Hearing the Beat: Young Children's Perceptual Sensitivity to Beat Alignment Varies According to Metric Structure

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Adults can extract the underlying beat from music, and entrain their movements with that beat. Although infants and children are poor at synchronizing their movements to auditory stimuli, recent findings suggest they are perceptually sensitive to the beat. We examined five-year-old children's perceptual sensitivity to musical beat alignment (adapting the adult task of Iversen & Patel, 2008). We also examined whether sensitivity is affected by metric complexity, and whether perceptual sensitivity correlates with cognitive skills. On each trial of the complex Beat Alignment Test (cBAT) children were presented with two successive videos of puppets drumming to music with simple or complex meter. One puppet's drumming was synchronized with the beat of the music while the other had either incorrect tempo or incorrect phase, and children were asked to select the better drummer. In two experiments, five-year-olds were able to detect beat misalignments in simple meter music significantly better than beat misalignments in complex meter music for both phase errors and tempo errors, with performance for complex meter music at chance levels. Although cBAT performance correlated with short-term memory in Experiment One, the relationship held for both simple and complex meter, so cannot explain the superior performance for culturally typical meters.

Rhythm in the most basic sense consists of sequences of sound events and silences (London, 2004), and represents physical properties of sound in terms of timing. Musical timing typically has two aspects, a *grouping* structure, which corresponds to the perception of phrases, and a *metrical* structure, which corresponds to the regular underlying pulse, or beat, which is extracted from the rhythmic surface but not directly present in the physical stimulus (Gjerdingen, 1989; Lerdahl & Jackendoff, 1983). Adult listeners readily extract the metrical structure from music, as evidenced by the fact that they can easily tap or move to the beat of music (e.g., Repp, 2005). This ability to detect the regularities in external auditory stimuli and synchronize movements to a perceived beat is widespread in humans (Iversen & Patel, 2008) and is referred to as auditory-motor *entrainment*. Adults' ability to entrain motor behavior to periodic auditory patterns has been extensively studied and a smaller number of investigations have examined adult's beat perception abilities in the absence of an overt motor response (for reviews see Repp, 2005; Repp & Su, 2013; Zatorre, Chen, & Penhune, 2007).

In contrast to the adult literature, few investigations of motor entrainment have been conducted with young children. Most timing tests assess rhythm perception rather than beat perception or motor synchronization, and these rhythm perception tests have been developed for both younger and older children, as well as for typical adult populations (Gordon, 1979, 1980). Perception tests can also be used to identify those with serious timing deficits or general amusia (Peretz, Champod, & Hyde, 2003). In quantifying children's ability to motorically entrain to rhythms, the limited range of speeds to which children can synchronize (Provasi & Bobin-Bègue, 2003) must be considered, as well as children's generally poor motor skills (Drake, 1993), which makes the use of tapping synchronization tasks of the type typically used with adult subjects difficult. Most synchronization tasks used with adults involve tapping a single finger, which requires a high degree of fine motor control (Repp, 2005), and synchronization over a wide range of speeds over a prolonged period of time (Repp & Su, 2013). Children's ability to synchronize movements to an external auditory stimulus, and the range of tempi at which they can do so, is thought to improve gradually during childhood (Drake, Jones, & Baruch, 2000) although it has not yet reached adult-like levels by 12 years of age (van Noorden & De Bruyn, 2009). Children have a faster spontaneous motor tempo (SMT) than adults, and have been shown to prefer faster tempi perceptually and motorically. This preferred rate slows throughout adolescence and adulthood, although

SMT remains correlated with tempo perception across the lifespan (McAuley, Jones, Holub, Johnston, & Miller, 2006).

However, there is a small body of work suggesting that infants and very young children exhibit periodic movement when listening to music, although this movement is rarely, if ever, synchronized to the music (Eerola, Luck, & Toiviainen, 2006; Zentner & Eerola, 2010). Furthermore, a preferential looking study using 7-month-old infants found that infants preferred to listen to music where metronomic beeps were overlaid on musical excerpts in a way that matched the beat, compared to where the overlaid beeps were too fast or too slow (Patel, Iversen, Brandon, & Saffran, 2011). This suggests that, although children have trouble synchronizing their movements to an external auditory stimulus, their perceptual systems are sensitive to the beat in music. Additionally, children may be particularly influenced by social aspects of the situation, as they show better synchronization with a human adult drumming partner than with a drumming machine (Kirschner & Tomasello, 2009).

Oscillatory models of attending suggest that neural entrainment is driven by attentional synchrony (Jones & Boltz, 1989) and that perceptual entrainment can occur to a regular stimulus (Jones, 1976). However, few studies have examined perceptual entrainment to the beat in children in a way that dissociates overt motor synchrony from perceptual sensitivity. Iversen and Patel (2008) developed a Beat Alignment Task (BAT) for adults that measures both perception of beat alignment, as well as ability to synchronize to a musical beat. Furthermore, it is suitable for musically untrained adults. In the BAT, subjects first tap isochronously at a self-selected tempo, then synchronize their tapping to an external, isochronous auditory metronome, then synchronize their own finger tapping to the beat of 12 short musical excerpts and, finally, perceptually judge whether an isochronous auditory tone superimposed over each of the 12 musical excerpts is correctly aligned with the beat of the underlying musical excerpt. In the last (perceptual) task, incorrectly assigned isochronous beat tracks were either 1) too fast or too slow by 10% of the interbeat interval, or 2) too early or too late by 25%. Iversen and Patel reported that for the beat synchronization task, the overall correlation between subjects' mean intertap interval and the tempo of the excerpts was $r = .98$ when calculated across all excerpts for all participants. This suggests that, on average, adult subjects were excellent at matching their tapping speed to a wide range of musical tempos. However, the experiment did not measure phase alignment between subjects' tapping and the beats of the excerpts so it is not known how closely the taps actually aligned with the music. Behavioral scores on the perception task varied much more than those for the synchronization task, and were distributed nearly uniformly from chance to perfect performance. Performance on the perception and synchronization tasks was moderately correlated ($r = .56$), and subjects' intertap interval variability in the beat synchronization task was negatively correlated with judgment accuracy on the beat perception task ($r = -.61$).

In the present study, we modified the beat perception component of the BAT measure used by Iversen and Patel in order to investigate five-year-old children's perceptual sensitivity to a musical beat, and their ability to perceive beat misalignment in the context of short musical samples. Our first goal was to ascertain the degree to which young children are perceptually sensitive to the beat in a musical stimulus, without requiring them to produce a motor response. Following the work of Corrigall and Trainor (2014), in which children watched videos of puppets playing the piano and judged which puppets play the best songs, we developed a novel and child-friendly testing paradigm called the complex Beat Alignment Test (cBAT). The task uses videos of hand puppets that drum along to short musical sequences (a drum beat is superimposed on musical tracks). On each trial, two videos are presented successively, each with the same musical track. On one video the puppet's drumming is correctly aligned to the beat of the music, while on the other, the puppet drums out of phase or at an incorrect tempo relative to the musical excerpt being presented. Children are required to choose which puppet in each pair drummed better. If five-year-old children are sensitive to the beat of the music, they should give the prize to the puppet whose drumming is correctly aligned more often than would be predicted by chance.

Our second goal in developing this task was to investigate the effect of metrical complexity on beat sensitivity. Metrical structure is hierarchical, with the beats at different levels occurring at faster or slower rates (Essens & Povel, 1985; Jones & Boltz, 1989; Lerdahl & Jackendoff, 1983). At a particular level, some beats are accented and thus are perceived as stronger than others, and only these accented beats are passed to the next level of the metrical hierarchy (Essens, 1986). Accents can be either physically present, as when some events are louder than others, or perceived based on how rhythmic and pitch features are temporally arranged (Grahn & Brett, 2007; Jones, 1976; Parncutt, 1994). For example, in a sequence of identical tones, the duration

of silences between those tones can alter perceived accent structure (Povel & Okkerman, 1981), and harmonically important events can also be perceived as being accented (Dawe, Platt, & Racine, 1993). The metrical structure is perceptually abstracted from the rhythmic surface (Lerdahl & Jackendoff, 1983). Most often, at a particular level of the hierarchy, either every second beat or every third beat is perceived as accented (Jones & Boltz, 1989).

