research has demonstrated that very young infants can match auditory and visual stimulus properties. Lewkowicz and Turkewitz (1980) habituated 3-week-old infants to one level of sound, and then attempted to dishabituate them with various levels of light, and vice versa. They found that infants seemed to "match" certain absolute levels of light intensity with certain absolute levels of sound intensity. Interestingly, the infants' matches of intensity level across modes were the same matches that adults chose. Some scientists consider these studies evidence for innate cross-modal transfer (Stern, 1998).

But while some researchers believe that infants are able to transfer information across sensory modalities from a very early age, some evidence suggests otherwise. Several studies have found that infants are not able to match stimulus properties across different sensory modalities until the second half of the first year (Rose, Gottfried, & Bridger, 1981a, 1981b; Bryan, et. al., 1972). Similarly, 6-month-olds, but not 4-month-olds, are able to learn arbitrary relationships between the shape of a haptically experienced object and its color or pattern (Hernandez-Reif & Bahrick, 2001). Gibson (1966, 1979) proposed that infants initially process stimuli amodally, and only later learn to differentiate and integrate information from the separate sensory modalities. Piaget also proposed a similar system, in which infants gradually learn to integrate touch and vision by acting on objects and calibrating one sense to the other through simultaneous experience. In the above-mentioned research in which the 6-month-olds, but not the 4-month-olds, were able to learn the relationship between the shape of an object and its color, the 4-month-olds were able to learn the relationship if amodal information specifying the common shape of the visual and tactual stimulation was available during the test, demonstrating their reliance on amodal information (Hernandez-Reif & Bahrick, 2001). Likewise, detection of amodal relations has been found to emerge developmentally prior to detection of arbitrary intersensory relations (Bahrick, 2001).

According to the amodal processing view, the young infants in the pacifier experiment are simply reacting to the same stimulus property (smoothness or bumpiness/roughness), and are unaware that one is tactile and the other visual. Similarly, in the experiment conducted by Lewkowicz and Turketwitz (1980), infants may simply be reacting to intensity; they may not be aware that one aspect of the stimulus is auditory and one is visual. This suggestion has several implications. First, if we take the information processing perspective, we can assume that this amodal processing is the lowest level of perception available; it is the "default" with which newborns begin. After gaining experience in the world, however, infants begin to differentiate the sensory modalities, so that visual information is processed separately from auditory information, and those are separate from tactile information, etc. Thus the infant builds up perceptual abilities for each sensory modality, at first engaging in them only separately. Then, after learning to differentiate between the senses, infants learn to integrate the information from the level of separate sensory perception. This is aided by intersensory redundancy (Bahrick & Lickliter, 2002), or the properties of some stimuli that can be sensed in separate modalities simultaneously, such as being able to see and hear a ball bounce; stimuli that can be perceived in two modalities simultaneously appear to be especially salient to infants. Bahrick proposes that infants' sensitivity to amodal, global relationships guides their attention and provides an organizational framework for development that constrains exploration and prevents them from learning incongruent relationships. According to the intersensory redundancy hypothesis (Bahrick, Lickliter, & Flom, 2004), processing of amodal information is facilitated in multimodal stimulation and attenuated in unimodal stimulation early in development. Later, however, when infants gain more experience processing amodal information, attention becomes more flexible, and amodal properties can be perceived in both multimodal and unimodal stimulation. Thus, amodal relationships can guide infants' attention and provide a framework for understanding both multimodal and unimodal sensory information. Young infants may initially engage in amodal processing and later learn to integrate information from the separate senses.

Review of music perception studies in infants and children

Much research provides evidence that infants are sensitive to pitch in both speech and music stimuli (McMullen & Saffran, 2004). Both speech and music are arranged as frequency spectra, conveyed as pitches (McMullen & Saffran, 2004). Indeed, one of the most salient features of auditory stimuli to young infants is pitch. Across the domains of both speech and music, infants show a preference for higher pitches (Trainor & Zacharias, 1998). In every language that has been studied, research indicates that infant-directed speech is characterized by higher frequency and greater pitch variation (Fernald, 1992), likely because infants are sensitive to pitch and respond more to speech with these characteristics.

Pitch contour, or the pattern of directionality changes in the pitches of subsequent sounds in a speech or musical phrase, is also one of the first musical features to be discriminated by infants (Trehub, 2003). Both infant-directed speech and lullabies written for infants tend to be dominated by simple, repeated pitch contours (Trehub & Trainor, 1998), which infants have shown preference for from very young ages (Trainor, 1996; Masataka, 1999).

Pitch contour plays an important role in delineating phrase and clause boundaries in both speech and music (McMullen & Saffran, 2004). Pitch contour is a prosodic cue that is correlated with boundaries: both speech clauses and musical phrases are marked by a drop in pitch, as well as a lengthening of the final sound. Research shows that by 7 months of age, infants are able to perceive clause boundaries in infant-directed speech, and they listen longer to speech samples in which pauses fall at clause boundaries than to speech samples in which pauses are placed in the middle of the clauses (Hirsh-Pasek, Kemler Nelson, Jusczyk, & Cassidy, 1987). Similarly, infants listen longer to musical passages from Mozart minuets when pauses are placed at the end rather than in the middle of phrases (Krumhansl & Jusczyk, 1990; Jusczyk & Krumhansl, 1993). Because one of the key markers of phrase and clauses boundaries is a drop in pitch, it seems evident that infants are using pitch contour (though likely in combination with at least one other parameter) to delineate these boundaries. Thus, infants are not only sensitive to pitch parameters in auditory stimuli, but they are also able to actively use this information to help process both speech and music.

Interestingly, considering that pitch is known to be a salient feature of speech and music to infants, several studies have found that 3- to 6-year-old children have difficulty discriminating pitches (high vs. low) and melodic direction (ascending vs. descending) (Hair, 1987b; Van Zee, 1976; Webster & Schlentrich, 1982; White, Dale, & Carlsen, 1990). However, this may be because these studies required the children to make a verbal response that involves using pitch terminology. Research indicates that young children often confuse pitch terminology with loudness terminology (Hair, 1981; Andrews & Diehl, 1970; McMahon, 1982); thus, they may be unable to accurately verbalize their perceptions because of the language barrier. This is likely due to the fact that the terms *high* and *low* have multiple meanings in the English language, referring to pitch, space, volume, and loudness.

One study that investigated English-speaking and Spanish-speaking children's ability to label pitches found that Spanish-speaking children were more accurate in their labeling than the English-speaking children (Flowers & Costa-Giomi, 1991). One reason for this is likely that the Spanish terms for *high* (*agudo*) and *low* (*grave*) musical pitch have no volume or loudness connotations. In French, there are two sets of terms that can be used to describe high and low pitch: *aigu* and *grave*, which refer exclusively to musical pitch, and *haut* and *bas*, which can refer to pitch height, volume, and loudness. Flowers & Costa-Giomi (1996) investigated whether French-speaking children who were taught to use the single-meaning terms (*aigu* and *grave*) were more accurate in their pitch identifications than French-speaking children who were taught to use the multiple-meaning terms (*haut* and *bas*). Indeed, children who used the single-meaning terms were more accurate in their identifications than children who used the multiple meaning terms, although children in both groups were able to identify the pitch changes with high accuracy. This indicates that terms with multiple meanings can be confusing to children and may underlie the difficulty that English-speaking children have verbalizing their responses on pitch discrimination tasks.

Studies with English-speaking children that included a nonverbal response have found that children as young as 3 years of age can accurately indicate their understanding of pitch-related elements (Scott, 1997; Hair, 1987a, 1987b; Webster & Schlentrich, 1982). In the Roffler and Butler (1968) study, 4- and 5-year-old children placed high-pitched tones higher on a vertical plane than low-pitched tones, indicating both that they can identify high and low pitches and that they associate pitch height with spatial verticality. The response required from the children in this study was nonverbal; the children only had to point to the panel from which they believed the tone originated. The children were also interviewed afterwards to ascertain whether they were aware of the usage of the words *high* and *low* to describe pitches, but none of the children reported knowledge of this association. Thus, their localization of the tones on the vertical plane can be assumed to be due to factors other than naming conventions. Taken together, the evidence from all of these studies suggests that young children are able to perceive pitch and musical directionality, though they may have difficulty expressing their understanding in musical terminology.

Review of music and spatial mapping studies in adults

Associations between music and motion have recently been investigated in adults with increasing interest. Much of this research concerns music listeners' body motion, but scientists have also examined relationships between musical parameters and spatial motion. Perceptual experiments have suggested that auditory parameters in music are often associated with visuospatial features. For example, pitch height and loudness interact with features such as shape, size, and height in perception (see Marks, 2000, for a review).

Some researchers have proposed that these associations may be explained in part by the auditory "where" system (Kubovy & Van Valkenburg, 2001); see above for further discussion. This system analyzes auditory input to aid visual orientation. Evidence from neuroimaging studies suggests that specific subcortical areas such as the superior colliculus combine visual, auditory, and somatosensory information into an amodal spatial representation (Spence & Driver, 1997; Stein, Wallace, & Meredith, 1995). Other studies report the activation of brain areas generally associated with visuospatial processing during music-related tasks (Nakamura et al., 1999; Penhune et al., 1998; Platel et. al. 1997; Zatorre, Evans, & Meyer, 1994).

