Babies know bad dancing when they see it: Older but not younger infants discriminate
between synchronous and asynchronous audiovisual musical displays

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ABSTRACT

Movement to music is a universal human behavior, yet little is known about how observers perceive audiovisual synchrony in complex musical displays such as a person dancing to music, particularly during infancy and childhood. In the current study, we investigated how perception of musical audiovisual synchrony develops over the first year of life. We habituated infants to a video of a person dancing to music, and subsequently presented videos in which the visual track was matched (synchronous) or mismatched (asynchronous) with the audio track. In a visual-only control condition, we presented the same visual stimuli with no sound. In Experiment 1, we found that older infants (8 to 12 months) exhibited a novelty preference for the mismatched movie when both auditory and visual information were available, and showed no preference when only visual information was available. By contrast, younger infants (5 to 8 months) in Experiment 2 did not discriminate matching from mismatching stimuli. This suggests that the ability to perceive musical audiovisual synchrony may develop during the second half of the first year of infancy.

Keywords: infant perception; audiovisual synchrony; intersensory perception; music; rhythm

Babies know bad dancing when they see it: Older but not younger infants discriminate between synchronous and asynchronous audiovisual musical displays

The capacity to dance to music is a human universal. In all cultures, people move spontaneously to music, entraining their body movements to the timing of a musical pulse or beat (Large, 2000; Nettl, 1983; Repp, 2005; Snyder & Krumhansl, 2001). Though commonplace, this capacity is not trivial but rather depends on complex and multisensory cognitive processes that develop with age and experience. Dancing to music requires listeners to actively infer a beat from a rich and dynamic musical stimulus, modulate attention towards regularly occurring time points within auditory, visual, and tactile sensory input, form expectations about future events that guide self-generated movements, and continuously monitor these movements for error (Jones & Boltz, 1989; Large & Jones, 1999; Repp & Su, 2013). The present paper takes an initial step towards understanding the development of these multisensory musical capacities by investigating whether or not young infants can tell when a seen dancer is in or out of synchrony with the beat of heard music.

The term musical “beat” refers to a regularly-occurring salient moment in time, often equally spaced or quasi-isochronous, when human listeners are most likely to tap their finger or foot during music listening (Honing, Bouwer, & Háden, 2014; Lerdahl & Jackendoff, 1983). The musical beat can be considered just one (the most salient) level of the musical “meter”, which is made up of multiple hierarchically nested faster and slower levels of pulsation, typically related to the beat by integer ratios (Lerdahl & Jackendoff, 1983; London, 2002). For example, a waltz and a tango might both have 100 beats per

minute, but a waltz has a higher-level, slower pulse every three beats, whereas a tango has higher-level pulses every two and four beats. The beat is often highlighted by acoustic features such as louder or longer notes, but a beat can also be perceived in the absence of loudness or duration changes (Brochard et al., 2003; Iverson, Repp, & Patel, 2009), and even when there is no acoustic event (Longuet-Higgins & Lee, 1984; Snyder & Krumhansl, 2001). Thus, beat perception is to a surprising extent a top-down, subjective and listener-driven process; we infer and predict the location of musical beats, and the percept of a beat is not solely the result of bottom-up perceptual input (Honing et al., 2014; Trainor & Hannon, 2013).

Beat perception and production play a central role in human musicality. Beat perception and production are relatively rare among other species, even after extensive training (Cook, Rouse, Wilson, & Reichmuth, 2013; Hattori, Tomonaga, & Matsuzawa, 2013; Honing et al., 2012; Schachner, Brady, Pepperberg, & Hauser, 2009; Zarco, Merchant, Prado, & Mendez, 2009). By contrast, this ability emerges spontaneously in most humans in early childhood, without explicit musical training. Within days of birth, infants show sensitivity to the beat in simple musical stimuli: While listening to drum patterns, newborns exhibit larger ERP responses (mismatch negativity) when events are omitted on strong versus weak beat positions (Winkler, Háden, Ladinig, Sziller, & Honing, 2009), and violations of temporal intervals or tempo in metronome-like rhythmic stimuli give rise to behavioral and neural detection responses in 2-month-old infants (Baruch & Drake, 1997; Otte et al., 2013). By the middle of the first year, infants categorize rhythms by their underlying beat: 7-month-olds habituated to a set of varied rhythmic sequences that all shared the same underlying beat subsequently exhibited

larger dishabituation responses (indicating perception of greater novelty) to rhythms that violated the familiar beat, versus those that maintained the beat they heard during the prior habituation phase (Hannon & Johnson, 2005).

Infants also begin to integrate their own body movements with their auditory perception sometime during the first year. For example, when bounced on every second or third beat of an ambiguous rhythm, 7-month-olds later prefer listening to a version of the rhythm containing loudness accents that match the prior bouncing pattern, suggesting they encode the temporal position of the bounces as reflecting the beat (Phillips-Silver & Trainor, 2005). Some evidence suggests 3- to 5-month-old infants engage in repetitive, rhythmic body movements such as kicking and arm-waving more often in the presence of music than during silence or other non-musical stimuli such as speech (Fujii et al., 2014; Ilari, 2015; Zentner & Eerola, 2010), however these movements are relatively infrequent (8% of the trial at most, observed in only some infants).