In simple metrical structures, accented beats occur at regular time intervals at each level of the hierarchy, and such regularly spaced beats are referred to as isochronous. Meter in Western music most commonly possesses an underlying binary structure, with a 2:1 ratio between beats at successive hierarchical levels being by far the most common (London, 2002). This music has familiar time signatures such as 4/4 and 2/4 when notated. Less commonly, Western music also employs a ternary structure, with a 3:1 ratio between beats at successive levels, which is notated as 3/4 or 6/8 time (Large & Palmer, 2002). However, not all music is composed of a pattern that produces equally spaced pulses at each level of the hierarchy. For example, at one level of the metrical hierarchy, accents can occur to form patterns containing groups of two or three beats and, thus, irregularly spaced accents. These complex metrical structures are referred to as non-isochronous. In music with more complex metric structure, the presence of two- and three-beat groupings produce ratios such as 3:2 and 4:3 between successive levels of the metrical hierarchy. Music notation reflects these complex patterns using notation such as 5/4 (which can consist of groups of 2 + 3 or 3 + 2 beats) and 7/8 (which can consist of groups of 3 + 2 + 2 or 2 + 3 + 2 or 2 + 2 + 3 beats).

In Western cultures, complex metrical structures are assumed to be beyond the limits of children's processing abilities, given that they remain challenging even for musically trained Western adults (Grahn & Brett, 2007). North American adults have difficulty reproducing complex metrical structures, especially in the absence of musical cues (Snyder, Hannon, Large & Christiansen, 2006). Drake (1993) investigated factors that influence rhythm reproduction, and found that both Western adults and Western children are better at reproducing rhythms that can be considered simpler in structure. Western music is primarily composed in simple meters, but music from a variety of other cultures employs complex metrical structures much more commonly. For example, folk music from parts of South Asia, Africa, the Middle East, and the Balkan region of southeastern Europe frequently contain a variety of

complex meters such as 5/4, 7/4, and 7/8, and adults from cultures such as Bulgaria and Macedonia demonstrate equal perceptual sensitivity to both simple and complex metrical stimuli (Snyder et al., 2006). By the same token, in cultures where complex metric structures are common, children also learn them with ease from a young age, seemingly without difficulty (Rice, 1994).

Hannon and Trehub (2005a) showed that North American adults have difficulty detecting metrical changes in complex meters, but succeed at detecting such changes in culturally familiar simple meter stimuli. In contrast, adults from Bulgaria and Macedonia succeed in detecting violations to both simple and complex metrical structures. Interestingly, six-month-old infants from North America showed the same pattern of results as the Balkan region adults, demonstrating equal ability to process stimuli with simple and complex meters. However, by 12 months, North American infants showed the same pattern of perceptual biases as North American adults (Hannon & Trehub, 2005b). This suggests that humans are unlikely to have an innate perceptual bias favoring simple over complex meters, and suggests that exposure to particular metrical structures can result in perceptual specialization for those culturally typical meters. There are, however, limits, as extremely irregular meters remain difficult for listeners across cultures (Hannon, Soley, & Levine, 2011). In any case, this perceptual narrowing according to early perceptual experience is analogous to that seen across many domains such as faces (Kelly et al., 2007), voices (Friendly, Rendall, & Trainor, 2014), phonemes (e.g., Werker & Tees, 1984), and musical tonal structures (Hannon & Trainor, 2007; Lynch, Eilers, Oller & Urbano, 1990; Lynch & Eilers, 1992; Trainor & Hannon, 2012; Trainor & Trehub, 1992).

This perceptual specialization for culturally relevant musical meters, although robust in adulthood, appears to be fragile and easily altered in infancy. After North American 12-month-olds were passively exposed to rhythms with complex meters at home for two weeks, the ability to perceive changes to these rhythms was regained. A subsequent and similar experiment with adults found that this brief exposure period did not result in increased sensitivity to Balkan rhythms (Hannon & Trehub, 2005b). Although this small body of literature demonstrates that perceptual specialization for musical meter is underway in infancy, little is known about its developmental trajectory through childhood.

To address the question of whether young children's sensitivity to the beat is affected by the metric structure of the music, in our complex Beat Alignment Test (cBAT) we extended the original BAT paradigm by

including music excerpts with both simple and complex meters. Here, we describe two experiments conducted to address the question of beat alignment and metric complexity. In Experiment One, half of the musical excerpts in the cBAT stimulus set were in 4/4 time (simple metric structure), while the other half were in 5/4 or 7/4 time (complex metric structure). In Experiment Two, half of the musical excerpts in the stimulus set were in 4/4 time (simple metric structure), while the other half were in 7/4 time only (complex metric structure) with no test excerpts having a 5/4 structure. This was done to ensure that children's performance on the cBAT task was not affected by the alternation of particular metric types within a category.

In addition to exploring the degree to which young children are perceptually sensitive to the beat and investigating the effect of metrical complexity on this sensitivity, our third goal in developing the cBAT was to examine whether children's performance on the beat perception task correlates with auditory memory. Adults' working memory capacity has been found to correlate with performance on rhythm reproduction tasks (Bailey & Penhune, 2010), and children's ability to discriminate rhythm sequences has been found to correlate with auditory working memory, as measured by a digit span task (Strait, Hornickel, & Kraus, 2011). Music training has been found to correlate with better memory in both children and adults (Kraus, Strait, & Parbery-Clark, 2012). Furthermore, short-term memory is necessarily involved when discriminating between two or more stimuli, as features of the stimulus presented first must be held in memory in order to be compared to subsequent presentations (Conway et al., 2005). Short-term memory and working memory are related processes but are thought to represent different cognitive constructs (Engle, Tuholski, Laughlin, & Conway, 1999). Short-term memory is a simple storage process, whereas working memory involves computational processes like the manipulation of information being held in short-term memory (Cantor, Engle, & Hamilton, 1991).

We examined the extent to which these two different aspects of memory were related to beat perception by having each child complete the forward and backward components of the digit span subtest from the Wechsler Intelligence Scale for Children (WISC-IV; Wechsler, 2003). The digits forward task is thought to measure short-term memory, and the digits backward task to measure working memory (Engle et al., 1999; Oberauer & Süß, 2000).

Because children needed to understand the instructions in order to perform the cBAT, we also administered the Peabody Picture Vocabulary Test (PPVT-4; Dunn & Dunn, 2007), which is a standardized measure of receptive vocabulary that can also serve as a proxy for verbal IQ, and correlates highly with various IQ instruments (Dunn & Dunn, 2007). In this way we could determine whether poor beat perception performance might be related to understanding the task.

Using our novel and child-friendly cBAT testing paradigm, we predicted that five-year-old children would be sensitive to beat alignment in the context of tempo- and phase-related errors, but that they would be more accurate at detecting beat alignment in musical excerpts with simple metric structures compared to in musical excerpts with complex metric structures. We also hypothesized that memory, as measured by the digit span task, would correlate with beat perception, as measure by performance on the cBAT.

Experiment 1

METHOD

Participants. Participants were 32 five-year-old children (17 female, $M_{age} = 5$ years, 6 months) who were not enrolled in formal instrumental music lessons at the time of testing. None of the children had previous experience with formal music training and only one child had participated in an infant music class. Eleven of 32 households reported having a parent with some form of prior instrumental training. All children in the final sample had normal hearing and were in good health, as reported by their parents on a background questionnaire. An additional nine children were excluded from the sample for the following reasons: technical problems ($n = 4$), diagnosed developmental delays ($n = 2$), failure to complete all tasks ($n = 2$), and hearing impairment ($n = 1$). Annual family income was measured on a six-point scale ($1 = <\$30,000$, $6 = >\$150,000$; Canadian dollars, data missing for five children). The average family income was between $90,000 and $120,000 per year for children in both conditions. Parent education was also measured on a six-point scale ($1 = no high school diploma$, $6 = graduate or professional degree$; data missing for two children). For children in both conditions the average formal education was a completed college diploma or certificate both for mother/parent one and for father/parent two. All participants were recruited from the McMaster Infant Studies Group database, and all protocols were approved by the McMaster Research Ethics Board.