Roffler and Butler (1968) investigated the ability of subjects to place tonal stimuli originating from a loudspeaker on a vertical plane. Adults with normal vision, blind adults, and 4- and 5-year-old children with normal vision were tested. The results indicated that all groups of subjects placed higher-pitched sounds higher on the vertical plane than lower-pitched sounds, despite the fact that all sounds originated from the same loudspeaker in the center. The tones also retained their spatial orientation in a condition in which “up” and “down” were confounded by changing the subjects’ body orientation. Also, the only apparent effect of vision on the subjects’ placement of the sounds was that adults with normal vision tended to state that the sounds originated across the entire range of the panel, whereas blind adults placed the sounds closer together in a more restricted range. This is likely because the height of the panel was less salient to them. But nonetheless, all of the adults and children placed the sounds in the same order, with lower pitches on the bottom and higher pitches on the top. It was noted that all of the subjects in this study seemed somewhat less confident in their judgments than subjects locating stimuli on a horizontal plane, but despite their uncertainty, “their localization judgments produced an orderly scale as if tones do, indeed, possess a spatial attribute consonant” (Roffler & Butler, 1968).

Research investigating adult listeners’ imagined changes in physical space and bodily motion in association with changes in musical parameters suggests that pitch is associated with spatial motion (Eitan & Granot, 2006). University students were asked to imagine an animated human character of their choice. They then listened to brief melodies and were asked to visualize their character moving in an imaginary film shot, with the melody serving as the soundtrack. For each melody, subjects specified their character’s imagined motion on eight dimensions, including vertical and horizontal direction. The results reveal that falls in pitch contour, or descending musical phrases, were very strongly associated with vertical descent of the imaginary characters. Rises in pitch contour, or ascending musical phrases, were significantly associated with vertical ascent of the imaginary characters, though the relationship was not as strong as the relationship between descending pitch and vertical descent. Additionally, pitch falls were associated with leftward horizontal direction, but pitch rises were only weakly associated with rightward horizontal motion. Thus, pitch falls evoke stronger visual motion imagery in both vertical and horizontal directions compared to pitch rises. They found strong music-motion associations with dynamics (loudness) and acceleration as well as with vertical and horizontal motion. Eitan and Granot also investigated whether music training had any effect on music-motion associations. They found that in some relationships, particularly the association of pitch with vertical and horizontal motion, musicians showed much stronger associations than did subjects with no musical training.

Eitan and Granot note that musical parameters such as pitch and dynamics that are common to various types of auditory stimuli are more strongly associated with motion than is melodic interval, which is an exclusively musical parameter. They also discuss associations between musical parameters and spatial motion in terms of intensification, though they note that not all of the associations can be clearly explained by a cross-modal intensification analogy. However, music and motion may be related through cross-dimensional intensity: musical parameters perceived as intensifying (increasing volume or tempo, or ascending pitch) may map onto motion that is perceived as intensifying (increasing speed, forward motion, or upward motion), while musical parameters perceived as abating (decreasing volume or tempo, or descending pitch) may map onto motion that is perceived as abating (decreasing speed, backward motion, or downward motion). It is interesting that rightward motion seems to be associated with forward motion and leftward with backward, even in cultures in which the written language reads from right to left, as in the Hebrew-speaking Tel Aviv University students tested in some of Eitan and Granot's experiments. Eitan and Granot suggest that the mapping between pitch and horizontal space may be an indirect outcome of the more obvious mapping between pitch and vertical space. If pitch easily maps onto vertical space, vertical space may become mapped onto horizontal space through associations with *x, y* graphs, which place right and up together, and left and down together (Weeks & Proctor, 1990; Cho & Proctor, 2005). Additionally, this mapping of vertical and horizontal space could be affected by familiarity with the piano keyboard, which places higher pitches to the right and lower pitches to the left (Stewart, Walsh, & Frith, 2004). This explanation is supported by the stronger associations demonstrated by musicians than non-musicians, as musicians are more familiar with the piano keyboard even if they are not professional piano players.

Purpose and Design of the Current Studies

The current set of studies was designed to illuminate the associations between musical pitch and visuospatial motion. Only one previous study had examined the relationship between these parameters in infants, and that study used static rather than dynamic visual stimuli (Wagner et. al., 1981). The origins of the associations between musical pitch and visuospatial motion are unknown, and may begin as simple automatic or amodal perceptions in infants. Alternately, these associations may be acquired or enhanced through experience with music. Infants may not yet have had enough experience to have learned these relationships, so it was possible that they would not demonstrate *a priori* knowledge of them during the current experiments. However, whatever way they are acquired, these associations may eventually take on metaphorical meaning in adults.

A pilot study suggested that 11-month-old infants in a preferential looking paradigm have a tendency to look longer at a moving object whose direction matches that of an auditory stimulus that is playing simultaneously. This experiment employed audio and visual stimulation in animated movies to test whether infants could match ascending objects with ascending scales and glissandos and descending objects with descending scales and glissandos in a preferential looking paradigm. Each infant viewed 8 test trials in which a 10-second scale or glissando played while two red balls moved on a widescreen plasma television. One ball moved from the top to the bottom on one side of the screen, and the other moved from the bottom to the top on the other side. The motion of both objects was synchronized with the scale or glissando that played during the trial; only the direction of the two objects was different. The direction of the objects on the left and right sides of the screen and the side on which the object moving in the correct direction was located were randomized and counterbalanced. An experimenter coded the infants' looking direction during the trials.

The results indicate that infants (N=47) looked longer at the object whose motion matched the direction of the music that was playing during the trial. A one-sample t-test comparing the percentage of time spent looking at the correct side during test trials (53%) to chance (50%) reveals *t* (324) = 1.84, *p* = .03, one-tailed. A regression analysis indicates that neither the direction of the music (ascending vs. descending) nor the type of music (scale vs. glissando) had an effect on infants' ability to match the music with the motion of the objects. Thus, it seems that infants have a tendency to match the musical parameter of pitch in both scales and glissandos with ascending and descending visuospatial motion. Eleven-month-olds' ability to associate these parameters without explicit training indicates that this association is very salient to infants. This result is quite surprising, considering the difficulty of the task. The preferential looking task is complex because infants must look back and forth between the two moving objects several times to assess the direction of their motion, and then settle on one side versus the other. Because each trial only lasts 10 seconds and infants must look back and forth between the two sides several times, we cannot expect large differences in the amount of time infants look at one side versus the other. We expected that infants may be able to demonstrate their ability to make these associations between musical pitch and visuospatial motion more effectively in a looking-time procedure in which only one object is moving on the screen during each trial.

The current experiments with 11-month-old infants used a habituation/looking-time procedure. The first and second experiments employed synchronized audio and visual stimulation in animated movies to test whether infants are able to process the audio and vertically-moving visual components contingently. In the first experiment, infants were habituated to audio and vertically-moving visual stimuli that were paired in a matching fashion. The infants were then tested with audio and vertically-moving visual stimuli that were paired in a non-matching fashion. In the second experiment, infants were habituated to audio and vertically-moving visual stimuli that were paired in a non-matching fashion, and they were then tested with audio and vertically-moving visual stimuli that are paired in a matching fashion.

The third and fourth experiments tested whether infants show the associations of rightward motion with ascending pitch and leftward motion with descending pitch that adults have demonstrated in some experiments (Eitan & Granot, 2006). This relationship is of particular interest, as no studies have investigated this phenomenon in infants. These two experiments used the same paradigm as the first two experiments, except that the visual stimuli moved in horizontal directions. Infants in the matching experiment were habituated to rightward motion paired with ascending musical stimuli and leftward motion paired with descending musical stimuli. They were then tested with non-matching pairings. Infants in the non-matching experiment were habituated to leftward motion paired with ascending musical stimuli and rightward motion paired with descending musical stimuli, and were then tested with matching pairings. As in the first two experiments, we examined whether infants in both experiments looked longer at the test trials in which the audio and visual stimuli are paired in different ways than they were in the habituation trials.

Some scientists have proposed that ascending/rightward and descending/leftward associations in adults are due to the fact that ascending pitch is perceived as intensifying, and thus matches “forward” motion. In cultures in which the language reads from left to right, rightward motion could easily be considered “forward” motion. However, this association has been documented in a population whose language reads from right to left instead of left to right (Eitan & Granot, 2006). There could be other explanations for the phenomenon, though. On the piano keyboard, higher pitches are located on the right side, and lower pitches are located on the left side. Additionally, on a graph, higher numbers are located on the right side of the horizontal axis, and lower numbers are located on the left side. It seems likely that these associations are culturally ingrained and are probably not present in infants. If that is the case, the test trials of the infants in the third and fourth experiments of the current study should not show any significant differences.

