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SHORT REPORT

Musical rhythm discrimination explains individual differences in grammar skills in children

Reyna L. Gordon,[1] Carolyn M. Shivers,[1] Elizabeth A. Wieland,[2] Sonja A. Kotz,[3,4] Paul J. Yoder[1] and J. Devin McAuley[5]

1. *Vanderbilt Kennedy Center, Vanderbilt University, USA*
2. *Department of Communicative Sciences and Disorders, Michigan State University, USA*
3. *Department of Neuropsychology, Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig, Germany*
4. *School of Psychological Sciences, The University of Manchester, UK*
5. *Department of Psychology and Neuroscience Program, Michigan State University, USA*

Abstract

This study considered a relation between rhythm perception skills and individual differences in phonological awareness and grammar abilities, which are two language skills crucial for academic achievement. Twenty-five typically developing 6-year-old children were given standardized assessments of rhythm perception, phonological awareness, morpho-syntactic competence, and non-verbal cognitive ability. Rhythm perception accounted for 48% of the variance in morpho-syntactic competence after controlling for non-verbal IQ, socioeconomic status, and prior musical activities. Children with higher phonological awareness scores were better able to discriminate complex rhythms than children with lower scores, but not after controlling for IQ. This study is the first to show a relation between rhythm perception skills and morpho-syntactic production in children with typical language development. These findings extend the literature showing substantial overlap of neurocognitive resources for processing music and language.

Research highlights

- Rhythm perception and expressive language were tested in typically developing school-aged children.
- Rhythm skills were highly correlated with grammar skills.
- After controlling for IQ, rhythm still accounted for individual differences in skill for grammar, but not in phonological awareness.

Introduction

A number of studies have suggested that musical abilities are associated with enriched language skills (Milovanov & Tervaniemi, 2011). This relation has been shown for children with and without music training. Higher levels of musical aptitude are associated with enhancement in a number of reading-related skills in children without formal music training (Anvari, Trainor, Woodside & Levy, 2002; Forgeard, Schlaug, Norton, Rosam & Iyangar, 2008; Strait, Hornickel & Kraus, 2011; Rautenberg, 2013). In the domain of musical rhythm, kindergarteners' rhythmic aptitude has been found to predict their second grade phonological awareness and word identification proficiency (Moritz, Yampolsky, Papadelis, Thomson & Wolf, 2013). Formal music training is additionally associated with a wide range of language processing benefits, including enhanced brain responses to subtle acoustic variations in speech syllables (Chobert, Marie, François, Schön & Besson, 2011) and better foreign language pronunciation skills (Milovanov, Huotilainen, Esquef, Alku, Valimaki & Tervaniemi, 2009).

Some recent studies suggest that the effects of music training on language skills are causal. In one study, kindergarteners randomly assigned to a music training

Address for correspondence: Reyna L. Gordon, Vanderbilt Kennedy Center, Vanderbilt University, 230 Appleton Place, PMB 74 Nashvillle, TN 37203, USA; e-mail: reyna.gordon@alumni.usc.edu

group improved their phonological awareness skills more than those randomly assigned to a sports training group (Degé & Schwarzer, 2011). In studies that compared children randomly assigned to either music or art training, music training led to better linguistic pitch perception and reading skills (Moreno, Marques, Santos, Santos, Castro & Besson, 2009), and to enhanced brain responses indexing speech segmentation (François, Chobert, Besson & Schön, 2013), syllabic duration and voice-onset-time (Chobert, François, Velay & Besson, 2012).

One possible explanation for the relation between music training and normal language development is that the greater acoustic precision required by musical activities benefits brain networks involved in speech processing (Patel, 2011). Enhanced precision in auditory processing may specifically aid syntactic acquisition because typically developing infants may rely on timing cues to acquire syntax, e.g. timing variations that mark phrase boundaries (Fernald & McRoberts, 1996). Even 6-month-olds are sensitive to prosodic markers of syntactic units (Soderstrom, Seidl, Kemler Nelson & Jusczyk, 2003).