Stimuli

1. Complex Beat Alignment Test. The stimulus set for the complex Beat Alignment Test (cBAT) consisted of

TABLE 1. *Characteristics of Musical Stimulus Set for cBAT*

Musical Excerpt (Length in seconds)	Genre	Artist/Composer	Meter Type	Average BPM
The Spam Song *(12)*	Hawaiian	Tia Carrere & Daniel Ho	Simple	87.8
Undercurrent *(18)*	Indian	Toronto Tabla Ensemble	Simple	114.1
Alice in Wonderland *(12)*	Jazz	Dave Brubeck	Simple	170.2
Holst Suite No. 1 *(22)*	Classical	Gustav Holst	Simple	130.3
One Way or Another *(12)*	Pop	Blondie	Simple	164.6
Hurt So Good *(18)*	Rock	John Mellencamp	Simple	126.3
Hula in Seven *(10)*	Hawaiian	Tia Carrere & Daniel Ho	Complex	159.5
Joyfully in Seven *(13)*	Indian	Toronto Tabla Ensemble	Complex	129.2
Take Five *(15)*	Jazz	Dave Brubeck	Complex	171.7
Planets Suite: Mars *(15)*	Classical	Gustav Holst	Complex	150.8
Money *(18)*	Pop	Pink Floyd	Complex	100.9
Solsbury Hill *(19)*	Rock	Peter Gabriel	Complex	120

videos of hand puppets drumming along to 12 musical excerpts chosen from a variety of genres, including Western pop, rock, classical, and jazz, as well as East Indian and Hawaiian. Excerpts were organized in pairs that were matched according to genre, tempo, timbre, and overall musical style as well as metric structure type (see Table 1). Six of the musical excerpts had simple metric structure (in this case, 4/4 time signatures) common in Western music compositions. Complex meter excerpts had either 5/4 or 7/4 time signatures, which are less common in Western music compositions. Each excerpt ranged in length from 10 to 22 s. Length varied in order to preserve the phrase boundaries of each excerpt. Song tempos ranged from 88 to 172 beats per minute (see Table 1). Audio files were created by combining existing commercial audio recordings with a series of isochronous woodblock taps, and then aligning the audio files with the video files of the puppets drumming. The creation of both components of these stimuli is detailed below.

1a. Auditory Stimuli. The auditory components of the stimuli were created as follows. First, the average beats per minute (BPM) of each musical excerpt was determined using *MixMeister BPM Analyzer* software. Using *Apple Garageband 2009* software, a woodblock sound effect was used to create a series of isochronous metronomic taps that matched each excerpt's BPM. The isochronous tap sequences were then superimposed over each excerpt and manually inspected by a human rater. Small manual adjustments were made to a subset of individual woodblock taps to account for small deviations from isochrony as a result of the expressive timing in each recording.

The final stimulus set contained 54 audio files (2 standard practice trial tracks, 2 randomized practice trial

tracks, 10 standard test trial tracks, 10 misaligned tracks that had been phase-shifted to be early, 10 misaligned tracks that had been phase-shifted to be late, 10 misaligned tracks that had been tempo-shifted to be fast, and 10 misaligned tracks that had been tempo-shifted to be slow). Each of these audio tracks served as the audio component that accompanied the visual stimulus of small puppets drumming on a toy drum (see below).

To create the standard, *correctly aligned* ("on-the-beat") tapping tracks for each excerpt, the woodblock tapping sound was superimposed over the musical excerpt to create a single auditory item where the woodblock tapping aligned with the beat of the musical sample. Following the creation of these standard tracks, four types of misaligned stimuli were created.

To create *phase error* tracks, the isochronous woodblock tracks from the original stimuli were phase shifted by 25% of each excerpt's average BPM to create audio files where the isochronous sequence of woodblock taps maintained the correct interbeat interval, but occurred either 25% too early or 25% too late relative to the beat of the music. To create the *tempo error* tracks, the speed of the woodblock tracks was increased or decreased by 10% of each excerpt's average BPM to create audio files where the woodblock taps occurred either 10% too fast or 10% too slow relative to the beat of the music. For both phase and tempo misalignments, the magnitude of the misalignment between the musical excerpt and the superimposed isochronous woodblock sequence (tempo shift of $\pm10\%$ IBI or phase shift of $\pm25\%$ IBI) remained constant for the duration of the excerpt.

One correctly aligned standard track, two out-of-phase tracks, and two incorrect-tempo tracks were created for each of ten of the twelve musical excerpts and were used to create the test trials in the cBAT. The remaining matched pair of musical excerpts, one with

simple meter and one with complex meter, served as practice trials. Correctly aligned standard tracks were created for these remaining two musical excerpts. Additionally, *randomized* woodblock tracks were created to serve as the "wrong" answer for both of the practice excerpts, by superimposing the same number of woodblock taps as in the correctly aligned practice trial stimuli (32 taps for both the simple meter excerpt and complex meter excerpt) but randomizing the IBIs to generate pseudorandom non-isochronous sequences. A single 'random' woodblock track was created in *Apple GarageBand 2009*, containing 11 possible interbeat intervals ranging from 580 ms and 1280 ms, at intervals of 70 ms, randomly distributed throughout. The overall tempo of this random sequence was then adjusted to match to the average tempo of each of the two practice trial excerpts so that each randomized sequence could be superimposed over the corresponding musical excerpt. This process created two excerpts in which the woodblock tracks occurred randomly off the beat, but matched the total number of woodblocks taps and average tempo of the original musical excerpts.

To ensure that enculturated Western adults did indeed perceive the phase and tempo errors as being misaligned, and the standard sequences as being appropriately aligned, we first had adult listeners perform a shorter, modified version of the task. Twelve adults (7 females) between the ages of 18 and 27 years (M_{age} = 21.9 years, SD = 1.4 years) each listened to 4 correctly aligned musical tracks and 8 misaligned musical tracks. The error type of the misaligned tracks was balanced between subjects, with 6 receiving phase errors and 6 receiving tempo errors. Adults were asked to rate whether the woodblock tapping for each of the 12 excerpts sounded like it was aligned with the beat on a scale of 1 to 5, where 3 was perfect alignment. In the phase error condition, a rating of 1 indicated that the beat was very early and 5 that it was very late. In the tempo condition, a rating of 1 indicated that the beat was very slow, and 5 that it was very fast. Ratings were not significantly different from 3 for correctly aligned tracks (M = 2.96, SD = .14, p = .23), but were significantly different than 3 for both types of phase errors (early: M = 2.63, SD = .55, p = .01; late: M = 3.23, SD = .25, p = .005) and both types of tempo errors (slow: M = 2.02, SD = .56, p < .001; fast: M = 4.13, SD = .52, p < .001), confirming the appropriateness of our stimuli.

1b. Visual Stimuli. The visual stimuli were created by filming 24 hand puppets tapping on a toy drum along to the auditory stimuli described above. After filming, each of the auditory samples was individually aligned to the corresponding puppet video clip using *Apple's iMovie* software. The puppets' drumming movements occurred at tempi that matched the woodblock taps in the audio files, with the same number of drum taps in each video as there were woodblock taps in the corresponding audio file, so that after editing was complete each puppet appeared to be producing the tapping sounds. The two puppets on each trial were semantically related (e.g., lion and tiger), and each puppet in the pair drummed along to a single simple-meter musical excerpt in the first error condition, and a complex-meter excerpt for the other error condition.

Five types of test trial videos were created, corresponding to the audio types above. Each puppet drummed the standard version of one simple meter and one complex meter excerpt. Additionally, either two phase error videos (early and late) or two tempo error videos (fast and slow) were created for each puppet. Error presentation was balanced within each pair of puppets, so that the puppet who drummed the standard in the simple meter condition had misaligned drumming in the complex meter condition. Error type within each condition was balanced between subjects so that half of the children in each condition saw a particular puppet make one type of error (e.g., fast, or early) and the other half of the children saw that puppet make the other error type (e.g., slow or late). Tempo error videos were created by having the puppet drum at a different speed than the standard. Phase error videos were created by aligning the standard drumming video along with a misaligned audio track, since the tempo was the same in both cases.

To create practice trial videos, additional video clips were recorded to correspond to the two standard and two randomized practice trial audio files described above. Two pairs of puppets were filmed drumming to all four practice trial audio files, for a total of eight videos. Presentation of these pairs of videos was completely counterbalanced across subjects, so that half the children saw each pair drum each meter type, and half saw each puppet drum the standard versus the randomized version.

The results of this balanced design was the creation of 6 videos for each of the musical excerpts that was used as a test trial (one standard video of each puppet in the pair, two phase shifted error videos from one puppet, and two tempo shifted videos from the other puppet), for a total of 60 test videos, and 8 practice videos (4 standard and 4 randomized videos). Puppet pairs were kept constant across both phase and tempo error conditions, and balanced for order of presentation and frequency of beat misalignment errors.