The fifth experiment tested the influence of ascending and descending musical sequences on making a visuospatial motion to a target location. Adult subjects were seated at a computer and heard either an ascending or descending scale or glissando. After the auditory stimulus began, a cursor appeared in the center of the screen, along with a target location. The target location was indicated with a red circle and was located above, below, to the left, or to the right of the cursor in the center of the screen. During half of trials, the direction of the necessary motion to move the cursor to the target location matched the direction of the auditory stimulus. Matching trials paired an ascending auditory stimulus with a target location either above or to the right of the cursor in the center of the screen, or a descending auditory stimulus with a target location either below or to the left of the cursor in the center of the screen. During the other half of the trials, the direction of the necessary motion to move the cursor to the target stimulus did not match the direction of the auditory stimulus. Reaction times were measured.

Experiment 1

Method

Participants

Twenty-eight 11-month-old infants were tested. Infants' and parents' names were obtained through birth records from the Texas Department of Health. Parents were contacted by telephone and/or email to invite them to participate. Participants were given a small gift at the end of the study, such as a t-shirt or a bib, for participating.

Stimuli

The stimuli were presented on a plasma television screen. The attention-getter consisted of an expanding and contracting green circle on a black background. The visual stimuli consisted of 10-second animated videos depicting a red circle moving up or down on a white background. The auditory stimuli consisted of computer-generated musical scales and glissandos in a clarinet timbre. Each scale or glissando ranged five octaves: from two octaves below Middle C to three octaves above Middle C. The movement of the red circle in the videos was synchronized with the scale or glissando that is played simultaneously.

Apparatus

During the testing period, infants were seated in their parent's lap in a dimly lit room adjacent to the control room. The infants were seated directly in front of the screen approximately 48" away. A closed circuit television camera was mounted below the screen which allowed the experimenter seated in the control room to view the infants on a television monitor. All sessions were recorded on DVD. The parents were instructed not to interact with their infant and to keep their eyes closed during the experiment to eliminate any subtle cues or interaction between infant and parent.

The experimenter presented the stimuli on a PowerMac G4 using the habituation software Habit X 1.0 (Cohen, Atkinson, & Chaput, 2000). Infants' looking behavior was recorded by keypress.

Design

Each infant viewed a habituation sequence of up to 20 10-second videos accompanied by musical stimuli. Each trial was separated by an attention-getting stimulus to ensure that the infant was looking at the screen at the beginning of each trial. The habituation trials paired the ascending visual stimulus with an ascending musical scale and the descending visual stimulus with a descending musical scale.

The infants' looking time was measured during the habituation trials. The total looking time from the first four habituation trials was calculated. When the infants' looking time decreases from this number by 50% on any subsequent consecutive set of four trials, the testing phase began. If the infants' looking time never decreased by 50% from the first four trials, the test trials began after 20 habituation trials.

The test trials consisted of a familiar trial, a switched trial, and a novel trial. The familiar trial paired the ascending visual stimulus with an ascending musical stimulus or the descending visual stimulus with a descending musical stimulus, as in the habituation trials. The switched trial paired the ascending visual stimulus with a descending musical stimulus or the descending visual stimulus with an ascending musical stimulus. Both the familiar trial and the switched trial used musical stimuli of the same music type (scale) that was used in the habituation trials. The novel trial paired the ascending visual stimulus with an ascending musical stimulus or the descending visual stimulus with a descending musical stimulus, but the music type was a glissando instead of a scale.

Procedure

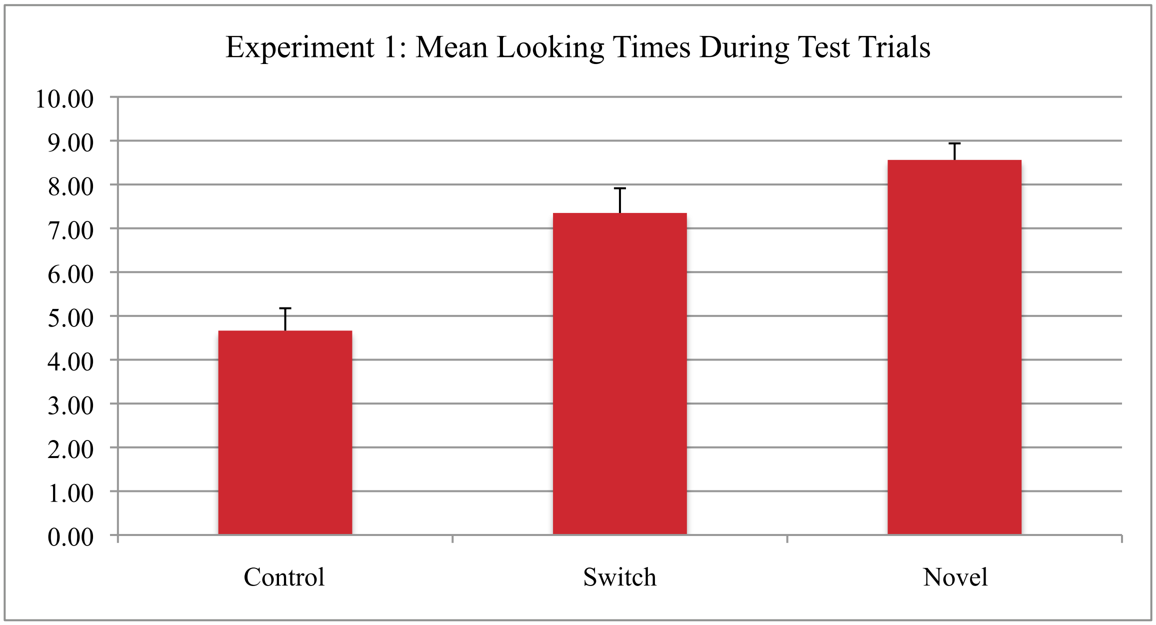
Infants and their parents came to the laboratory after being contacted and scheduled. Experimenters explained the study and procedure and answered any questions the parent(s) had. Informed consent was obtained for each participant. Infants and their parents were seated in the testing room as described above.

Results

Twenty-eight healthy, full-term infants completed Experiment 1; of those, 16 habituated. The mean number of habituation trials for the 16 infants who habituated was 13.31, while non-habituators viewed 20 habituation trials.

See Figure 1 for mean looking times on test trials from Experiment 1. Looking times from all infants' test trials from Experiment 1 were entered into a repeated measures ANOVA. The results revealed a significant effect of trial type; F (2, 52) = 16.87, $p < .001$, with partial eta squared = .39. Pairwise comparisons revealed that infants' looking time during the control, or matching, trial was significantly different from the switch, or non-matching, trial ($p = .001$) and the novel trial ($p < .001$). Looking times during the switch trial and the novel trial were not significantly different ($p = .08$). There was not a significant interaction between trial type and habituation; non-habituators did not have significantly different looking times on the test trials compared to habituators. Thus, data from both habituators and non-habituators were included in further analyses. The results indicate that 11-month-old infants are able to contingently process the musical stimuli and the direction of the motion of the object. Of greater interest is that these infants dishabituated to a non-matching pairing of the musical stimuli and the object motion after habituation to a matching pairing.

Figure 1. Bars depict mean looking times in seconds during test trials for Experiment 1.



Discussion

The results of Experiment 1 are discussed in conjunction with Experiment 2 in the next section.

Experiment 2

Method

Participants

Twenty-eight 11-month-old infants were tested. Infants' and parents' names were obtained through birth records from the Texas Department of Health. Parents were contacted by telephone and/or email to invite them to participate. Participants were given a small gift at the end of the study, such as a t-shirt or a bib, for participating.

Stimuli

The stimuli were the same as in Experiment 1.

Apparatus

The apparatus was the same as in Experiment 1.

Design

Each infant viewed a habituation sequence of up to 20 10-second videos accompanied by musical stimuli. Each trial was separated by an attention-getting stimulus to ensure that the infant was looking at the screen at the beginning of each trial. The habituation trials paired the ascending visual stimulus with a descending musical scale and the descending visual stimulus with an ascending musical scale.

The infants' looking time was measured during the habituation trials. The total looking time from the first four habituation trials was calculated. When the infants' looking time decreased from this number by 50% on any subsequent consecutive set of four trials, the testing phase began. If the infants' looking time never decreased by 50% from the first four trials, the test trials began after 20 habituation trials.

The test trials consisted of a familiar trial, a switched trial, and a novel trial. The familiar trial paired the ascending visual stimulus with a descending musical scale or the descending visual stimulus with an ascending musical scale, as in the habituation trials. The switched trial paired the ascending visual stimulus with an ascending musical scale or the descending visual stimulus with a descending musical scale. Both the familiar trial and the switched trial used musical stimuli of the same music type (scale) that was used in the habituation trials. The novel trial paired the ascending visual stimulus with a descending musical stimulus or the descending visual stimulus with an ascending musical stimulus as in the habituation, but the music type was a glissando instead of a scale.

Procedure

The procedure was the same as in Experiment 1.