As in other domains such as language, production appears to lag behind perception during development of beat-based musical behavior. Even though infants can perceive the beat and sometimes move in response to music, they do not move in precise synchrony with music (Ilari, 2015; Zentner & Eerola, 2010). It is not until later childhood that children are capable of consistently moving in precise synchrony with a musical beat (Kirschner & Tomasello, 2009; McAuley, Jones, Holub, Johnston, & Miller, 2006; Provasi & Bobin-Begue, 2003). Between the ages of 2 and 8, children become better at adjusting their regular rhythmic movements to the tempo of an external stimulus (McAuley et al., 2006; Provasi & Bobin-Begue, 2003) or another drummer (Kirschner & Ilari, 2014) but even 10-year-olds are more variable than adults when tapping to simple

rhythms and to music (Drake, Jones, & Baruch, 2000). Thus, the capacity for adult-like entrainment to music does not appear to be fully developed until later childhood.

The later arrival of precise synchronization with music suggests that despite infants' early perceptual sensitivity to the beat in some tasks, many aspects of beat processing develop gradually. Much evidence suggests that this slow development includes acquisition of abstract, higher-level aspects of musical meter and beat, and their multisensory correlates. For example, representations of musical meter and beat undergo substantial developmental changes during early childhood: Young infants are initially able to discriminate rhythmic structures from any culture (Hannon & Trehub, 2005a), but between 5 and 12 months begin to preferentially listen to and better discriminate metrical structures from their own culture (Hannon, Soley, & Levine, 2011; Hannon & Trehub, 2005b; Soley & Hannon, 2010). Listening experience during infancy appears to increase perceptual biases for the more common meters within a given culture, leading to enhanced encoding of duple meters (groups of two or four beats) compared with less common triple meters (groups of three beats) in North America (Bergeson & Trehub, 2006; Gerry, Faux, & Trainor, 2009). The malleability of culture-specific metrical representations may extend into later childhood, as exposure to foreign music can reverse or reduce own-culture metrical biases among children up to age 7 but not among 9-year-olds and adults (Hannon & Trehub, 2005b; Hannon, Vanden Bosch der Nederlanden, & Tichko, 2012). Although only a handful of studies provide data on the development of beat perception and production during childhood (e.g. Drake et al., 2000; Hannon et al., 2012; McAuley et al., 2006; Provasi & Bobin-Begue, 2003), findings generally support the notion that nuanced aspects of beat perception develop slowly as listeners become

more familiar with the music around them and form stable cognitive representations of musical meter.

The Development of Audiovisual Synchrony Perception

Our earliest encounters with music include coordinated auditory, visual, tactile, and sensorimotor input: As infants we are often rocked and bounced during face-to-face caregiver singing and vocal play (Phillips-Silver, 2009; Trainor & Hannon, 2013). Nevertheless, relatively little is known about the development of intermodal music perception. When presented with simple, non-musical displays of audible and visible events, infants between 1 and 10 months of age expect to hear a sound when they see an impact between a bouncing ball, toy, hammer, or object and a surface, or between two clapping hands (Bahrick, 1983, 1987, 1988, 2001; Kopp, 2014; Kopp & Dietrich, 2013; Lewkowicz, 1992a, 1992b, 1994, 1996; Spelke, 1979). In these studies of simple non-musical events, infants behaviorally and neurally detect disruption of audiovisual synchrony relations, and they prefer synchronous over asynchronous audiovisual displays. Low-level audiovisual synchrony may also boost young infants' sensitivity to the patterning of multisensory input. For example, 4-month-olds can classify audiovisual patterns on the basis of rhythm, tempo, or emotional content, but cannot perform the same classification when stimuli are presented unimodally (e.g. using auditory or visual information alone) until they are a few months older (Bahrick & Lickliter, 2000; Flom & Bahrick, 2007; Pickens & Bahrick, 1995, 1997; Walker-Andrews, 1986).

Perception of audiovisual synchrony nevertheless changes with age, particularly for complex multimodal structures such as language. This suggests that experience and

acquired knowledge may be prerequisites for perceiving some types of audiovisual synchrony. For example, infants readily detect synchrony between the audio and visual components of isolated, spoken syllables (Lewkowicz, 2003, 2010), but they have greater difficulty when syllables form a rhythmic pattern (Lewkowicz, 2003), and only inconsistently respond to audiovisual asynchrony in fluent speech, having particular trouble with foreign speech or non-infant-directed speech (Dodd, 1979; Kubicek et al., 2014; Kubicek, Gervain, de Boisferon, Pascalis, Loevenbruck, & Schwarzer, 2014; Lewkowicz & Pons, 2013).