2. Digit Span Test. All participants completed a subtest of the Working Memory Index (WMI) from the Wechsler Intelligence Scale for Children (WISC-IV, 4th edition; Wechsler, 2003). There are two parts to the task. In the digits forward section, the child is required to repeat back a string of digits uttered by the experimenter. The task begins with two digits, and the number of digits increases by one on every second trial. Testing stops once the child fails to correctly repeat both strings of digits of a given length. The digits backward section follows the same procedure, except that it requires the child to repeat the digits in the reverse order from the experimenter. Raw scores on the digits forward task were used as a measure of verbal short-term memory, and raw scores on the digits backward task were used as a measure of verbal working memory.

3. Peabody Picture Vocabulary Test. All participants completed the Peabody Picture Vocabulary Test (PPVT-IV, 4th edition; Dunn & Dunn, 2007), a standardized measure of receptive vocabulary. In this test, the experimenter says a word, and the child chooses the appropriate picture from a set of four provided in order to determine which image best represents the vocabulary item. Vocabulary items gradually increase in difficulty, and testing is terminated when the child incorrectly identifies eight or more of the words in a twelve-item set. Raw scores were standardized according to the subject's age, and normed as described in the Examiner's Manual.

4. Parental Questionnaire. While the child was being tested, parents completed a questionnaire covering such topics as their child's health, language experience, extracurricular activities, and formal or informal music experience. Demographic information regarding parental education and income was also requested, although these questions were answered by only a subset of parents.

Procedure. Children were tested during one session that was approximately 45 min in length. The cBAT was administered in two separate blocks, where one block consisted of the simple meter stimuli and the other the complex meter stimuli. Block order was counterbalanced across children.

Each trial of the cBAT consisted of a pair of two individual videos. In one video, the puppet drummed along to the beat of a particular musical excerpt (the correctly aligned stimuli). In the other video the puppet's drumming was either out of phase or out of tempo relative to the excerpt, as described above. Error type was a between-subjects variable, so that half of the 32 participants were presented with only tempo shift errors for all test trials, and the other half with only phase shift

errors. As such, 16 children were tested in the tempo error condition, and 16 children in the phase error condition. Within each error condition, the error types were balanced so that each type (fast and slow tempo shift errors or early and late phase shift errors) occurred in equal proportion. For example, in the tempo shift group, three of the errors presented were beats that were too fast, and the other three were beats that were too slow. Additionally, three of the errors were presented first in the pair, and three were presented second. Each block consisted of one practice trial (with one puppet whose drumming was correctly aligned, and one that drummed along to the randomized woodblock stimuli), followed by five test trial pairs of puppet stimuli.

Before the cBAT was administered, participants were instructed that they were about to watch two puppets drumming along to the same song, and that they were going to be a judge who had to determine which puppet would be a better drummer for a band. Before each trial, the experimenter showed the child the two puppets that would be presented in the videos for that trial, and identified them by name (for example, "This is my friend the bunny, and this is my friend the dog"). After the child viewed each video in the pair one time, the experimenter placed the two actual puppets in front of the child on the table, and asked the child to place a ribbon on the puppet who should win the prize. The practice trial at the beginning of each block was repeated until the participant correctly identified the puppet whose drumming was correctly aligned to the music. Test trials were not repeated, and the child received no feedback regarding their choice. The order of tasks was Block 1 of the cBAT, Digit Span Task, Block 2 of the cBAT, followed by the PPVT. Upon completion, participants received a certificate of participation and a small prize.

RESULTS

Complex Beat Alignment Test (cBAT). The dependent measure was the proportion of the time the five-year-old children selected the puppet that played the standard version as the best drummer. To directly compare the children's performance in detecting beat misalignment in the context of simple meter and complex meter, we conducted a 2 x 2 ANOVA with error type (phase, tempo) as a between-subjects factor and meter type (simple, complex) as a within-subjects factor. The only significant effect was meter type, $F(1, 30) = 23.78$, $p < .001$, indicating that five-year-old children are better at detecting beat misalignment in simple meters (proportion correct = .67, $SD = .20$) than complex meters (proportion correct = .46, $SD = .22$) and that this is not
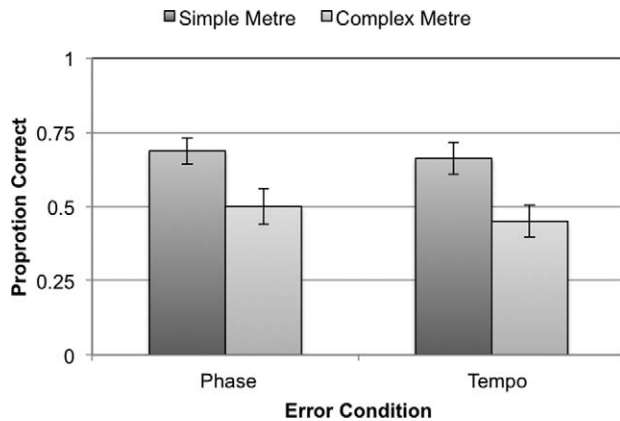
FIGURE 1. Perception scores from cBAT in Experiment One. The proportion of trials on which 5-year-old children chose the correctly aligned drumming is shown for phase and tempo conditions for simple and complex meter stimuli. Error bars represent standard error.
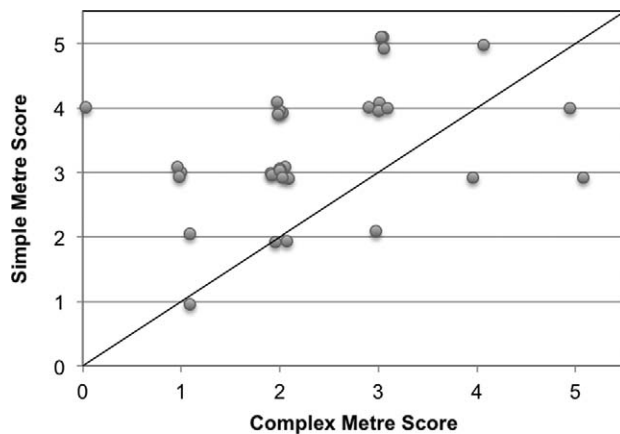

FIGURE 2. Individual results for the cBAT in Experiment One. Each point represents the data for one child, with the x-axis showing the number of trials on which the correctly aligned drumming excerpt was chosen for simple meter stimuli and the y-axis for complex meter stimuli. The preponderance of data above the diagonal indicates that performance was better for excerpts with simple compared to complex meter for the majority of children.

affected by whether the error is a phase or tempo error (Figure 1).

Examination of individual data for the cBAT task showed that 28 of 32 participants selected the puppet whose drumming was correctly aligned more often for the simple meter excerpts than they did for excerpts in complex meters (Figure 2). Thus, it is clear that a small subset of our sample was not driving our effect. There was no significant difference in judgment accuracy for simple meter excerpts between subjects who completed the simple block first (mean proportion correct $= .66$) or second (mean proportion correct $= .69$; $p = .87$).

There was also no significant difference in judgment accuracy for complex meter excerpts between subjects who completed the simple block first (mean proportion correct $= .53$) or second (mean proportion correct $= .42$; $p = .21$). This suggests that there were no carry-over effects as a result of presentation order.

We conducted a series of t-tests to compare the children's performance to chance (.50). Performance on the simple meter stimuli was significantly better than chance for tempo errors, $t(15) = 3.01$, $p = .005$, $M = .66$, $SE = .05$, as well as for phase errors, $t(15) = 4.20$, $p = .001$, $M = .69$, $SE = .04$. Performance on the complex meter stimuli was not significantly different from chance for tempo errors, $t(15) = -0.94$, $p = .36$, $M = .45$, $SE = .05$, or for phase errors, $t(15) = 0.001$, $p = 1.00$, $M = .50$, $SE = .06$. Despite children's inability as a group to judge beat alignment in complex meter stimuli, judgment accuracy for the simple meter stimuli was significantly correlated with judgment accuracy for the complex meter stimuli, $r = .37$, $p = .02$, suggesting that there are underlying factors that affect performance on both.