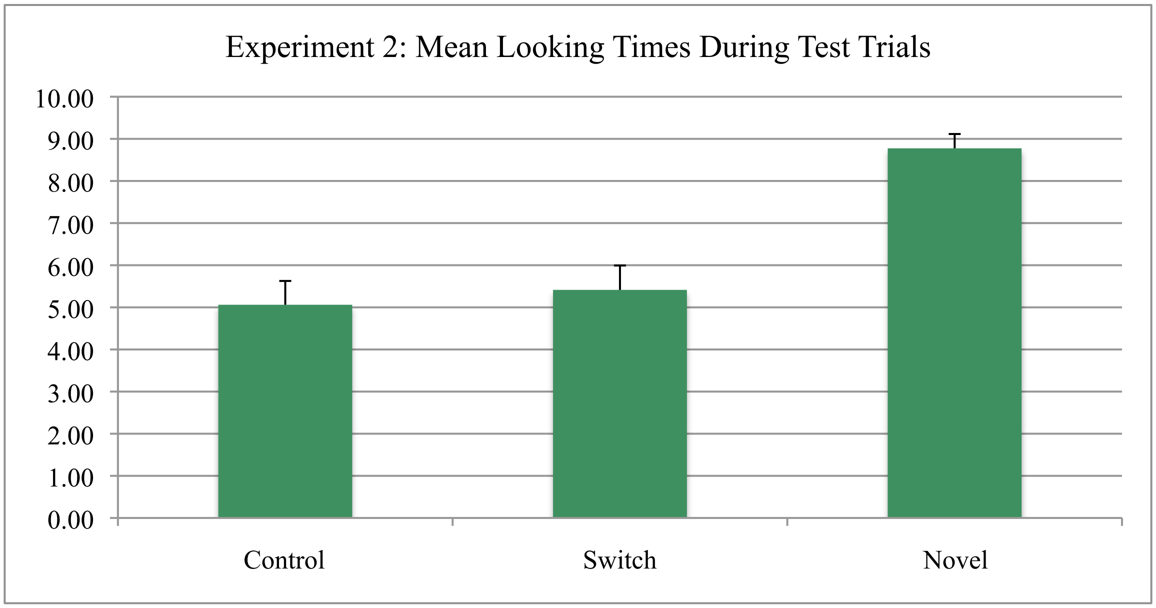
Results

Twenty-eight healthy, full-term infants also completed Experiment 2; of those, 19 habituated. The mean number of habituation trials for the 19 infants who habituated was 15.21, while non-habituators viewed 20 habituation trials. The proportion of infants who habituated in Experiment 2 was not statistically different from the proportion of infants who habituated in Experiment 1; χ^2 (1) = 1.313, $p = .2519$.

See Figure 2 for mean looking times during test trials from Experiment 2. Looking times from all infants' test trials from Experiment 2 were entered into a repeated measures ANOVA. The results revealed a significant effect of trial type; *F* (2,

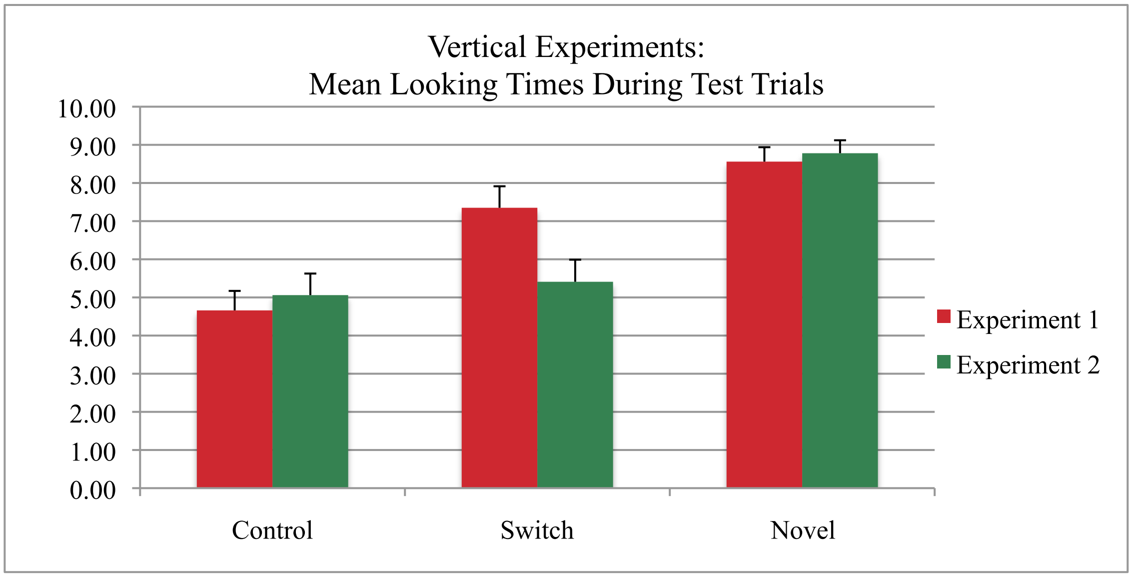
52) = 11.69, $p < .001$, with partial eta squared = .59. Pairwise comparisons revealed that infants' looking times during the control, or non-matching, trial were significantly different from the novel trial ($p < .001$). Looking times during the control trial and the switch, or matching, trial, however, were not significantly different ($p = .76$). The switch trial was significantly different from the novel trial ($p = .001$). There was not a significant interaction between trial type and habituation; non-habituators did not have significantly different looking times on the test trials compared to habituators. Thus, data from both habituators and non-habituators will be included in further analyses. These results indicate that infants who are habituated to a non-matching pairing of music direction and object motion do not dishabituate to a matching pairing.

Figure 2. Bars depict mean looking times in seconds during test trials for Experiment 2.



Collapsing the data across Experiments 1 and 2 allows us to directly compare the differences between the two experiments. See Figure 3 for mean looking times from Experiment 1 and Experiment 2. Looking times for all infants' test trials from both Experiments 1 and 2 were entered into a repeated measures ANOVA with experiment as a between-subjects factor. Because previous analyses indicated no differences on test trials between habituators and non-habituators in either experiment, data from both habituators and non-habituators were included. The results reveal a significant interaction of trial type by experiment; *F* (2, 108) = 3.63, *p* = .03. There was also a significant main effect of trial type; *F* (2, 108) = 31.67; *p* < .001. This indicates that infants in Experiment 1 who were habituated to the matching pairings of musical stimuli and object motion reacted differently to the test trials than infants in Experiment 2, who were habituated to non-matching pairings of musical stimuli and object motion.

Figure 3. Bars depict mean looking times in seconds during test trials for Experiment 1 and Experiment 2.



Discussion

The results from Experiments 1 and 2 suggest that young infants are predisposed to learn matching relationships between musical pitch and the direction of an object's motion in the vertical plane. The previously reported pilot study suggests that by 11 months of age, infants may be able to match musical pitch and the direction of an object's motion without any training or habituation, but Experiments 1 and 2 provide more conclusive evidence that infants of this age view matching and non-matching relationships between musical pitch and the direction of an object's vertical motion differently.

The infants in Experiment 1 who were habituated to the matching music and object motion dishabituated to the non-matching pairing of the music and object motion, but the infants in Experiment 2 who were habituated to the non-matching music and object motion did not dishabituate to the matching pairing. This suggests that the infants in Experiment 2 had difficulty "learning" the non-matching pairing of musical pitch and the direction of the object's motion during the habituation phase of the experiment. It is possible that the infants in this experiment had difficulty processing the non-matching music and object motion contingently; the incongruity of the stimuli may have only allowed infants to process the music and the object motion independently. Indeed, infants may have only been able to process either the auditory component or the visual component, but not both. Other evidence suggests that infants preferentially process amodal information in multimodal stimulation; according to the intersensory redundancy hypothesis (Bahrick, Lickliter, & Flom, 2004), processing of amodal information is facilitated in multimodal stimulation and attenuated in unimodal stimulation early in development. However, if the multimodal information that infants are receiving is incongruent, they may be unable to process the information from the separate senses contingently. If this were the case in Experiment 2, the infants would have simply habituated to the ascending and descending musical scales and the ascending and descending object motion, but not to any particular combinations of these stimuli because they would have been processing each aspect of the stimuli independently. Thus, the switched pairing of the familiar stimuli would not be expected to elicit longer looking times. This is consistent with the results of Experiment 2. Note, however, that the infants in Experiment 2 did dishabituate to the last test trial, the novel music type. This indicates that the infants were paying attention to the task and had habituated to the musical scales and noticed the difference between the scales and the glissando.

The results of Experiment 1 and Experiment 2 are consistent with a recent study of 4-month-old infants' mapping of musical tones and spatial dimensions. Katz, et. al. (2010) habituated 4-month-old infants to flowers dancing in three vertical positions in time to ascending or descending three-note tone sequences. Equal numbers of infants viewed forward, or matching, and reverse, or non-matching, pairings of tones and flower positions. After habituation, all infants viewed two new tones and flower positions with matching and non-matching mappings. They found that the infants in the matching condition looked longer at the test trial depicting the matching pairing, but infants in the non-matching condition looked equally at the two test trials. The researchers concluded that 4-month-old infants are predisposed to learn a matching mapping of tone pitch and object height. A previous experiment had examined whether 4-month-olds exhibit a spontaneous preference for matching pairings of two-note sequences of high and low tones and flower positions and found no difference. This indicates that although 4-month-old infants more easily learn matching relationships between musical pitch and an object's position in space than non-matching relationships, they do not show an intrinsic preference for matching relationships in simple, discrete tone sequences.