In typical adult language comprehension, temporal and/or rhythmic cues to prominent words permit the listener to focus attention on important parts of the speech signal as it unfolds in time (Schmidt-Kassow & Kotz, 2008; Kotz & Schwartze, 2011; Rothermich, Schmidt-Kassow & Kotz, 2012). Similarly, rhythmic context in speech has been found to influence word segmentation and lexical access (Magne, Astésano, Aramaki, Ystad, Kronland-Martinet & Besson, 2007; Dilley & McAuley, 2008; Dilley, Mattys & Vinke, 2010) as well as syntactic processing (Schmidt-Kassow & Kotz, 2008, 2009a). With respect to the latter, rhythmically regular sentence contexts have been found to facilitate syntactic ambiguity resolution (Roncaglia-Denissen, Schmidt-Kassow & Kotz, 2013) and detection of syntactic violations (Schmidt-Kassow & Kotz, 2008, 2009b). Moreover, these effects are enhanced by attention to the rhythmic structure of sentences (Schmidt-Kassow & Kotz, 2009a).

In children with language acquisition difficulties, below-average musical rhythm skills (Alcock, Passingham, Watkins & Vargha-Khadem, 2000; Corriveau & Goswami, 2009; Corriveau, Pasquini & Goswami, 2007) and impaired prosodic sensitivity have been reported (Weinert, 1992; Wells & Peppé, 2003; Fisher, Plante, Vance, Gerken & Glattke, 2007). Rhythm skills are also thought to be relevant to reading in children both typically developing (Tierney & Kraus, 2013) and with dyslexia (Huss, Verney, Fosker, Mead & Goswami, 2010; Leong & Goswami, 2014), who show some deficits with syllable timing and musical rhythm. Neural evidence favoring the domain-generality of rhythmic processing (Gordon, Magne & Large, 2011; Peter, McArthur & Thompson, 2012; Hausen, Torppa, Salmela, Vainio & Sarkamo, 2013) and its relation to language skills is consistent with both the Temporal Sampling Framework (Goswami, 2011) and Dynamic Attending Theory (Large & Jones, 1999).

Here we tested the hypothesis that individual differences in rhythm perception skills are positively related to individual differences in grammatical production in typically developing children. This contrasts with previous work, which has focused on atypical development (Weinert, 1992). We also examined the possible relation between rhythmic skills and phonological awareness, as suggested in past work examining the role of rhythm in learning to read (Anvari *et al*., 2002; Forgeard *et al*., 2008; Rautenberg, 2013).

Methods

Participants

Twenty-five children (n = 12 female), aged 5;11 to 7;1 years (M = 6;6 years, SD = 4 months) participated in this study. All were native speakers of English with less than two years of formal music training, with parents reporting that their child had normal hearing, language, cognitive, and emotional development. The study received Institutional Review Board of Vanderbilt University approval. Parents gave written consent for their child to participate, and children gave their separate assent. Parents completed a questionnaire that included questions about their education, as well as their child's race, ethnicity, and musical activities. There were nine levels of education (M = 7.32, SD = 0.83), corresponding to an average of three to four years of college/technical school. Music experience (adapted from Lense & Dykens, 2013) was measured by summing the number of years of each child's formal and informal musical activities (including individual and group lessons inside/outside of school, as well as ensemble participation). Scores ranged from 0 to 3 (M = 1.08, SD = 0.81). Children received a small toy and parents received a $40 gift card for compensation.

Rhythm measures

Children completed two rhythm measures: a rhythm discrimination task called the beat-based advantage (BBA) assessment and the rhythm section of the Primary Measures of Music Audiation (PMMA; Gordon, 1979b).

BBA

Children made same/different judgments about simple and complex rhythms. Previous research has shown that simple rhythms with a strong beat are better discriminated than rhythms with a weak beat (Grahn & Brett, 2009). Both rhythm types were included here to explore the possibility that aspects of language processing might be more/less associated with the presence/absence of a beat. Table 1 shows notation for the seven simple and seven complex rhythms selected from Grahn and Brett (2009); sound examples are available online in Data S1 and S2. For simple rhythms, intervals were organized such that a tone onset occurred every four base inter-onset-intervals (IOIs), which would be expected to induce a strong beat (Povel & Essens, 1985). For complex rhythms, intervals were organized so that accents were not periodic, and thus less expected to induce a beat; see Figure 1. Simple rhythms had corresponding complex rhythms that were matched in the number of intervals.