Relation Between cBAT and the Cognitive Tasks. PPVT standard scores did not significantly correlate with overall performance on the cBAT, $r = .20$, $p = .14$ and this correlation did not reach significance when considering only the simple meter portion of the cBAT, $r = .12$, $p = .26$, or only the complex meter portion of the cBAT $r = .21$, $p = .13$. There was variability in PPVT scores across children, $M = 114.28$, $SD = 9.30$, so the lack of correlation is not because all children performed equally well on the PPVT. Thus, performance differences between children do not appear to be driven by general differences in language ability that could underlie understanding the task.

However, overall cBAT performance was significantly correlated with performance on the forward digit span test ($M = 6.80$ $SD = 1.42$), $r = .51$, $n = 32$, $p = .001$. Furthermore, performance on the forward digit span test was correlated with both cBAT simple meter scores, $r = .45$, $n = 32$, $p = .005$, and with cBAT complex meter scores, $r = .39$, $n = 32$, $p = .01$ (Figure 3).

On the other hand, overall cBAT performance did not correlate significantly with the backward digit span test ($M = 4.56$, $SD = 1.56$), $r = -.09$, $p = .31$. This was also true for correlations between performance on the backward digit span test and cBAT simple meter scores alone ($r = -.07$, $p = .36$) and cBAT complex meter scores alone ($r = -.08$, $p = .33$; Figure 3). If we exclude two subjects whose backward digit span scores were more than 2.5 standard deviations below the mean in an outlier analysis, the significance of these correlations does
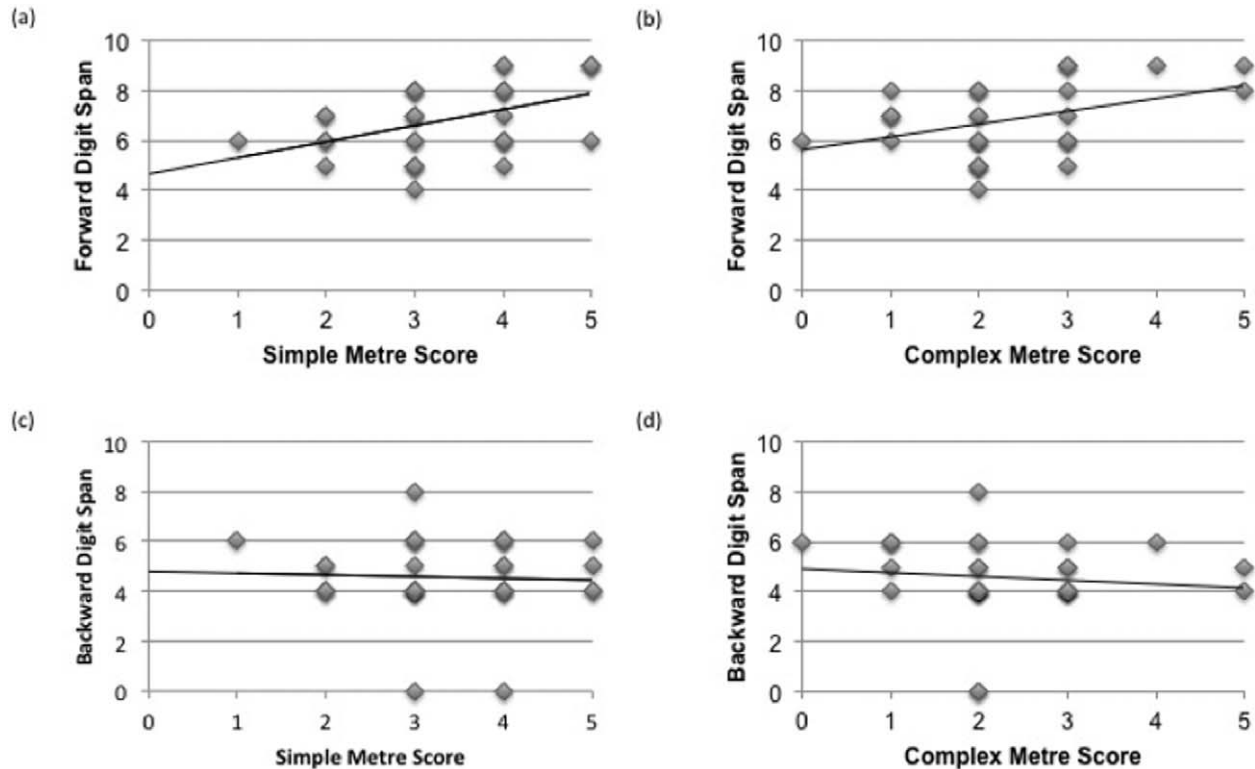
FIGURE 3. Correlations between performance on cBAT (including phase and tempo conditions) and forward and backward digit span in Experiment One. (a) cBAT simple meter scores and forward digit span, (b) cBAT complex meter scores and forward digit span, (c) cBAT simple meter scores and backward digit span, (d) cBAT complex meter scores and backward digit span. It can be seen that cBAT correlated with performance on forward digit span but not backward digit span.

not change. Thus, performance on the cBAT appears to be related to short-term memory but not to working memory.

Neither maternal education nor paternal education correlated with individual children's overall beat perception, simple meter beat perception, complex beat perception, or any of the cognitive measures (all p's > .05). Household income level was also not significantly correlated with any of these measures (all p's > .05). A post hoc comparison of cBAT performance for children whose parents either did or did not have formal music training revealed no difference between groups ($p = .98$). However, given that only one child had taken music lessons and none of the parents had extensive music training, more research is needed to determine whether early musical experience affects performance on these tasks.

Experiment 2

The simple meter music and complex meter music in the cBAT perception task were matched according to genre, tempo, and timbre in order to minimize differences between paired excerpts that were unrelated to metric structure. All simple meter excerpts had 4/4 metric structures; however, excerpts from the complex meter category were in either 5/4 or 7/4 time. As such, participants were required to make judgments about more than one meter type within the complex meter block of test trials.

Although we found no effects of presentation order on judgment accuracy *between* the simple and complex meter blocks in Experiment One, it is possible that there was an effect of presentation order *within* the complex meter block. To ensure that less accurate performance in the complex meter condition was not a result of making judgments about both 5/4 and 7/4 structures within the same block, we created a modified version of the cBAT for Experiment Two. In this modified version the two excerpts with 5/4 metric structure were removed along with their corresponding 4/4 pairs. As a result, test trials in the simple meter block were in 4/4 time only, and paired test trials in the complex meter block were in 7/4 time only.

METHOD

Participants. Participants were 24 five-year-old children (12 female, M_{age} = 5 years, 6 months) who were not enrolled in formal music lessons at the time of testing. No children had taken music lessons previously, and no children had participated in an infant music class. Seventeen of 24 households in our sample reported having a parent with some form of prior instrumental training. All children in the final sample had normal hearing and were in good health, as reported by their parents on a background questionnaire. An additional 5 children were excluded from the sample because of diagnosed developmental delays (n = 2), or failure to complete all tasks (n = 3). Annual family income and parental education were measured the same way as in Experiment One. Neither family income nor parental education levels were significantly different between children in the phase condition or the tempo condition of Experiment Two (all p's > .50). There was also no difference between average family income or parental education of children in Experiments One and Two (all p's > .50). All participants were recruited from the McMaster Infant Studies Group database, and the McMaster Research Ethics Board approved all protocols.

Stimuli. The stimulus set for the modified version of the complex Beat Alignment Test (cBAT) used in Experiment Two consisted of a subset of the same videos of drumming hand puppets used in Experiment One. In the modified version of the cBAT, the two excerpts in 5/4 time and their corresponding genre- and style-matched excerpts in 4/4 time were removed from the modified version of the task, so that test trials in both blocks contained only one meter type (either 4/4 in the simple block or 7/4 in the complex block).

As such, the modified cBAT used the same videos as the original cBAT, presented in the same manner. Each block in the modified cBAT consisted of one practice trial (with one puppet whose drumming was correctly aligned, and one that drummed along to the randomized woodblock stimuli), followed by four test trial pairs of puppet stimuli. In the simple meter block, all excerpts had 4/4 time signatures. In the complex meter block, all excerpts had 7/4 time signatures. The digit span task, receptive vocabulary task, and parent questionnaire did not differ from those used in Experiment One, and the equipment and software used were also the same.