Another recent study, however, suggests that 3- and 4-month-old infants may be sensitive to matching relationships between musical pitch and object motion in continuously changing sequences (Walker, et. al., 2010). In this experiment, 3- and 4-month-old infants viewed an orange ball moving up and down in front of a dark background with a grid of small white dots. The ball moved at a constant speed across the grid but paused for 50 ms at each dot. The animation was accompanied by the sound of a slide whistle with either an ascending or descending pitch profile. Each infant viewed three congruent, or matching, pairings of the object's motion and the slide whistle, and three incongruent, or non-matching, pairing of the object's motion and the slide whistle. Twelve of the sixteen infants looked longer at the matching pairings than at the non-matching pairings, and after a log-transformation of the total looking times, an ANOVA revealed a significant effect of congruity. The researchers conclude that 3- and 4-month-old infants are sensitive to a correspondence linking auditory pitch with visuospatial height and that this synesthetic cross-modality correspondence is an unlearned aspect of perception. They propose that this evidence supports previous claims (James, 1890/1950, Maurer, Pathman, & Mondloch, 2006; Mondloch & Maurer,

2004) that prenatal experiences are synesthetic and that cross-modality correspondences are an innate aspect of perception. The claim of infant synesthesia may be a rich interpretation of the results, but this study provides at least weak evidence that 3- and 4-month-old infants may be sensitive to the same associations between musical pitch and visuospatial motion that were found in Experiment 1 and Experiment 2 of the current studies.

Experiment 3

Method

Participants

Twelve 11-month-old infants were tested. Infants' and parents' names were obtained through birth records from the Texas Department of Health. Parents were contacted by telephone and/or email to invite them to participate. Participants were given a small gift at the end of the study, such as a t-shirt or a bib, for participating.

Stimuli

The stimuli were presented on a plasma television screen. The attention-getter consisted of an expanding and contracting green circle on a black background. The visual stimuli consisted of 10-second animated videos depicting a red circle moving across a white background. The auditory stimuli consisted of computer-generated musical scales and glissandos in a clarinet timbre. Each scale and glissando ranged five octaves: from two octaves below Middle C to three octaves above Middle C. The movement of the red circle in the videos was synchronized with the scale or glissando that was played simultaneously.

Apparatus

The apparatus was the same as in Experiment 1.

Design

Each infant viewed a habituation sequence of up to 20 10-second videos accompanied by musical stimuli. Each trial was separated by an attention-getting stimulus to ensure that the infant was looking at the screen at the beginning of each trial. The habituation trials paired the rightward moving visual stimulus with an ascending musical scale and the leftward moving visual stimulus with a descending musical scale.

The infants' looking time was measured during the habituation trials. The total looking time from the first four habituation trials was calculated. When the infants' looking time decreased from this number by 50% on any subsequent consecutive set of four trials, the testing phase began. If the infants' looking time never decreased by 50% from the first four trials, the test trials began after 20 habituation trials.

The test trials consisted of a familiar trial, a switched trial, and a novel trial. The familiar trial paired the rightward moving visual stimulus with an ascending musical scale or the leftward moving visual stimulus with a descending musical scale, as in the habituation trials. The switched trial paired the rightward moving visual stimulus with a descending musical scale or the leftward moving visual stimulus with an ascending musical scale. Both the familiar trial and the switched trial used musical stimuli of the same music type (scale) that was used in the habituation trials. The novel trial paired the rightward moving visual stimulus with an ascending musical stimulus or the leftward moving visual stimulus with a descending musical stimulus, but the music type was a glissando instead of a scale.

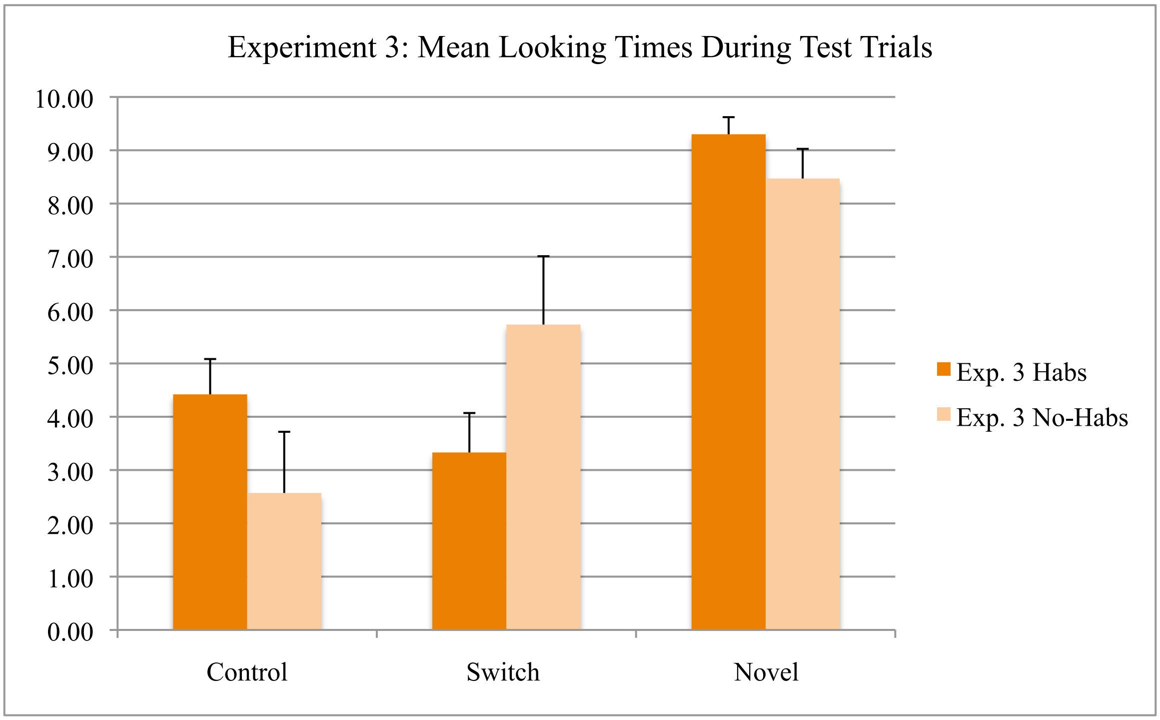
Procedure

The procedure was the same as Experiment 1.

Results

Twelve healthy, full-term infants completed Experiment 3; of those, 9 habituated. The mean number of habituation trials for habituators was 12.56, while the 3 non-habituators viewed 20 trials. See Figure 4 for mean looking times for habituators and non-habituators from Experiment 3. The data from Experiment 3 and Experiment 4 were analyzed together to allow direct comparison between the two experiments, and the results of that analysis are in the following section.

Figure 4. Bars depict mean looking times in seconds during test trials for Experiment 3.



Discussion

The results of Experiment 3 are discussed in conjunction with Experiment 4 in the next section.

Experiment 4

Method

Participants

Thirteen 11-month-old infants were tested. Infants' and parents' names were obtained through birth records from the Texas Department of Health. Parents were contacted by telephone and/or email to invite them to participate. Participants were given a small gift at the end of the study, such as a t-shirt or a bib, for participating.

Stimuli

The stimuli were the same as in Experiment 3.

Apparatus

The apparatus was the same as in Experiment 1.

Design

Each infant viewed a habituation sequence of up to 20 10-second videos accompanied by musical stimuli. Each trial was separated by an attention-getting stimulus to ensure that the infant was looking at the screen at the beginning of each trial. The habituation trials paired the leftward moving visual stimulus with an ascending musical scale and the rightward moving visual stimulus with a descending musical scale.

The infants' looking time was measured during the habituation trials. The total looking time from the first four habituation trials was calculated. When the infants' looking time decreased from this number by 50% on any subsequent consecutive set of four trials, the testing phase began. If the infants' looking time never decreased by 50% from the first four trials, the test trials began after 20 habituation trials.

The test trials consisted of a familiar trial, a switched trial, and a novel trial. The familiar trial paired the leftward moving visual stimulus with an ascending musical scale or the rightward moving visual stimulus with a descending musical scale, as in the habituation trials. The switched trial paired the leftward moving visual stimulus with a descending musical scale or the rightward moving visual stimulus with an ascending musical scale. Both the familiar trial and the switched trial used musical stimuli of the same music type (scale) that was used in the habituation trials. The novel trial paired the leftward moving visual stimulus with an ascending musical stimulus or the rightward moving visual stimulus with a descending musical stimulus, but the music type was a glissando instead of a scale.