Evidence from studies of language suggest that audiovisual perception may undergo a progression wherein young infants initially rely on low-level perceptual aspects of audiovisual synchrony, but increasingly learn about and rely on higher-level structures such as language identity (including phonetic and prosodic structure), person identity, emotion, gender, and so on (Lewkowicz, 2014). While very young infants (under 5 months) can use phonetic information to match vowels with facial movements (Kuhl & Meltzoff, 1982; Patterson & Werker, 1999, 2003) and know that human faces go with human voices (and not with monkey vocalizations or tones; Kuhl, Williams, & Meltzoff, 1991; Spelke, 1976; Vouloumanos, Druhen, Hauser, & Huizink, 2009), mounting evidence suggests that experience-driven language- and species-specific knowledge influences how infants match visual and auditory components of vocal stimuli (Lewkowicz, 2014). For example, younger infants perform audiovisual matching equally well whether vocalizations are human or non-human, and whether syllables are from a native or non-native language. However, by 8-10 months of age infants show an advantage for audiovisual matching of species- and language-specific stimuli

(Grossmann, Missana, Friederici, & Ghazanfar, 2012; Lewkowicz & Ghazanfar, 2006; Lewkowicz, Leo, & Simion, 2010; Pons et al., 2009). Similarly, adults are more likely to detect asynchrony in audiovisual speech when facial movements are accompanied by natural speech than by sine wave speech (a non-speech analogue), whereas infants show no such advantage for natural speech (Baart, Vroomen, Shaw, & Bortfeld, 2014).

Recent work has emphasized the notion that similar trajectories may characterize perceptual development of both language and music abilities during infancy and early childhood, particularly those related to rhythm and timing (Brandt, Gebrain, & Slevc, 2012; Hannon, Leveque, Nave, & Trehub, in press). Just as audiovisual perception of speech may depend on gradual acquisition of higher-level knowledge of language, so too might accurate perception of audiovisual synchrony between dance and music depend on acquired musical knowledge. Music is comparable to speech both in its complexity and reliance on abstract, culture-specific knowledge that is acquired gradually over the course of development. In addition, although speech is often considered the most ecologically relevant instance of complex audiovisual synchrony perception, perceiving the audiovisual synchrony of a dancer moving to music is equally ecologically valid—this experience is a similarly universal and ancient part of human culture (Large, 2000; Nettl, 1983; Repp, 2005; Snyder & Krumhansl, 2001).

Perceiving audiovisual synchrony of a dancer moving to music may also pose unique challenges, distinct from those involved in speech perception. Perceiving dance involves coordinating complex, dynamic, inferred structures from both auditory and visual input. The perceiver must infer the beat within a rich and dynamic musical surface, while also determining whether the movement/gesture patterns are consistent with that

inferred beat. Because there are many potential points of synchrony between heard auditory events and seen movements, this determination is itself complex. For example, some metrical levels are reflected in movement of extremities, others expressed by the trunk, and still others by movements towards the boundaries versus center of the personal space (Burger, Thompson, Luck, Saarikallio, & Toiviainen, 2013, 2014; Naveda & Lehman 2010; Toiviainen, Luck, & Thompson, 2010; Su, 2016). Thus, perceiving audiovisual synchrony in dance displays may depend on musical knowledge and expectations that are acquired during development.

The Current Study

Prior work suggests infants can detect asynchronies in the simplest audiovisual manifestations of musical beat, such as a drummer hitting a drum (Bahrick & Lickliter, 2000; Gerson, Shiavio, Timmers, & Hunnius, 2015; Kopp, 2014). However, to date no studies have investigated infants' perception of audiovisual synchrony in complex musical displays, even though music is an inherently rich and multimodal component of infants' experiences. As an ecologically valid, complex, and non-speech audiovisual stimulus, music has unique potential to shed light on general aspects of intersensory development. In addition, because musical beat perception is essential for perceiving audiovisual synchrony of dance, a universal human behavior, infants' perception of audiovisual synchrony in music can inform basic questions about the developmental origins of beat-based musical behaviors.

To examine infants' perception of audiovisual synchrony in musical displays, we employed an infant-controlled habituation paradigm, which is used widely in research on infants' intermodal perception (Bahrick & Lickliter, 2000; Bremner et al., 2011; Flom &

Bahrack, 2007; Lewkowicz, 1992b, 1996) and may be more sensitive than other infant methods such as paired preference (Lewkowicz, 1992a). In two experiments, we habituated infants to a movie of a person dancing in synchrony with one of two songs. After habituation, we presented infants with two novel movies whose audio tracks were identical and taken from the previously heard song, but whose video tracks (of the same dancer) either matched or mismatched the audio track. To determine whether infants could discriminate movies solely on the basis of visual information, we also had a “visual only” condition in which infants were presented only with the visual component of movies. If infants are able to extract the beat from the music and match it with regular movements of a dancer, they should look longer when the visual and auditory components of the movies are asynchronous. Moreover, this effect should occur only when both auditory and visual components are available. To determine whether or not musical audiovisual synchrony perception changes over the course of infancy, we examined performance among older infants (Experiment 1) and younger infants (Experiment 2).

Experiment 1

Experiment 1 investigated audiovisual synchrony perception of rich musical stimuli among infants between 8 and 12 months of age. We made the a priori decision to first target this age range, because previous research suggests that during the latter part of the first year after birth, infants begin to exhibit more specialized perceptual abilities for both musical rhythm (Hannon et al., 2011; Hannon & Trehub, 2005b; Soley & Hannon, 2010) and audiovisual synchrony in vocal stimuli (Grossmann et al., 2012; Lewkowicz et al., 2010; Lewkowicz & Ghazanfar, 2006). We reasoned that if infants are capable of

perceiving audiovisual synchrony in musical stimuli, we would be most likely to observe this ability in the latter part of the first year.