Procedure. Children were tested during one session that was approximately 45 minutes in length. The tasks, order of presentation, and test procedure were identical to Experiment One, except for the alterations made to the complex meter block of the cBAT. The order of tasks was Block 1 of the cBAT, Digit Span task, Block 2 of the cBAT, followed by the PPVT. Upon completion, participants received a certificate of participation and a small prize.

As in Experiment One, error type was a between-subjects variable in the cBAT perception task, so that half the participants were presented with only tempo shift errors for all test trials, and the other half with only phase shift errors. As such, 12 children were tested in the tempo error condition, and 12 children in the phase error condition.

RESULTS

As in Experiment One, the dependent measure was the proportion of the time the five-year-old children selected the puppet that played the standard version as the best drummer. To directly compare the children's performance in detecting beat misalignment in the context of simple meter and complex meter, we conducted a 2 x 2 ANOVA with error type (phase, tempo) as a between-subjects factor and meter type (simple, complex) as a within-subjects factor. The only significant effect was meter type, $F(1, 22)$ = 8.25, p = .009, indicating that five-year-old children are better at detecting beat misalignment in simple meters (proportion correct = .74, SD = .21) than complex meters (proportion correct = .61, SD =.20) and that this is not affected by whether the error is a phase or tempo error. This is consistent with the results of Experiment 1.

As in Experiment 1, performance on the simple meter stimuli was significantly better than chance for tempo errors, $t(11)$ = 4.01, p = .002, M = .73, SE = .06, as well as for phase errors, $t(11)$ = 4.06, p = .002, M = .75, SE = .06. Performance on the modified complex meter stimuli (containing only 7/4 meter) was not significantly better than chance for tempo errors, $t(11)$ = −2.16, p = .05, M = .59, SE = .05, or for phase errors, $t(11)$ = 1.92, p = .08, M = .62, SE = .07. Judgment accuracy for the simple meter stimuli was again correlated with judgment accuracy for the complex meter stimuli, r = .45, p = .03, suggesting that there are underlying factors that affect performance on both types of judgments for the modified task.

Like in Experiment 1, PPVT standard scores in Experiment 2 also did not significantly correlate with overall performance on the modified cBAT, p = .23 and this correlation did not reach significance when considering only the simple meter portion of the cBAT, p = .82, or only the complex meter portion of the cBAT p = .07. Unlike in Experiment One, however, in Experiment Two overall performance on the cBAT was *not* significantly correlated with children's total score on the digit

span test ($M = 11.89$, $SD = 1.19$), $p = .17$. Judgment accuracy for simple meter stimuli only was not correlated with forward digit span, $p = .35$, or backward digit span, $p = .40$. Judgment accuracy for complex meter stimuli only was also not significantly correlated with forward digit span, $p = .87$, or backward digit span, $p = .16$.

We also compared the judgment accuracy of children from Experiments 1 and 2 directly, to determine whether there were significant differences in performance between the two versions of the cBAT. This was done using a 2 x 2 x 2 ANOVA with cBAT version (Experiment 1, 2) and error type (phase, tempo) as between-subjects factors and meter type (simple, complex) as a within-subjects factor. The only significant effect was meter type, $F(1, 52) = 29.07$, $p < .0001$, indicating that judgment accuracy was not significantly different for children who completed the original version of the cBAT (with two types of complex metric structures) compared to children who completed the modified version (with only one type of structure in the complex meter block of the task).

Neither maternal education nor paternal education correlated with individual children's overall beat perception or any of the cognitive measures (all p's >.15). Household income level was also not significantly correlated with any of the cognitive measures (all p's > .15), although it did correlate with children's overall beat perception ($p = .02$). A post hoc comparison of cBAT performance for children whose parents either did or did not have formal music training revealed no difference between groups ($p = .45$).
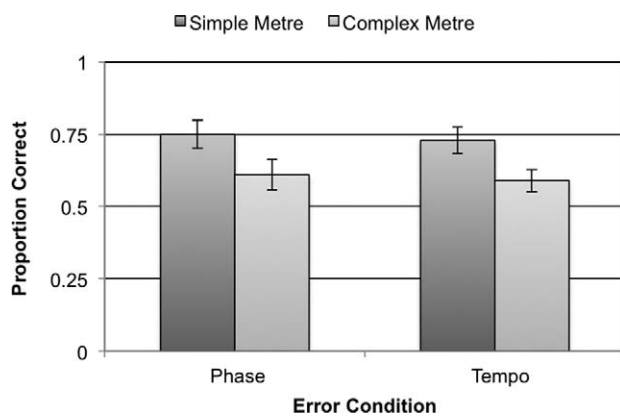

FIGURE 4. Perception scores from cBAT in Experiment Two. The proportion of trials on which 5-year-old children chose the correctly aligned drumming is shown for phase and tempo conditions for simple and complex meter stimuli. Error bars represent standard error.

General Discussion

We set out to examine the degree to which 5-year-old Western children are perceptually sensitive to a musical beat in the absence of requiring overt motor synchronization, and whether they show better beat processing for culturally typical simple, compared to culturally atypical complex, musical meters. We developed a novel method of assessing sensitivity to the alignment of musical beats, in the form of a child-appropriate version of the original BAT test (Iversen & Patel, 2008), named the complex Beat Alignment Test (cBAT), in which children were asked to listen to pairs of videos of puppets, one of whom drummed on time and one of whom did not, and to judge which one drummed better. We also expanded the original BAT test to include independent measures of the ability to detect phase and tempo misalignment as well as to include musical excerpts with both simple and complex meters.

When musical excerpts had simple metric structure, children were able to detect drumming that was out of phase with the music (either earlier or later than the beat by 25%) or at the wrong tempo (either 10% too fast or too slow). This demonstrates that by the age of five, children have the ability to make explicit judgments about beat alignment and it extends previous literature on children (Bobin-Bègue & Provasi, 2009; Drake, 1993; Kirschner & Tomasello, 2009; Provasi & Bobin-Bègue, 2003; van Noorden & De Bruyn, 2009; Zentner & Eerola, 2010) by showing that 5-year-olds are sensitive to both phase and tempo misalignment in the context of simple-metered music.

However, when musical excerpts had complex metric structures, performance was significantly worse than when excerpts had simple metric structures, and performance was not above chance when metrical structure was in five or seven. This is despite the fact that for both the simple meter and the complex meter stimuli, the drumming was composed solely of isochronous woodblock taps with no accents or other distinguishing characteristics. Subsequent work (Einarson & Trainor, 2015) has also demonstrated that children's performance on the task is not driven by the dynamic visual component of the stimulus, and remains comparable even when children are shown static images accompanied by the same auditory information. It is possible, however, that the tempo and phase misalignment manipulations in the cBAT index overlapping aspects of timing sensitivity. The tempo error created by an inappropriate interbeat interval also necessarily has inappropriate phase alignment with the beat of the musical excerpt, although the magnitude of

this misalignment will not be constant as it is in the phase misalignment condition.

Previous studies have shown that 6-month-old Western infants are equally able to process simple and complex metrical structure, but by 12 months are better able to process the simple meters common in Western music (Hannon & Trehub, 2005a; 2005b). In a rhythm reproduction task, Drake (1993) found that Western children also performed better on rhythms with simple compared to complex meters. The present results are consistent with these findings, and extend them by showing that young Western children also show better perception of *beat alignment* in music with simple compared to complex meters, supporting the notion that an enculturation-based perceptual bias is maintained into childhood. A full test of this hypothesis would, of course, require a crossover design in which children from a culture where complex meters are prevalent were also tested. Interestingly, despite the fact that the 5-year-olds as a group were at chance levels with excerpts with complex meters, the correlation between performance with simple and complex meters was significant. This suggests that, despite overall better performance with simple meter stimuli, there is overlap in the skills needed to perceive beat alignments in stimuli with simple and complex meters.