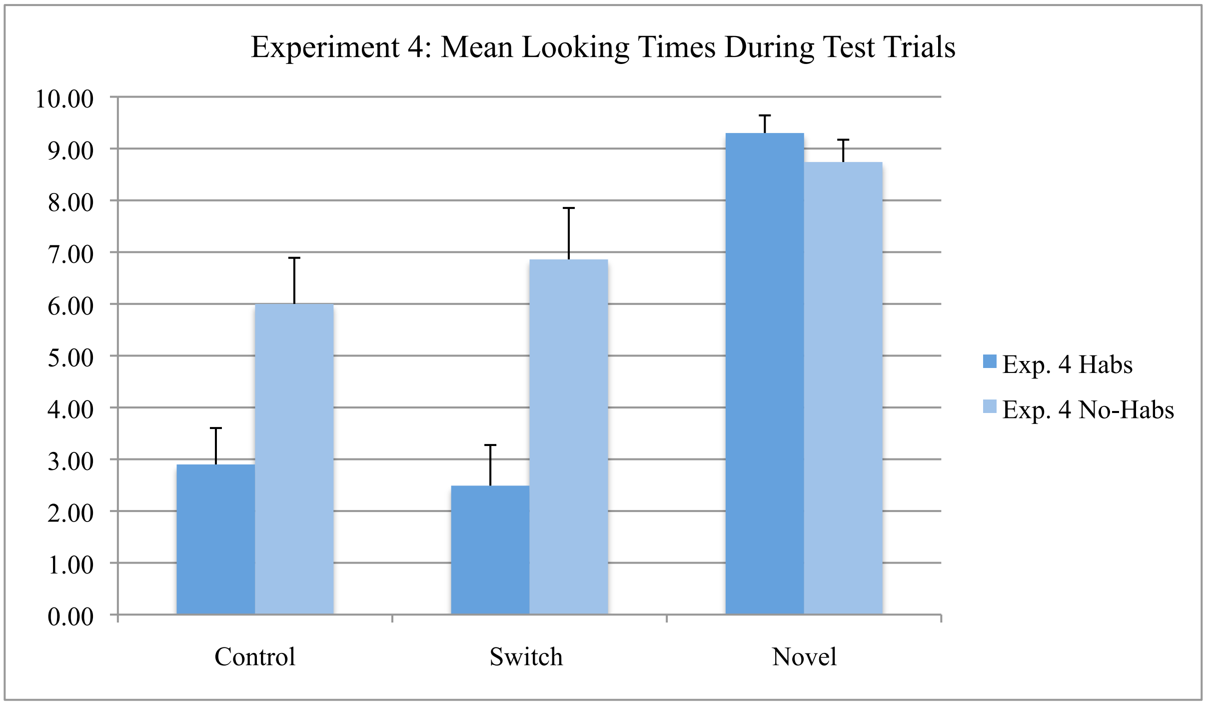
Procedure

The procedure was the same as in Experiment 1.

Results

Thirteen healthy, full-term infants completed Experiment 4; of those, 8 habituated. The mean number of habituation trials for habituators was 12.50, while the 5 non-habituators viewed 20 trials. See Figure 5 for mean looking times for habituators and non-habituators from Experiment 4.

Figure 5. Bars depict mean looking times in seconds during test trials for Experiment 4.



The data from Experiment 3 and Experiment 4 were analyzed together to allow direct comparison between the two experiments. Looking times for all infants' test trials from both Experiments 3 and 4 were entered into a repeated measures ANOVA with experiment and habituation as between-subjects factors. The results reveal a significant effect of trial type; $F(2, 42) = 62.09$, $p < .001$. Pairwise comparisons indicate that the novel trial was significantly different from both the control trial ($p < .001$) and the switch trial ($p < .001$). Looking times during the control trial and the switch trial, however, were not significantly different ($p = .237$). This indicates that infants did not dishabituate to the switched pairing of the musical stimulus and the direction of the object's motion. There was no interaction between trial type and experiment; $F(2, 42) = .470$, $p = .628$. This indicates that the infants who were habituated to the matching horizontal object motion in Experiment 3 did not react differently to the test trials than the infants who were habituated to the non-matching horizontal object motion in Experiment 4.

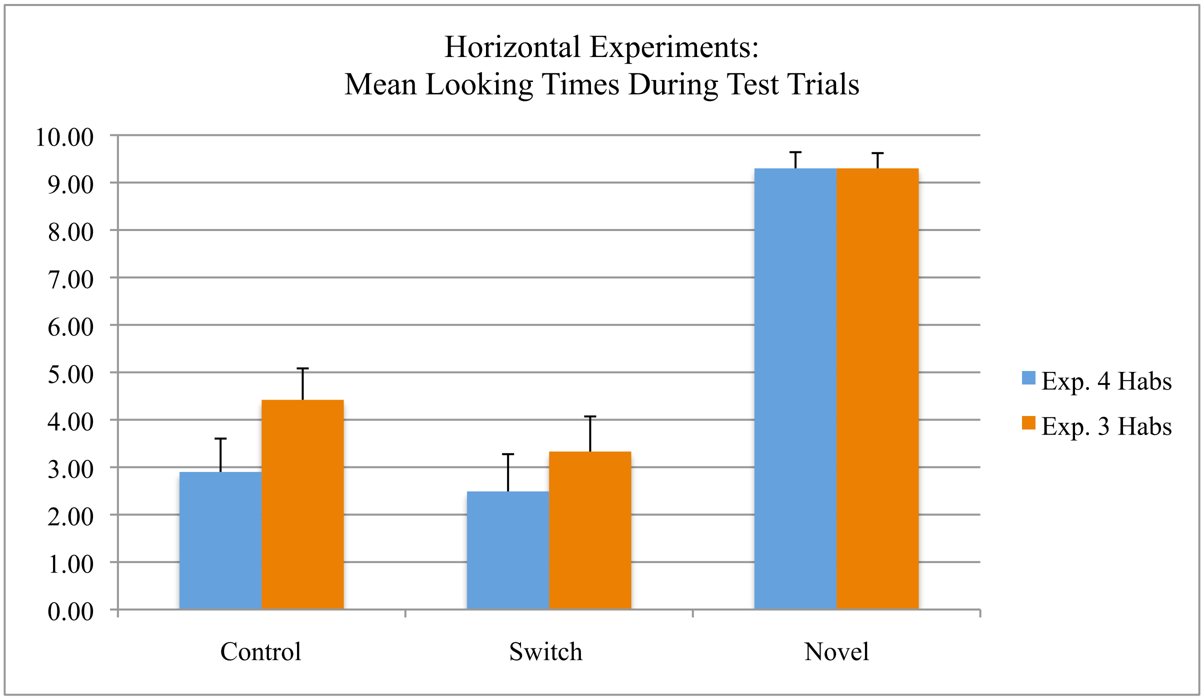
There was an interaction between trial type and habituation; $F(2, 42) = 9.169$, $p < .001$, and a marginally significant three-way interaction between trial type, habituation, and experiment; $F(2, 42) = 2.966$, $p = .062$. Both of these interactions seem to be driven by a few non-habituators in Experiment 4 who exhibited longer looking times during the control trial and the switch trial; see Figure 5. It is not uncommon for infants who have not met the habituation criterion to have long looking times during familiar test trials. Because of the small number of non-habituators in this experiment, the looking times from these few long lookers created a statistically significant effect, but this is likely due to chance and is of little interest.

Because non-habituators showed a less clear pattern of looking behavior during the test trials, an additional analysis was performed using only the data from the habituators from Experiment 3 and Experiment 4. Means for habituators from Experiment 3 and Experiment 4 are shown in Figure 6. Looking times from the habituators from these two experiments were entered into a repeated measures ANOVA with experiment as a between subjects factor. The results reveal a significant effect of trial type; $F(2, 30) = 133.702$, $p < .001$. Pairwise comparisons indicate that the novel trial was significantly different from both the control trial ($p < .001$) and the switch trial ($p < .001$). The control trial and the switch trial were not significantly different ($p =$

.126). Thus, the habituators did not dishabituate to the switch trial that demonstrated the unfamiliar pairing of the musical scale and the direction of the object's motion, but they did dishabituate to the novel music type.

There was no significant interaction between trial type and experiment; *F*(2, 30) = 1.594; *p* = .220. This indicates that the infants in Experiment 3 who were habituated to the matching association between musical pitch and the direction of an object's motion in the horizontal plane did not react differently to the test trials compared to the infants in Experiment 4, who were habituated to the non-matching association. This is the same conclusion that was reached when both habituators and non-habituators were included in the analysis.

Figure 6. Mean looking times in seconds during test trials for habituators in Experiment 3 and Experiment 4.



Discussion

The results from Experiment 3 and Experiment 4 indicate that infants are not sensitive to matching relationships between musical pitch and an object's motion in the horizontal plane. Infants in both of these experiments failed to dishabituate to a switched pairing of the musical stimulus and the object's motion. It is possible that the infants in these two experiments were unable to contingently process the direction of the musical scale and the direction of the object's motion in the horizontal plane. However, infants in both Experiments 3 and 4 did dishabituate to the novel test trial, indicating that they were paying attention to the task. The infants in both of these experiments had habituated to the musical scales and noticed the difference between the scales and the glissando.

Experiment 5

Method

Participants

Eight adults were tested. Participants were recruited through the University of Texas at Austin Department of Psychology OPERA system. Participants were undergraduate students taking an introductory psychology course and received course credit for participation in the experiment.