On each trial, children heard two successive presentations of a standard rhythm and then judged whether a third (comparison) rhythm was the same or different from the standard. Different rhythms were constructed by swapping a pair of adjacent intervals, identical to Grahn and Brett (2009). The IOI between stimulus presentations was 1200 ms. The task was presented in the form of a computer game, in which 'Randy Drummer' would play the standard rhythm two times and then either the same rhythm would be played back to Randy by his twin brother 'Sandy Same', who liked to 'be a copycat', or a different rhythm would be played back by 'Doggy Different', who liked to 'be different'. Children indicated whether the third rhythm was being played by 'Sandy Same' (same rhythm) or 'Doggy Different' (different rhythm) by pressing the respective button on the response pad (see Figure 2). The experiment was presented to participants using E-Prime v2.0 Professional (Psychology Software Tools, Inc.) running on a Dell Latitude E6510 laptop, Intel® Core™ i5 CPU with a 15-inch screen. Sounds were presented over Alesis M1Active 320 speakers at a comfortable listening level. Response side-associations were counterbalanced across participants.

Table 1 *Simple and complex rhythm sequences used in the beat-based advantage (BBA) assessment*

	Simple		complex	
	Standard	Different	Standard	Different
5 intervals	31422	13422	23241	23214
	41331	43131	33141	31341
6 intervals	211413	211431	214221	214212
	311322	313122	321411	324111
	422112	422211	421311	412311
7 intervals	1122114	1121124	1132131	1131231
	2211114	2112114	2141211	2142111

Swapped intervals for the 'different' variant of the rhythm are indicated as underlined.

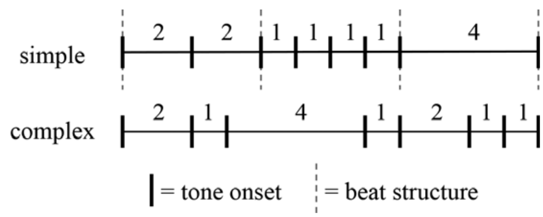

Figure 1 *A schematic example of the types of rhythmic sequence stimuli (from Grahn & Brett, 2009) used in the beat-based advantage (BBA) assessment. The numbers represent the relative length of intervals in each sequence with 1 = 165 to 205 ms (value chosen at random on each trial) in steps of 8 ms. All intervals within a rhythm were integer multiples of a base time unit, notated by a '1'. The values 2, 3, and 4 indicate that the temporal intervals were 2 ×, 3 ×, or 4 × the duration of the base inter-onset-interval (IOI) unit, respectively. The 'different' variant of a rhythm involved swapping the order of a pair of intervals (underlined in Table 1).*

Four practice trials were same/different variants of one simple and one complex rhythm not used in the test, and 28 test trials consisted of same/different variants of all seven simple and complex rhythms. Correct/incorrect feedback was provided during practice, but not during the test. Six short breaks occurred during testing where children received encouragement and were given a sticker. The base IOI varied randomly from trial to trial between 165 ms and 205 ms in 8-ms increments. Tone frequency varied across trials among six values: 294, 353, 411, 470, 528, or 587 Hz.

Responses were subjected to a signal detection analysis (Macmillan & Creelman, 2005). Hits were 'different' responses on trials where the comparison rhythm was different, and false alarms were 'different' responses on trials where the comparison rhythm was the same. For each participant and condition (simple, complex), hit rate (HR) and false alarm rate (FAR) were used to calculate *d'* (a measure of discrimination ability; z(HR) − z(FAR); values of *d'* = 0 correspond to chance performance, with larger values corresponding to better discrimination).