Although the cBAT test likely depends less on memory than a rhythm reproduction task, children's performance on the cBAT was correlated with forward digit span in Experiment One, suggesting that sensitivity to beat misalignment may be related to children's short-term memory. It is not clear whether this whether this would represent a better ability to remember whether or not the first puppet was a good drummer while watching the second puppet, or whether it is more directly related to the ability to perceive beat alignment itself. Indeed, previous studies have linked musical abilities in young children to auditory working memory (Kraus et al., 2012; Strait et al., 2011) and particularly to the digit span subtest of the WISC (Anvari, Trainor, Woodside, & Levy, 2002). However, the fact that digit span forward was significantly correlated with cBAT performance on musical excerpts with both simple and complex meters suggests that the correlation was not related to the difficulty of the beat alignment task itself and, thus, perhaps simply reflects that ability to remember from one video to the next. However, given that the correlation with forward digit span did not reach significance in Experiment Two with a smaller sample size, this relationship remains unclear. Furthermore, digit span backwards was not significantly correlated with cBAT performance in Experiment 1 or 2, suggesting that

any relationship would involve short-term memory as opposed to the ability to manipulate auditory information in working memory. It is possible that short average backward digit span length and the low variability in raw backward span scores in our sample ($M = 4.56$, $SD = 1.56$), although typical for young children, made it difficult to observe the relationship between working memory and beat perception. However, it also is worth noting that a subsequent study using the same stimuli with a larger population of 84 five-year-old children (Einarson & Trainor, 2015) found no relationship between children's forward or backward digit span and their performance on the cBAT perception task. This held true for overall score, simple meter only, or complex meter only.

Children's PPVT standard score did not correlate with beat perception in Experiment 1 or Experiment 2. However, the correlation between receptive vocabulary and complex meter performance approached significance in Experiment 2 ($p = .07$). Using a similar video-based task in a musical tonality test with four- and five-year-old children, Corrigall and Trainor (2014) also found a weak (nonsignificant) correlation between PPVT standard scores and performance ($p = .08$). They posited that children with better vocabularies might be better able to understand the instructions of the task. However, as in the case with our data, any such relationship is weak and not found consistently, suggesting that vocabulary is not having a strong influence on performance in this task.

While information on the development of musical perception in general in preschool children is sparse, a recent study using similar behavioral methodology to the present study indicates that 5-year-old children can also make explicit judgments about key membership, that is, whether or not a particular note belongs in the key or set of pitches used in a particular melody (Corrigall & Trainor, 2014). As indicated by event-related potential (ERP) measures, the same work has shown that some knowledge of key membership and harmony is present as young as 3 years of age. Little work on the rhythmic abilities of toddlers has been done (but see Eerola et al., 2006; Provasi & Bobin-Bègue, 2003), but finding behavioral and ERP paradigms in which to test children between 2 and 4 years of age remains a challenge for future research.

The development of the cBAT test enables further testing of a number of important questions in the development of rhythm skills. For example, the development of a purely perceptual task opens the possibility for testing perception and production separately and determining whether there is a dissociation between these

skills in young children. In adults, Iversen and Patel (2008) found that beat perception and synchronization abilities were highly correlated, and there is some evidence that beat perception and production abilities are related in children as well (Corriveau & Goswami, 2009). In addition, auditory and motor areas of the brain appear to be connected in infants and adults, even in the absence of self-generated movements (e.g., Fujioka, Trainor, Large, & Ross, 2012; Iversen, Repp, & Patel, 2009; Phillips-Silver & Trainor, 2005; Trainor, Gao, Lei, Lehtovarara, & Harris, 2009). However, recent evidence for a dissociation between deficits in pitch perception and pitch production has been reported (Dalla Bella, Giguere, & Peretz, 2007; Loui, Guenther, Mathys, & Schlaug, 2008). Given that existing literature suggests that children's motor skills and auditory-visual coordination are somewhat limited (Drake, 1993; Eerola et al., 2006; Kirschner & Tomasello, 2009; Provasi & Bobin-Bègue, 2003), combined with our finding that children are fairly proficient at detecting beat alignment in music with simple meter, it is important to explore the developmental relation between beat perception and production.

The cBAT also offers a means to test metrical enculturation in young children across cultures without confounds from different motor experience and ability. Children from some Balkan regions, for example, grow up being exposed to a much wider variety of musical meters, and it has been claimed that they learn these structures from a young age, and seemingly with ease (Rice, 1994). However, the only cross-cultural investigation of simple and complex musical meter processing to date tested Bulgarian and Macedonian adults (Hannon & Trehub, 2005a). If the better performance of Western children in the present study on musical excerpts with simple compared to complex meter is a function of enculturation, then children who are raised in a culture where complex meter music is widespread should show equal ability for beat alignment in music with simple and complex meters.

In sum, we found that Western five-year-old children are sensitive to a musical beat, and can detect misalignments in both the tempo and phase of a beat relative to a musical sample with culturally typical simple meter. However, in the context of less familiar complex meter music, children's ability to detect misalignments in both the tempo and phase of a musical beat was at chance levels. The development of the cBAT enables future investigation of the relation between children's perceptual sensitivity and their ability to produce a musical beat by synchronizing to music. It also provides a means by which to investigate effects of enculturation on beat sensitivity by comparing the performance of children in cultures where complex meters are rare to those where complex meters are widespread.

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References

ANVARI, S. H., TRAINOR, L. J., WOODSIDE, J., & LEVY, B. A. (2002). Relations among musical skills, phonological processing and early reading ability in preschool children. *Journal of Experimental Child Psychology, 83*, 111-130.

BAILEY, J. A., & PENHUNE, V. B. (2010). Rhythm synchronization performance and auditory working memory in early- and late-trained musicians. *Experimental Brain Research, 204*, 91-101.

BOBIN-BÈGUE, A., & PROVASI, J. (2009). Tempo discrimination in 3- and 4-year-old children: Performances and threshold. *Current Psychology Letters, 2*, 1-13.

CANTOR, J., ENGLE, R. W., & HAMILTON, G. (1991). Short-term memory, working memory, and verbal abilities: How do they relate? *Intelligence, 15*, 229-246.

CONWAY, A. R., KANE, M. J., BUNTING, M. F., HAMBRICK, D. Z., WILHELM, O., & ENGLE, R. W. (2005). Working memory span tasks: A methodological review and user's guide. *Psychonomic Bulletin and Review, 12*, 769-786.

CORRIGALL, K. A., & TRAINOR, L. J. (2014). Enculturation to musical pitch structure in young children: Evidence from behavioral and electrophysiological methods. *Developmental Science, 17*, 142-158.

CORRIVEAU, K. H., & GOSWAMI, U. (2009). Rhythmic motor entrainment in children with speech and language impairments: tapping to the beat. *Cortex, 45*, 119-130.

DALLA BELLA, S., GIGUERE, J-F., & PERETZ, I. (2007). Singing proficiency in the general population. *Journal of the Acoustical Society of America, 121*, 1182-1189.

DAWE, L. A., PLATT, J. R., & RACINE, R. J. (1993) Harmonic accents in inference of metrical structure and perception of rhythm patterns. *Perception and Psychophysics, 54*, 794-807.

DRAKE, C. (1993). Reproduction of musical rhythms by children, adult musicians, and adult nonmusicians. *Perception and Psychophysics*, *53*, 25-33.

DRAKE, C., JONES, M. R., & BARUCH, C. (2000). The development of rhythmic attending in auditory sequences: attunement, referent period, focal attending. *Cognition, 77*, 251-288.

DUNN, L. M., & DUNN, D. M. (2007). *Peabody Picture Vocabulary Test Manual* (4th ed.). Minneapolis, MN: Pearson Assessments.

EEROLA, T., LUCK, G., & TOIVIAINEN, P. (2006). An investigation of pre-schoolers' corporeal synchronization with music. In M. Baroni, A. R. Addessi, R. Caterina, & M. Costa (Eds.), *Proceedings of the 9th International Conference on Music Perception and Cognition (ICMPC9)* (pp. 472-476). Bologna, Italy: ICMPC.

EINARSON, K. M., & TRAINOR, L. J. (2015). The effect of visual information on young children's perceptual sensitivity to musical beat alignment. *Timing and Time Perception, 3*, 88-101.

ENGLE, R. W., TUHOLSKI, S. W., LAUGHLIN, J. E., & CONWAY, A. R. (1999). Working memory, short-term memory, and general fluid intelligence: A latent-variable approach. *Journal of Experimental Psychology. General*, *128*, 309-331.

ESSENS, P. J. (1986). Hierarchical organization of temporal patterns. *Perception and Psychophysics*, *40*, 69-73.

ESSENS, P. J., & POVEL, D. J. (1985). Metrical and nonmetrical representations of temporal patterns. *Perception and Psychophysics*, *37*, 1-7.

FRIENDLY, R. H., RENDALL, D., & TRAINOR, L. J. (2014). Learning to differentiate individuals by their voices: Infants' individuation of native- and foreign-species voices. *Developmental Psychobiology, 56*, 228-237.