Method

Participants. A total of 32 infants between 8 and 12 months of age ($M=10$ months 25 days, Range: 8 months 1 day to 11 months 28 days) were recruited from the Cambridge, MA (20 infants) and Las Vegas, NV (12 infants) communities, using birth lists from hospitals and marketing companies. Infants were born full-term and had no known hearing difficulties at the time of testing. Three additional infants were excluded from the final sample due to fussing preventing completion of the experiment. Half of the infants were randomly assigned to the audiovisual condition and half to the visual only condition.

Stimuli. Stimuli consisted of four videos of a smiling adult female dancing to two pre-recorded songs. The dancer was instructed to dance in an exaggerated manner to reflect the musical meter. At level of the beat, she used broad, repetitive body movements and gestures (e.g., arm-waves) and at the measure level (a higher metrical level) she moved her full body with additional emphasis. In separate takes, the dancer performed two unique dance patterns to each song, with no movements present in both sequences. The dancer wore dark clothing and stood in front of a white backdrop. The videos were recorded using a Sony camcorder (DCR – HC32) in well-lit conditions. Two audiovisual excerpts (denoted A and B) were selected from each song, each one 60 seconds in length (using Apple iMovie HD 6). The audio tracks of the two excerpts differed minimally, with only subtle acoustic differences in tempo and dynamics across the A and B audio excerpts for each song. The dancer used slightly different gestures across the A and B

excerpts of each song, minimizing the likelihood that specific dance movements would cue subjects to the matching stimulus during the test phase.

To minimize the influence of a familiar language/lyrics, we selected songs that would not be highly familiar to subjects: Two primarily instrumental songs from a CD collection of children's world music having musical meters familiar to Western listeners ("Hendry," by Tarika Sammy, Tempo of 136 beats per minute, 4/4 meter, vocals in Malagasy; and "Five," by Bobby McFerrin, average tempo of 130 beats per minute, 3/4 meter, vocals were nonsense syllables and vocal patterns). Post-experiment parental report confirmed that songs were novel to all infants.

For the visual only condition, audio tracks were removed from the four movies. For the audiovisual condition, a clean recording of each song excerpt was added back to the audio track of the movie to create matching and mismatching audiovisual versions of each of the four excerpts. For the matching stimuli, the clean recording of the song precisely matched the original musical excerpt. Thus repetitive dance movements such as waving arms or kicks lined up with the beats heard in the music, and larger body movements, such as shifting body orientation or changing of movement from arms to legs or vice versa, emphasized the measure-level beat in the song. For the four mismatching stimuli, the video track of one movie was paired with the audio excerpt from the other song. For example, one mismatching stimulus contained the video track of the dancer moving to the song "Hendry" during excerpt A but the audio track was from excerpt A of "Five." Thus, due to the different metrical grouping of the beats (three or four per measure/group) and slightly different rates of speed (130 versus 136 beats per minute),

the dancer's movements were out of synchrony with the beats in the music (see Videos 1-4 of Supplemental Files).

Apparatus and Procedure. Infants sat in their parents' lap in a dim, sound-attenuated room. The experiment was conducted in a sound-proof booth (Industrial Acoustics) in Cambridge, MA, and in a similar sound-treated room in Las Vegas, NV. Participants saw the visual component of each movie on a centrally placed 43.2 cm (17 inch) color monitor (Acer AL715), located 173 cm away from the infant. Sound in the experiment came from two hidden speakers (Genelec, model 8020A).

An experimenter monitored infant behavior over closed-circuit television (Trutech, model DW27TT) with an infrared digital video camera (Sony DCR-HC32), located above the video monitor, focused on the infant. The experimenter was blind to condition (audiovisual vs. visual-only), and observed the infant while wearing headphones playing music or noise to mask any available sounds, and while sitting outside the booth (MA) or behind a curtain (NV). The experiment was run on a PowerMac Dual 2GHz PowerPC G5 computer, using Habit X software (Cohen, Atkinson, & Chaput, 2004) to control the presentation of stimuli, and to code infant visual fixations during the experiment. A second experimenter, also blind to condition, later performed off-line frame-by-frame coding of infant looking time using Supercoder v1.5 (Holich, 2005), with a third coder performing additional off-line coding of a subset of the data to check for reliability. To "blind" infants' caregivers to condition, caregivers holding the infants listened to classical music presented over noise-cancelling headphones (Sony MDR-NC6) for the duration of the experimental session. We

instructed the caregivers to face the monitor with a neutral expression and not interact with or cue their infants at any time during the experiment.

The experiment used an infant-controlled habituation paradigm. Prior to the beginning of each trial, the monitor flashed red to orient the infant's attention towards the monitor and loudspeaker. When the infant's gaze was directed to the video screen, the experimenter began the trial. The experimenter monitored the infants' looking behavior in real time, pressing a button to record the onset and offset of looks toward the stimulus. The trial automatically ended when the infant looked away from the monitor for more than two consecutive seconds. The monitor would then again flash red to re-capture the infant's attention and begin the subsequent trial.