PMMA

The rhythm portion of the Primary Measures of Music Audiation (PMMA; Gordon, 1979b) is a section of a

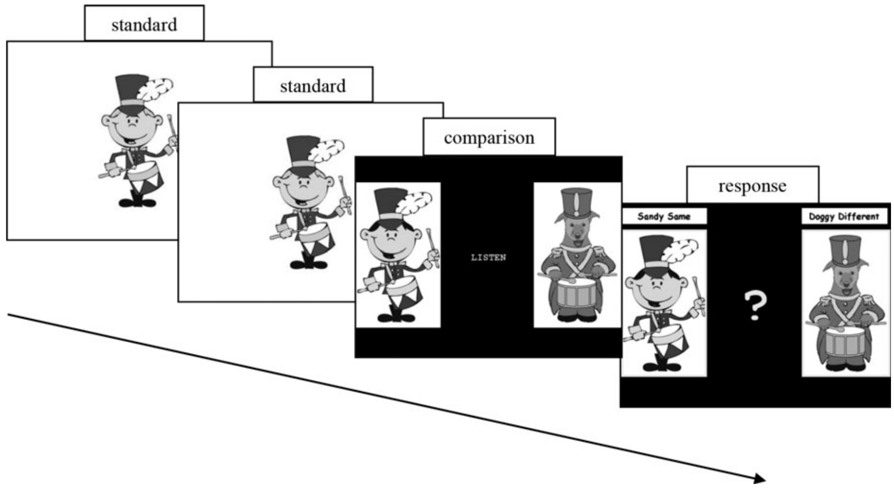

Figure 2 *Visual representation of a trial for the beat-based advantage (BBA) assessment. The standard rhythm was played twice by 'Randy Drummer', then the comparison rhythm was either same or different, then the participant responded 'Sandy Same' or 'Doggy Different'.*

computer-based test that has been shown to be sensitive to developmental changes in music aptitude (Gordon, 1979a; Flohr, 1981). Testing is structured as a game, in which children 'help' a dog reach 'home' by determining whether two short monotonic melodies have the same or different rhythms. The test yields a raw score[1] (i.e. how many items children answered correctly out of 40 questions).

Language measures

Morpho-syntax

Children's expressive grammatical abilities were measured using the Structured Photographic Expressive Language Test (SPELT-3; Dawson, Stout & Eyer, 2003). The SPELT-3 has a high degree of sensitivity and specificity in identifying grammatical impairments in children (Perona, Plante & Vance, 2005). For this measure, children are shown various photographs and asked to describe what they see. Specific questions about the photographs are asked in an attempt to elicit answers in certain morpho-syntactic constructions (i.e. irregular past tense verbs or reflexive pronouns). Standardized scores measuring performance relative to age expectations were used in the analysis.

Phonological awareness

The phonological awareness composite from the Comprehensive Test of Phonological Processing (CTOPP; Wagner, Torgesen & Rashotte, 1999) was used to measure phonological ability. Children completed three tasks: Elision, which involves verbally removing phonological sounds from words (e.g. 'Say "tiger" without saying /g/'), Blending Words, which involves verbally combining phonological sounds to make new words (e.g. 'What word do these sounds make: /s/ - /û/ - /n/?'), and Sound Matching, which involves identifying pictures that share the same beginning or ending sound (e.g. 'Which of these starts with the same sound as "sun": man, bug, or sack?'). Standard scores are calculated for each of the three subtests, which are then summed; this sum is then transformed to obtain a standardized phonological awareness composite score that measures performance relative to age expectations.

Non-verbal intelligence

In order to control for individual differences in IQ when examining the relation between rhythm and language measures, the Primary Test of Nonverbal Intelligence (PTONI; Ehrler & McGhee, 2008) was used. The test format requires children to look at a series of pictures on each page and identify which picture does not belong with the others based on various characteristics such as

[1] The PMMA also provides a percentile ranking, but unlike the standard scores from the language assessments which are age-relative, ranking on the PMMA is done by grade and is therefore less precise; for this reason we opted to use raw scores from the PMMA, and then included age as a covariate in analyses, as described in the Results section.