Stimuli

The stimuli were presented on a computer, and the subjects used a trackball to drag the cursor to the target location on the screen. Each trial began with a 2-second musical stimulus of either an ascending or descending scale or glissando. One second after the audio stimulus began, a cursor appeared in the center of the screen, along with a target location to which the subject must drag the cursor. The target location was above, below, to the left, or to the right of the center of the screen where the cursor appeared. The target location was indicated by the presence of a red circle.

Apparatus

The stimuli were presented on a Macintosh computer using MatLab 7.6.0 software. Subjects responded with a Kensington Expert Mouse Optical USB Trackball.

Design

Adult subjects were seated at a computer and heard either an ascending or descending scale or glissando through headphones. All of the musical stimuli were 2 seconds in duration. One second after the auditory stimulus began, a cursor appeared in the center of the screen, along with a target location. The target location was indicated with a red circle and will be located above, below, to the left, or to the right of the cursor in the center of the screen. During half of trials, the direction of the necessary motion to move the cursor to the target location matched the direction of the auditory stimulus. Matching trials paired an ascending auditory stimulus with a target location either above or to the right of the cursor in the center of the screen, or a descending auditory stimulus with a target location either below or to the left of the cursor in the center of the screen. During the other half of the trials, the direction of the necessary motion to move the cursor to the target stimulus did not match the direction of the auditory stimulus. Trials in which the target locations are above and below the center were presented in a separate block than trials in which the target locations were to the left and to the right of the center, and subjects were allowed to practice before each block. In both blocks, trials were randomized with the constraint that no more than 3 auditory stimuli of the same direction played in a row. There was a 1-second inter-stimulus interval between each trial. Reaction times were measured.

Procedure

Subjects were seated in front of a computer and completed 48 practice trials in which they moved the cursor on the computer screen to a target location using the trackball. In the first practice, the target locations were above and below the center. After the practice block, the subjects completed a block of 200 trials in which the target locations were above and below the center. Then they completed another 48 practice trials in which the target locations were to the left and to the right of the center. Finally, they completed a block of 200 trials in which the target locations were to the left and to the right of the center.

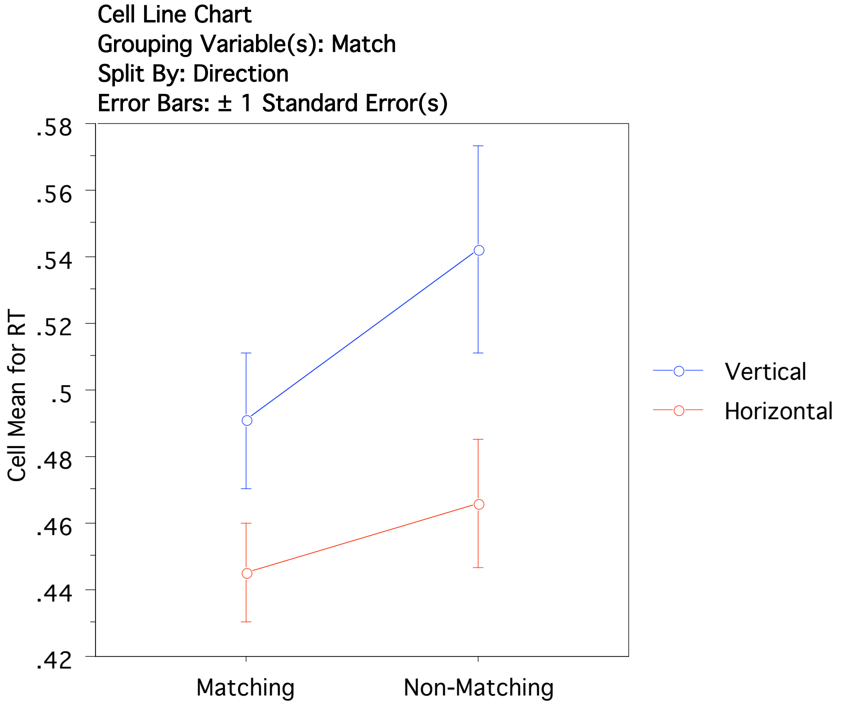
Results

Eight adults completed Experiment 5. Preliminary analyses indicated no significant effect of music type (scale vs. glissando), so the final analyses do not include music type as a factor. This is consistent with the infant pilot study in which both scales and glissandos were used, and no effect was found for music type. Reaction times more than 2.5 standard deviations above or below the mean for each block were excluded.

Each subject completed two test blocks, one vertical and one horizontal. For each block, half of the trials were matching and half were non-matching. Mean reaction times for matching and non-matching trials were computed for each subject for the matching and non-matching trials from each block. Of the eight subjects, seven demonstrated a slower mean reaction time for the non-matching trials compared to the matching trials on the vertical blocks. All eight subjects demonstrated a slower mean reaction time for the non-matching trials compared to the matching trials on the horizontal blocks, though the differences were small.

Mean reaction times for matching and non-matching cells for the vertical and horizontal blocks were entered into a repeated-measures ANOVA. The results reveal a significant interaction between direction (vertical vs. horizontal) and match (matching vs. non-matching); $F(7, 1) = 6.367$, $p = .0396$. This indicates that subjects performed differently on matching vs. non-matching trials in the vertical and horizontal blocks. See Figure 7 below.

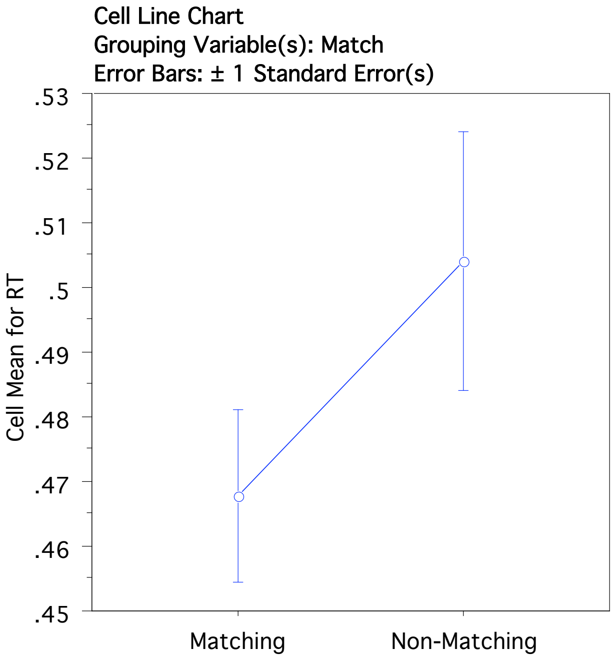
Figure 7. Cell means for reaction times in seconds for Experiment 5 for matching and non-matching vertical and horizontal trials.



Though subjects demonstrated faster reaction times for the matching trials in both the vertical and horizontal blocks, the difference between the matching and non-matching trials is greater in the vertical blocks than in the horizontal blocks.

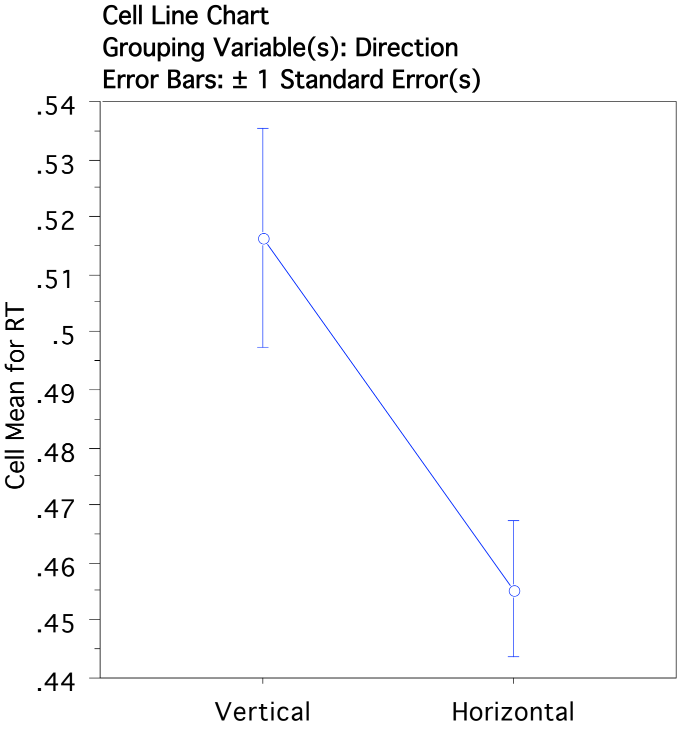
There was a significant main effect of matching; $F(7,1) = 9.420$, $p = .0181$. This indicates that there is a significant difference between mean reaction times for the matching and non-matching trials. See Figure 8 for the mean reaction times for matching and non-matching trials. The difference is in the predicted direction, with slower reaction times for the non-matching trials and faster reaction times for the matching trials. Given the interaction between direction (vertical vs. horizontal) and matching, this effect is largely driven by the vertical blocks.

Figure 8. Cell means for reaction times in seconds for Experiment 5 for matching and non-matching trials.