During the habituation phase of the audiovisual condition, we repeatedly presented infants with one synchronous 60-second movie of the dancer moving to song excerpt A or B of either "Hendry" or "Five." During the habituation phase of the visual only condition, the same movies were presented but with no sound. On each habituation trial, the movie played for 60 s or until the infant looked away for more than 2 s, whichever occurred first. The same movie was played on every trial until the infant reached criterion for habituation (average fixation decrement of 50% over three trials relative to the average fixation of the first three trials, using a sliding window) or until twelve trials had elapsed.

During the test phase of the audiovisual condition, three matching and three mismatching trials were presented in alternation, for up to 60 s per trial. As described above, the audio track for both matching and mismatching trials contained a new excerpt from the same song heard during habituation (e.g. if the infant heard excerpt A of

“Hendry” during habituation, she heard excerpt B of “Hendry” during test). For matching trials, the video track matched the original video-recording, so the dancer was in synchrony with the music, whereas for mismatching trials, infants saw a video track from a different song, so the dancer was out of synchrony with the music (Figure 1). Thus, both stimuli used during the test phase had identical audio tracks but contrasting video tracks, one synchronous and the other asynchronous with the audio.

In the visual only condition, infants saw the same movies in the same alternating trial orders, but saw video tracks only, without auditory accompaniment. Since no audio was present, there was no possibility of synchrony or asynchrony, and thus no ‘matching’ or ‘mismatching’ between audio and visual. In principle, silent videos could contain dynamic tempo cues or movement patterns that might allow them to be matched across A and B excerpts, so the same match-mismatch terminology was also applied to trials in the visual only condition. Thus, on ‘matching’ trials infants in the visual-only condition saw a novel video excerpt of the dancer, moving to the same song she had been moving to during habituation (though the music was never present), and on ‘mismatching’ trials they saw a novel video clip of the dancer moving to a different song (though again the music was not present).

Equal numbers of infants were tested in the audiovisual ($N = 16$) and visual only ($N = 16$) conditions. The order in which movies were presented (A or B during habituation) and the order of test stimuli (matching or mismatching first) were counterbalanced between subjects. Thus, each video was used for both matching and mismatching trial types. Infants were randomly assigned to excerpts from each song. Slightly more infants were presented with “Hendry” ($N = 18$) than with “Five” ($N = 14$).

To ensure that this asymmetry did not affect results, song was included as a factor in the analysis below.

Results and Discussion

Inter-rater reliability for frame-by-frame video coding was high, $r=.99$. Post-habituation looking times (in s) were averaged across the three matching and mismatching trials, and submitted to a $2 \times 2 \times 2$ mixed design ANOVA including a within-subjects factor of trial type (Matching or Mismatching), and between-subjects factors of condition (Audiovisual or Visual Only) and song (Hendry or Five). This analysis revealed a main effect of trial type, $F(1,28) = 7.74, p = .01, \eta^2_p = 0.22$. Overall, infants looked longer during mismatching ($M = 20.4, SEM = 2.7$) than during matching trials ($M = 16.3, SEM = 2.2$). Although there was a trend towards longer overall looking in the audiovisual ($M = 22.2, SEM = 3.9$) than visual only conditions ($M = 14.5, SEM = 2.78$), this main effect of condition was not significant, $F(1,28) = 2.41, p = .13$. As predicted, there was an interaction between trial type and condition, $F(1,28) = 6.14, p = .02, \eta^2_p = 0.18$. As illustrated in Figure 2, after habituation to audiovisual synchrony, infants in the audiovisual condition looked significantly longer during mismatching trials ($M = 26.02, SEM = 4.01$) than during matching trials ($M = 18.4, SEM = 3.8$), $t(15) = 3.33, p = .005$. By contrast, infants in the visual only condition looked for comparable durations during matching ($M = 14.2, SEM = 2.4$) and mismatching trials ($M = 14.8, SEM = 3.2$), $t(15) = .34, p = .74$. There were no other significant main effects or interactions.

Of the 32 infants tested, 30 reached the criterion for habituation (average # of trials to habituation = 7.3; $SD = 2.8$), with two infants failing to reach criterion (one in the

audiovisual and one in the visual only condition). When the same analyses as above were repeated excluding these two infants, the same results were obtained.

Infants only discriminated matching from mismatching movies when the audio track was available, providing evidence that audiovisual synchrony between the inferred musical beat and the dance movements was critical to successful discrimination of test stimuli. The results of Experiment 1 thus suggest that by 8 to 12 months of age, infants are able to extract the beat from heard music and match it with regular movements of a seen dancer.

Experiment 2

Experiment 2 examined whether the audiovisual synchrony perception observed among older infants would also be observed among younger infants. If basic sensitivity to the beat is sufficient for perceiving audiovisual synchrony in complex music displays, then young infants should also succeed on the present task, given prior evidence of beat sensitivity even among newborns (Winkler et al., 2009). However, if higher-level knowledge plays a role in audiovisual synchrony perception, younger infants should have difficulty, because they are less likely to have acquired nuanced and culture-specific knowledge of musical beat and meter.

Method

Participants. Thirty-two infants participated in Experiment 2, with a mean age of 6 months ($M = 6$ months 10 days, Range: 4 months 25 days to 7 months 29 days). Infants were recruited from the Las Vegas, NV community, using family marketing lists. All infants were born full-term and had no known hearing difficulties at the time of testing. Three additional infants were excluded from the final sample due to technical error (1),

premature birth (1), or fussiness preventing completion of the experiment (1). As in Experiment 1, half of infants were randomly assigned to the audiovisual condition and half to the visual only condition.