FUJIOKA, T., TRAINOR, L. J., LARGE, E. W., & ROSS, B. (2012). Internalized timing of isochronous sounds is represented in neuromagnetic beta oscillations. *The Journal of Neuroscience*, *32*, 1791-1802.

GJERDINGEN, R. O. (1989). Meter as a mode of attending: A network simulation of attentional rhythmicity in music. *Intégral*, *3*, 67-91.

GORDON, E. E. (1979). Developmental music aptitude as measured by the Primary Measures of Music Audiation. *Psychology of Music*, *7*, 42-49.

GORDON, E. E., (1980). *Manual for the Primary Measures of Music Audition and the Intermediate Measures of Music Audiation*. Chicago, IL: G.I.A.

GRAHN, J. A., & BRETT, M. (2007). Rhythm and beat perception in motor areas of the brain. *Journal of Cognitive Neuroscience*, *19*, 893-906.

HANNON, E. E., SOLEY, G., & LEVINE, R. S. (2011). Constraints on infants' musical rhythm perception: Effects of interval ratio complexity and enculturation. *Developmental Science, 14*, 865-872.

HANNON, E. E., & TRAINOR, L. J. (2007). Music acquisition: Effects of enculturation and formal training on development. *Trends in Cognitive Sciences*, *11*, 466-472.

HANNON, E. E., & TREHUB, S. E. (2005a). Metrical categories in infancy and adulthood. *Psychological Science*, *16*, 48-55.

HANNON, E. E., & TREHUB, S. E. (2005b). Tuning in to musical rhythms: Infants learn more readily than adults. *Proceedings of the National Academy of Sciences, 102*, 12639- 12644.

IVERSEN, J. R., & PATEL, A. D. (2008). The Beat Alignment Test (BAT): Surveying beat processing abilities in the general population. In K. Miyazaki, M. Adachi, Y. Hiraga, Y. Nakajima, & M. Tsuzaki (Eds.), *Proceedings of the 10th International Conference on Music Perception and Cognition (ICMPC10)* (pp. 465-468). Sapporo, Japan. Adelaide: Causal Productions.

IVERSEN, J. R., REPP, B. H., & PATEL, A. D. (2009). Top-down control of rhythm perception modulates early auditory responses. *Annals of the New York Academy of Sciences, 1169*, 58-73.

JONES, M. R. (1976). Time, our lost dimension: Toward a new theory of perception, attention, and memory. *Psychological Review, 83*, 323-355.

JONES, M. R., & BOLTZ, M. (1989). Dynamic attending and responses to time. *Psychological Review*, *96*, 459-491.

KELLY, D. J., QUINN, P. C., SLATER, A. M., LEE, K., GE, L., & PASCALIS, O. (2007). The other-race effect develops during infancy: Evidence of perceptual narrowing. *Psychological Science*, *18*, 1084-1089.

KIRSCHNER, S., & TOMASELLO, M. (2009). Joint drumming: Social context facilitates synchronization in preschool children. *Journal of Experimental Child Psychology, 102*, 299-314.

KRAUS, N., STRAIT, D. L., & PARBERY-CLARK, A. (2012). Cognitive factors shape brain networks for auditory skills: Spotlight on auditory working memory. *Annals of the New York Academy of Sciences, 1252*, 100-107.

LARGE, E. W., & PALMER, C. (2002). Perceiving temporal regularity in music. *Cognitive Science*, *26*, 1-37.

LERDAHL, F., & JACKENDOFF, R. (1983). *A generative theory of tonal music*. Cambridge, MA: MIT Press.

LONDON, J. (2002). Cognitive constraints on metric systems: Some observations and hypotheses. *Music Perception*, *19*, 529-550.

LONDON, J. (2004). *Hearing in time: Psychological aspects of musical meter*. New York: Oxford University Press.

LOUI, P., GUENTHER, F. H., MATHYS, C., & SCHLAUG, G. (2008). Action–perception mismatch in tone-deafness. *Current Biology, 18*, R331-R332.

Lynch, M. P., Eilers, R. E., Oller, D. K., & Urbano, R. C. (1990). Innateness, experience, and music perception. *Psychological Science, 1*, 272-276.

Lynch, M. P., & Eilers, R. E. (1992). A study of perceptual development for musical tuning. *Perception and Psychophysics, 52*, 599-608.

McAuley, J. D., Jones, M. R., Holub, S., Johnston, H. M., & Miller, N. S. (2006). The time of our lives: Life span development of timing and event tracking. *Journal of Experimental Psychology. General, 135*, 348-367.

Oberauer, K., & Süß, H. M. (2000). Working memory and interference: A comment on Jenkins, Myerson, Hale, and Fry (1999). *Psychonomic Bulletin and Review, 7*, 727-733.

Parncutt, R. (1994). A perceptual model of pulse salience and metrical accent in musical rhythms. *Music Perception, 11*, 409-464.

Patel, A. D., Iversen, J. R., Brandon, M., & Saffran, J. (2011). Do infants perceive the beat in music? A new perceptual test. Abstract in *Proceedings of the 2011 Biennial Meeting of the Society for Music Perception and Cognition (SMPC 2011)*. Rochester, NY: SMPC.

Peretz, I., Champod, S., & Hyde, K. (2003). Varieties of musical disorders: The Montreal Battery of Evaluation of Amusia. *Annals of the New York Academy of Sciences, 999*, 58-75.

Phillips-Silver, J., & Trainor, L. J. (2005). Feeling the beat: Movement influences infant rhythm perception. *Science, 308*, 1430.

Povel, D. J., & Okkerman, H. (1981). Accents in equitone sequences. *Perception and Psychophysics, 30*, 565-572.

Provasi, J., & Bobin-Bègue, A. (2003). Spontaneous motor tempo and rhythmical synchronisation in 2½- and 4-year-old children. *International Journal of Behavioral Development, 27*, 220-231.

Repp, B. H. (2005). Sensorimotor synchronization: A review of the tapping literature. *Psychonomic Bulletin and Review, 12*, 969-992.

Repp, B. H., & Su, Y. H. (2013). Sensorimotor synchronization: A review of recent research (2006–2012). *Psychonomic Bulletin and Review*. DOI: 10.3758/s13423-012-0371-2

Rice, T. (1994). *May it fill your soul: Experiencing Bulgarian music*. Chicago, IL: University of Chicago Press.

Snyder, J. S., Hannon, E. E., Large, E. W., & Christiansen, M. H. (2006). Synchronization and continuation tapping to complex meters. *Music Perception, 24*, 135-146.

Strait, D. L., Hornickel, J., & Kraus, N. (2011). Subcortical processing of speech regularities underlies reading and music aptitude in children. *Behavioral and Brain Functions, 7*, 1-11.

Trainor, L. J., Gao, X., Lei, J., Lehtovarara, K., & Harris, L. R. (2009). The primal role of the vestibular system in determining musical rhythm. *Cortex, 45*, 35-43.

Trainor, L. J., & Hannon, E. E. (2012). Musical development. In D. Deutsch (Ed.), *The psychology of music* (3rd ed., pp. 423-497). San Diego, CA: Academic Press.

Trainor, L. J., & Trehub, S. E. (1992). A comparison of infants' and adults' sensitivity to Western musical structure. *Journal of Experimental Psychology: Human Perception and Performance, 18*, 394-402.

van Noorden, L., & De Bruyn, L. (2009). The development of synchronization skills of children 3 to 11 years old. In P. Toiviainen (Ed.), *Proceedings of ESCOM—7th Triennial Conference of the European Society for the Cognitive Sciences of Music*. Jyväskylä, Finland: University of Jyväskylä.

Wechsler, D. (2003). *Wechsler Intelligence Scale for Children* (4th ed.). San Antonio, TX: The Psychological Corporation.

Werker, J. F., & Tees, R. C. (1984). Cross-language speech perception: Evidence for perceptual reorganization during the first year of life. *Infant Behavior and Development, 7*, 49-63.

Zatorre, R. J., Chen, J. L., & Penhune, V. B. (2007). When the brain plays music. Auditory-motor interactions in music perception and production. *Nature Reviews Neuroscience, 8*, 547-558.

Zentner, M., & Eerola, T. (2010). Rhythmic engagement with music in infancy. *Proceedings of the National Academy of Sciences, 107*, 5768-5773.