There was also a significant main effect of direction; *F*(7, 1) = 15.796, *p* = .0054. Mean reaction times for the horizontal trials were faster than the mean reaction times for the vertical trials. See Figure 9 for the mean reaction times for vertical and horizontal trials. Though this difference was not predicted, it is likely a result of the ease and familiarity of lateral motion of the hand. The vertical trials required motion of the hand away from (for vertical) or towards (for horizontal) the body, and this is likely a less familiar motion than the lateral motion required by the horizontal trials.

Figure 9. Cell means for reaction times in seconds for Experiment 5 for vertical and horizontal trials.



Discussion

Adult subjects in Experiment 5 were able to use a trackball to move a cursor to a target location more quickly if the direction of the musical stimulus to which they were listening matched the direction of the target location in space. The difference between the matching and the non-matching trials was greater for the vertical blocks than for the horizontal blocks, which is consistent with previous research (Eitan & Granot, 2006).

Previous studies have documented associations between musical pitch or auditory tones and visuospatial direction in adults. However, most of these studies (Roffler & Butler, 1968; Eitan & Granot, 2006) involved cognitive tasks that required subjects to make a written or oral response based on their judgments or thoughts. The current study is one of few studies in which the task was psychophysical rather than cognitive. Similar results were found by Melara and O'Brien (1987) with high and low tones and dots placed in high and low positions on the screen: subjects were able to identify both tones and positions more rapidly if the stimulus of the other modality was congruent with the stimulus to which the subject had to respond. Responses were recorded by keypress.

While cognitive tasks allow subjects to think about their responses over a more extended period of time, reaction time studies like Experiment 5 require such a rapid response that the subjects have very little time to reflect on their responses. Thus, the results of Experiment 5 do not demonstrate subjects' reasoning about associations between musical pitch and space; they reflect basic psychophysical processes. This helps explain the results of Experiments 1 and 2, which indicate that 11-month-old infants are sensitive to associations between musical pitch and visuospatial motion.

Given that infants are subject to the phenomenon as well, it is unlikely that the association could be based upon complex cognitive judgments or semantic relationships.

General Discussion

Synesthesia, or the "joining of the senses," has long been a topic of discussion in the psychological sciences. Martino and Marks (2001) distinguish between strong and weak synesthesia. Strong synesthesia is characterized by "a vivid image in one sensory modality in response to stimulation in another one" (Martino & Marks, 2001, pp. 61). Weak synesthesia, on the other hand, is characterized by "cross-sensory correspondences expressed through language, perceptual similarity, and perceptual interactions during information processing" (Martino & Marks, 2001, pp. 61). Martino and Marks propose that the neural processes responsible for strong and weak synesthesia may draw on similar underlying mechanisms, though there are differences between the two types of experience.

Weak synesthesia is common and has been demonstrated in several experiments in the auditory and visual modalities. Marks (1978) demonstrated that most people make pitch-lightness associations: the higher the pitch of an auditory tone, the lighter the color subjects will pair with it. Like the experience of strong synesthesia, the cross-modal correspondences of weak synesthesia are systematic, but unlike strong synesthesia, the correspondences of weak synesthesia are contextual. The cross-modal associations produced by weak synesthesia are dependent upon the stimuli in the environment and do not display a one-to-one mapping like the vivid imagery of strong synesthesia. The correspondences of weak synesthesia are also typically bi-directional: a stimulus in either modality of the correspondence can elicit an association in the other modality.

Some scientists have suggested that synesthesia involves absolute correspondences produced by low-level sensory mechanisms, caused by sensory leakage (Harrison & Baron-Cohen, 1997). This hypothesis states that information leaks from one sensory channel into another, producing synesthesia. Researchers suggest that this could happen if nerve cells fail to form or migrate properly during neonatal development. This may be a plausible theory for explaining strong synesthesia, but an alternative hypothesis has been proposed to explain weak synesthesia. Martino and Marks (1999, 2001) believe that although cross-modal correspondences may arise from sensory mechanisms in infants, these correspondences reflect higher-level mechanisms in adults. The semantic coding hypothesis states that experience with percepts from various modalities and language produces an abstract semantic network that captures synesthetic correspondences. When people perceive synesthetically corresponding stimuli, they re-code these sensory experiences into abstract representations. The semantic coding hypothesis accounts for associations produced not only by sensory stimuli, but also by linguistic stimuli (see Martino & Marks, 1999).

According to the definition put forth by Martino and Marks (2001), both infants and adults have demonstrated some form of weak synesthesia in the current studies. The semantic coding hypothesis suggests that adults re-coded the synesthetically corresponding musical stimuli and target locations on matching trials and that this re-coded abstract representation aided their ability to rapidly locate the target. However, this hypothesis seems insufficient to explain the ability of infants to make the associations between musical pitch and an object's motion in the vertical plane. Though the semantic coding hypothesis allows for cross-modal correspondences from sensory mechanisms in infants, it fails to explain these sensory mechanisms themselves.

The origin of the rather abstract association between musical pitch and the direction of an object's motion in the vertical plane still remains a something of a mystery. There is not an obvious reason why increasingly faster frequencies should map onto ascending motion in the vertical plane, and vice versa for slower frequencies and descending motion. It is possible that the association either comes from or is strengthened by the fact that higher pitches originate higher in the throat than do lower pitches. High-pitched vocalizations are produced by tighter vocal folds in the larynx, which cause the larynx to contract upward in the throat. Likewise, lower-pitched vocalizations are produced by relaxing the vocal folds and allowing the larynx to sit lower in the throat. Thus, awareness of one's own body during the production of high- and low-pitched sounds may be the root of this association. The association may also be reinforced by watching others speak or sing: people commonly raise their eyebrows and lift their chins while singing high notes, or lower their chins while singing low notes or speaking in a low-pitched voice. The infants in the current studies are old enough to imitate pitch in their own vocalizations (Papousek, 1996) and may be more aware of the physical feeling of high- and low-pitched vocalizations. This could be one explanation for why the 4-month-old infants in Katz, et. al. (2010) did not show a spontaneous preference for matching pairings between high and low tones and high and low spatial positions, but the 11-month-old infants in the pilot study of the current studies did demonstrate evidence of spontaneous matching.

The lack of results from the horizontal experiments with infants compared to the vertical experiments suggests that although the associations between musical pitch and the direction of an object's motion in the vertical plane may be innate or easily learned, the same is not true of the associations between musical pitch and the direction of an object's motion in the horizontal plane. Thus, the associations that have been documented in previous adult studies and Experiment 5 of the current studies between musical pitch and motion in the horizontal plane are likely either the result of learning that occurs later during childhood or early adulthood from exposure to cultural tools such as the piano or the mathematical (*x, y*) graph, or the result of some awareness of direction that emerges when handedness develops. Because the majority of people are right-handed, it is possible that the associations that adults make between ascending musical pitch and rightward motion are a result of the majority of people mapping "upward" or "forward" associations onto rightward motion, and vice versa for "downward" or "backward" with leftward. Likewise, even if children are simply learning the associations during childhood from cultural tools such as mathematical graphs and musical instruments, the root of the directional mapping of these cultural tools themselves may lie in handedness.

If it is true that the association between musical pitch and an object's motion in the horizontal plane is rooted in handedness, we should not expect that infants at 11 months of age, who have not yet begun to exhibit handedness, would demonstrate this association. We should predict that this association would emerge as children begin to show hand preference sometime during the second and third years of life (Gesell & Ames, 1947). A good test of this hypothesis would be whether left-handed children who have not yet had much exposure to cultural icons that demonstrate the right/up vs. left/down relationship would make the opposite association and map left with up and right with down. This may be difficult, however, as strong handedness often does not fully develop until children are 8 or 9 years of age (Gesell & Ames, 1947), and by that age children may have already begun to learn the conventional right/up vs. left/down associations that are prevalent in Western culture. It may also be unlikely that young children would make any associations between musical pitch and visuospatial motion in the horizontal plane, as adult studies documenting this phenomenon note that the association is weak.

Taken together, the results from all four of the infant experiments suggest that infants are predisposed to making matching associations between musical pitch and an object's motion in the vertical, but not horizontal, plane. This may be because infants of this age are able to imitate pitch, which may be the origin of the vertical associations, but have not yet developed handedness, which may be the origin of the horizontal associations. Furthermore, infants may be unable to contingently process musical pitch and the direction of an object's motion unless they perceive that the direction of the object's motion matches the direction of the music.

Music is an inherently physical experience, eliciting movement from performers and listeners alike. Both tonal and rhythmic motion in music allude to the physical motion of bodies and objects. The associations that adults and infants make between musical pitch and visuospatial direction may be rooted in biological processes such as vocal pitch production and handedness. Though this hypothesis of the origin of the associations is speculative, these associations must be deep-seated in human psychology because they have been documented cross-culturally (Eitan & Granot, 2006) and in infants (current studies; Walker, et. al., 2010; Katz, et. al., 2010). The associations between music and motion are physical, and thus, universal. The feeling of music in tune with one’s own body is an integral part of what makes music a fundamental and uniquely human experience.

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