Stimuli, Apparatus and Procedure. We used the same stimuli as in Experiment 1: Four audiovisual matching, four audiovisual mismatching, and four visual-only dance stimuli. Infants were tested while sitting in their parent's lap in a sound-treated room. All aspects of the apparatus and procedure were identical to Experiment 1. Equal numbers of infants heard each of the two songs during habituation ("Hendry", $N = 16$; "Five", $N = 16$).

Results and Discussion

Inter-rater reliability for frame-by-frame video coding was high, $r = .99$. Post-habituation looking times (in s) were averaged across the three matching and mismatching trials and submitted to a $2 \times 2 \times 2$ mixed design ANOVA including a within-subjects factor of trial type (Matching or Mismatching) and between-subjects factors of condition (Audiovisual or Visual Only) and song (Hendry or Five). This analysis revealed a main effect of condition, $F(1,28) = 4.89$, $p = .035$, $\eta^2_p = 0.15$, but no other significant main effects or interactions. Infants looked longer during the audiovisual condition ($M = 15.83$, $SEM = 2.7$) than during the visual only condition ($M = 9.75$, $SEM = 1.52$) (Figure 3), a finding consistent with prior infant research (Bahrick & Lickliter, 2000). However unlike older infants, younger infants did not discriminate matching from mismatching stimuli in either condition.

Of the 32 infants tested, 23 reached the criterion for habituation (average # of trials to habituation = 7.5; $SD = 2.4$). Nine infants did not reach criterion. Of these, only

one was in the audiovisual condition. The same analyses as above were repeated without these infants, and the same results were found, again suggesting that younger infants did not discriminate matching from mismatching stimuli even in the audiovisual condition.

The present experiments also aimed to address the question of whether or not musical audiovisual synchrony develops during infancy. If it does develop, we would expect to see stronger novelty preferences in older than in younger infants. To examine novelty preference, we converted raw looking times from Experiments 1 and 2 to proportion of total looking time towards the mismatched stimulus (PTLT), by dividing the average duration of looking during the mismatching trials by the combined average looking during all test trials. Scores higher than 0.5 thus indicate a preference for the novel, mismatching stimulus. Because PTLT expresses novelty preferences as a proportion of total looking time, it removes other sources of variability such as age-driven changes in overall looking behavior, allowing us to directly compare novelty preference among infants of different ages.

A larger number of infants failed to habituate in Experiment 2 ($N=9$) than in Experiment 1 ($N=2$). When comparing the two age groups, this difference in prevalence of habituation could pose a problem, as dishabituation (i.e. the novelty preference) should be more systematic for infants who have fully habituated (Wetherford & Cohen, 1973). In accord with this idea, PTLT scores for infants who met habituation criterion were higher ($M=.54$, $SEM=.02$) than for infants who did not meet criterion ($M=.43$, $SEM=.027$), $t(62) = 2.61$, $p = .01$. We therefore included only those infants who successfully habituated ($N=15$ younger, $N=15$ older in the audiovisual condition; $N=8$ younger, $N=15$ older in the visual only condition).

We submitted PTLT scores of habituated infants to a 2 x 2 univariate ANOVA with between-subjects factors of condition (Audiovisual or Visual Only) and age group (Younger vs. Older). This analysis revealed an interaction between condition and age group, $F(1,49) = 4.56, p=.038, \eta^2_p = 0.085$, and no other significant effects. As shown in Figure 4, older infants' PTLT scores were significantly higher in the audiovisual ($M=.61, SEM = .028$) than in the visual only condition ($M=.47, SEM = .03$), $t(28) = 3.1, p<.01$, whereas younger infants' PTLT scores did not differ for the audiovisual ($M=.53, SEM = .03$) and visual only conditions ($M=.56, SEM = .067$), $t(21) = 0.42, p=.68$. One-tailed Bonferroni corrected t -tests confirmed that only older infants' PTLT scores in the audiovisual condition were significantly different from chance (.05), $t(14) = 3.75, p<.01$. Thus, older infants but not younger infants showed a novelty preference for the asynchronous audiovisual test stimulus. This result is unlikely to be an artifact of diminished attention or engagement on the part of younger infants during habituation, because the same number of infants successfully habituated in both age groups ($N = 15$), and looking times during the habituation phase (averaged over the final six trials) were comparable for younger infants ($M = 26.63, SEM = 2.43$) and older infants ($M = 25.2, SEM = 2.01$), $t(30) = 0.455, p=.65$. This suggests that the differences observed across the two age groups reflect a true developmental change in sensitivity to musical audiovisual synchrony.

Across both experiments, infants failed to differentiate silent test videos, even when we considered only those infants who successfully habituated. This indicates that successful discrimination depended on the presence of both auditory and visual information. Alternatively, it is possible that infants—regardless of age—were simply

more attentive in the audiovisual than visual conditions because of the arousing properties of the music, and their inattention in the visual only condition led to their failure. By this account, if infants paid closer attention to the stimuli in the visual only condition, they would have discriminated those test stimuli, just as did older infants in the audiovisual condition. To test this alternative account, we collected additional data from adults, reasoning that adults should have greater ability to control their attention during the task than infants. If even adults have difficulty discriminating the visual only stimuli, this would strongly suggest that infants' failure was not solely the result of inattention. We presented adults ($N=24$) with the same habituation and test videos that were shown to infants, and we asked them to provide similarity ratings for each of two test videos compared with one prior habituation video¹. We found that even adults had difficulty discriminating the matching from mismatching videos in the visual only condition. Adults robustly differentiated matching from mismatching audiovisual test stimuli, giving higher similarity ratings to matching ($M=4.04$, $SEM = 0.26$) than to mismatching test videos ($M=3.16$, $SEM = 0.22$), $t(23) = 2.64$, $p = .015$, but they did not differentiate matching from mismatching stimuli in the visual only condition (matching $M=3.36$, $SEM = 0.21$; mismatching $M=3.13$, $SEM = 0.18$), $t(23) = 1.13$, $p = .27$, Bonferroni-corrected t -tests. A repeated-measures ANOVA showed a significant interaction between trial type (Matching or Mismatching) and condition (Audiovisual or Visual Only) $F(1,23)=5.81$, $p=.024$, $\eta^2_p=0.20$, as well as main effects of trial type, $F(1,23)=5.27$, $p=.03$, $\eta^2_p=0.19$, and

¹ Ratings were on a 1-7 scale. Each subject participated in both conditions (Audiovisual and Visual only), counterbalanced for condition order and test video order.

condition, $F(1,23)=8.28$, $p=.008$, $\eta^2_p=0.27$. Adults' difficulty discriminating stimuli in the visual only condition strongly suggests that infants' similar failure in the visual only condition was not simply due to inattention. Instead, this failure appears to reflect a true inability to discriminate the stimuli when audiovisual synchrony/ asynchrony is not present.

General Discussion

In summary, across two experiments, older (8-12 mo.) but not younger (5-8 mo.) infants were able to perceive audiovisual synchrony of a person dancing to music. When both visual and auditory information (and thus information about audiovisual synchrony) were available, only older infants showed a post-habituation preference for a mismatched (asynchronous) video relative to a matched (synchronous) video. By contrast, when the same visual stimuli were presented without sound, neither younger nor older infants showed a preference for either test stimulus. This failure was not simply a result of lesser attention; Even adults performed poorly at discriminating the same visual-only videos. These data thus provide evidence that older but not younger infants were sensitive to the audiovisual synchrony of a dancer moving to music, suggesting that perception of complex musical audiovisual synchrony develops over the course of the first year of infancy.

To our knowledge, this paper presents the first evidence to date that infants can perceive audiovisual synchrony in a complex musical display such as a dancer moving to music. Music is comparable to speech in its richness and ecological validity, and both music and language are acquired in parallel during early childhood. Yet, despite a rich literature on development of audiovisual speech perception, relatively little work has

explored the development of audiovisual music perception. While prior work has shown that infants perceive audiovisual synchrony in very simple displays in which individual, temporally distinct sounds correspond precisely to individual visual trajectory reversals or impact events (Bahrick & Lickliter, 2000; Gerson et al., 2015; Kopp, 2014), the present experiments show that by the end of the first year infants succeed in a much more complex intermodal synchrony perception task. In order to succeed in this task, the subject must infer a musical beat from sound information and match it to seen movement patterns, parsing and comparing many potential points of synchrony between the complex movements of a dancer and the multi-layered event structure in real music (Burger et al., 2013, 2014; Naveda & Lehman, 2010; Toiviainen et al., 2010; Su, 2016). This paper therefore takes an important first step by revealing that the capacity to perceive this type of complex, real-world musical audiovisual synchrony emerges during infancy.

Interestingly, this is the same developmental time frame during which language experience begins to influence audiovisual synchrony perception of speech (Grossmann et al., 2012; Lewkowicz et al. 2010; Lewkowicz & Ghazanfar, 2006). In addition, culture-specific biases in rhythm and beat processing begin to emerge during this developmental window (Hannon et al., 2011; Hannon & Trehub, 2005b; Soley & Hannon, 2010). Thus, one account of the current data is that the developmental changes seen in the current studies are the result of acquired knowledge about music, similar to the experience-based nature of the changes seen in language. For instance, older infants may possess more robust representations of musical meter, which allows them to better compare the musical periodicities they hear with body movement periodicities they see.

If infants' culture-specific musical experiences influence their perception of musical audiovisual synchrony, this would predict that at some age, infants should better detect audiovisual asynchrony in dance to familiar music than in dance to music from another culture. In this light it is perhaps surprising that we did not observe any effects of song in either experiment, since the meter of one song (Hendry, in 4/4) is purported to be more prevalent in North American music than the meter of the other song (Five, in 3/4) (Gerry et al., 2009). However, these asymmetries in prevalence may not reflect all infant-directed music, as prevalence has been examined only in a limited (Kindermusik) repertoire (Gerry et al., 2009). Thus, infants in our sample may have had equal prior experience with both meters. To more directly address the role of experience, future research is needed to compare audiovisual synchrony perception of culturally familiar and unfamiliar music and dance displays with a larger sample. Ideally, this future work would involve a cross-cultural sample of infants with differing musical experience, to directly tease apart the effects of cultural familiarity from perceptual characteristics of the musical stimuli.

Perception of musical audiovisual synchrony may also be influenced by individual infants' specific experiences listening and moving to music. Audiovisual synchrony perception differs for adults with and without specific musical training, with piano players and drummers showing enhanced audiovisual synchrony perception only for displays of their own instrument (piano playing or drumming, respectively; Lee & Noppeney, 2011; Petrini, Russell, & Pollick, 2009). Adult dancers exhibit differential brain responses while watching videos of movements that are within their repertoire compared to movements from a different type of dance (Calvo-Merino, Glaser, Grezes,

Passingham, & Haggard, 2005). Exposure to specific dances (such as Charleston or Samba) may also determine whether or not adults can accurately perceive audiovisual synchrony in displays of those dances (Naveda & Leman, 2010). Recent evidence suggests that 6-month-olds who had just 5 minutes of experience attempting to play a drum outperformed 6-month-old controls without such experience on a simple audiovisual synchrony matching task (Gerson et al., 2015). Future work is needed to investigate whether or not individual differences in experience with drumming, dancing and perhaps even walking and crawling predict how well infants perceive musical audiovisual synchrony.

We observed success at discrimination of matching from mismatching test stimuli in the audiovisual condition but not in the visual only condition (for older infants, in Experiment 1). In principle, infants might have been able to distinguish matching from mismatching stimuli even without auditory information because the visual dance movements of the matching stimulus more closely matched the movements seen during habituation given that they were drawn from the same song. However, infants' failure to discriminate these test stimuli without sound, even when able to discriminate the audiovisual versions of the same stimuli, suggests that older infants' success in the audiovisual condition was based on detecting audiovisual synchrony and asynchrony, and not on visual information alone. In addition, even adults had difficulty discriminating matching from mismatching videos when they were presented without sound, further supporting the idea that visual information alone could not have driven infants' discrimination, and thus that audiovisual synchrony played a crucial role. Infants' (as well as adults') failure in the visual-only condition is also interesting because it suggests

that subjects may have been unable to perceive a beat or coherent pattern within the visual-only stimuli. This interpretation is consistent with the notion that intersensory redundancy enhances perception of temporal structures (Bahrick & Lickliter, 2000). It may be that only when auditory musical information was available were older infants and adults able to parse a regular beat and metrical patterning from the visual stimuli.

The current findings also constrain theoretical explanations for the slow, gradual development of the ability to move in synchrony with music. Although precocious sensitivity to a musical beat in simple auditory stimuli has been demonstrated among newborns and infants with some tasks and stimuli (Winkler et al., 2009), production (e.g. precise synchrony of movement to music) lags behind perception of rhythm and beat in music, such that young children are often unable to accurately move in time with a musical beat (Ilari, 2015; Zentner & Eerola, 2010). Our findings argue against a motor limitation account of this lag. By this motor account, infants and young children have an early-developing grasp of the beat, but are unable to dance in synchrony with music solely because they lack the necessary motor coordination (Cirelli, Wan, & Trainor, 2014; Trainor & Cirelli, 2015; Zentner & Eerola, 2010). In contrast to the predictions of this account, the present findings rather support the notion that the rich, multimodal perception of musical beat and its accompanying behaviors emerge slowly over the course of infancy and perhaps during childhood. The protracted development of musical audiovisual synchrony perception may reflect the relatively slow developmental trajectory of intermodal integration in general (Gori, Del Viva, Sandini, & Burr, 2008; Massaro, 1984; Nava & Pavani, 2013; Tremblay, et al., 2007), which may arise as children continuously recalibrate information across changing sensory modalities, as they

learn to establish correspondence between sensory signals, and as they adjust the weighting of information from earlier versus later developing sensory modalities (Ernst, 2008; Lewkowicz, 1988).

Overall, the current findings provide the first evidence that infants perceive musical audiovisual synchrony in complex, naturalistic stimuli by the end of their first year. In contrast, younger infants fail at the same task, suggesting that this capacity emerges in later infancy. These findings provide critical insight into the developmental origins of beat-based musical behavior, a universal and fundamentally human activity, and expand our growing understanding of how infants learn to combine and coordinate complex information to perceive audiovisual events in the world through multiple senses.

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Figure 1: Trial structure of audiovisual condition. A flashing red screen attracted the infant's gaze to the screen to begin each trial, and trials ended when the infant looked away for 2 seconds or more. During the habituation phase, an audiovisual movie of a person dancing in synchrony with music was repeatedly presented, until looking time (in s) declined to criterion. During the test phase, each of two videos was played in alternation: On matching test trials, infants viewed a novel video excerpt of the same person dancing in synchrony to the same song. On mismatching test trials, infants heard the same audio track as on matching trials, but viewed a mismatched video track, in which the person danced at a tempo and meter that was not synchronized with the music. We compared infants' looking time to the mismatched vs. the matched test trials.

Figure 2: Looking time (in seconds) of 8- to 11-month-olds in Experiment 1. Error bars represent standard error.

Figure 3: Looking time (in seconds) of all 6-month-olds in Experiment 2. Error bars represent standard error.

Figure 4: Percent total looking time (PTLT) towards the mismatching stimulus versus the matching stimulus, for infants who successfully habituated in Experiments 1 and 2. Error bars represent standard errors.