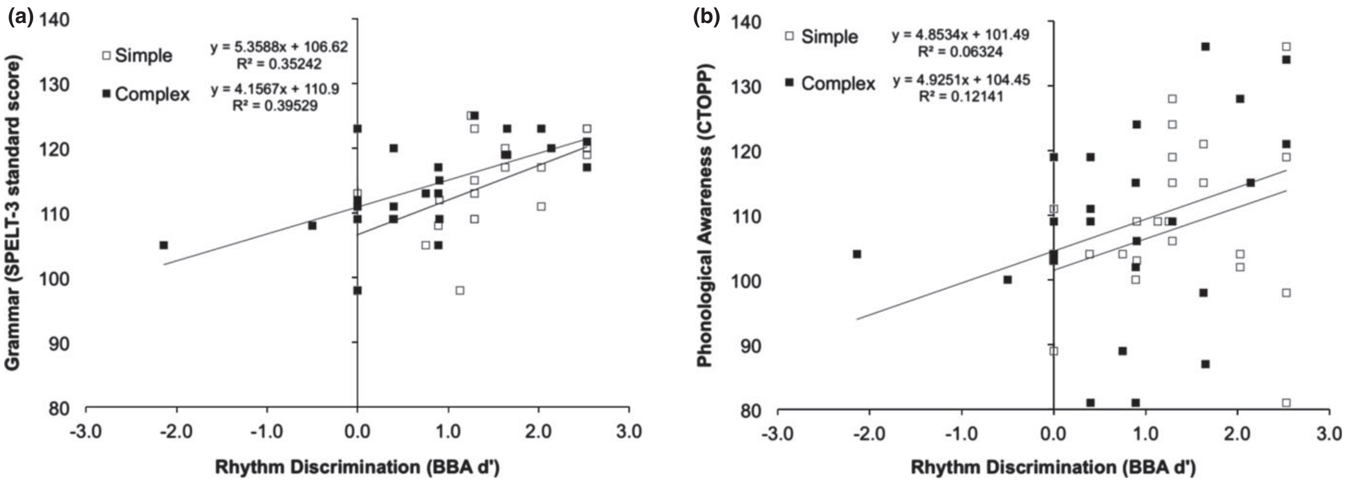

Figure 3 *Scatterplots showing the relationship between the Beat-Based Advantage (BBA) assessment for d′ values on simple and complex rhythms and (a) the grammar measure (SPELT-3) and (b) the phonological measure (CTOPP).*

color, shape, number, and function. As with the language assessments, we used the PTONI's standard score.

General procedure

Children completed the PMMA, followed by the CTOPP, PTONI, SPELT-3, and finally the BBA. The session lasted about 90 minutes including breaks, and occurred in a quiet room at Vanderbilt University.

Results

Figure 3a and Table 2 show that standard scores on the SPELT-3 were positively correlated with children's rhythm discrimination sensitivity (*d'* scores) on the BBA for both simple rhythms ($r(23) = .59$) and complex rhythms ($r(23) = .63$). Similarly, scores on SPELT-3 were positively correlated with performance on the PMMA ($r(23) = .51$). A Rhythm discrimination composite index was computed for each participant by averaging overall proportion correct on the BBA assessment and the PMMA; data on this composite metric were also highly correlated with the SPELT-3 ($r(23) = .73$; see Figure 4). Maximum Cook's d for all significant correlations reported in this section indicated no undue influence (i.e. max Cook's d < 1.00).

Next, we considered the relation between rhythm discrimination and phonological skills. CTOPP standard scores and rhythm discrimination were only weakly correlated for complex rhythms on the BBA ($r(23) = .35$, $p = .09$; see Figure 3b). CTOPP scores were not correlated for simple rhythms on the BBA ($r(23) = .25$), the PMMA ($r(23) = .05$), or the Rhythm composite index ($r(23) = .25$). To further explore the relation between complex rhythm discrimination and phonological skills, we performed a median split on CTOPP scores to consider potential differences in rhythm perception for children with high vs. low phonological abilities. CTOPP high scorers performed better ($d' = 1.16$) on BBA complex rhythm discrimination than did low scorers ($d' = 0.37$), $t(23) = 2.03$, $p = .05$, $d = 0.81$, but there were no other differences. Correlations between Music experience and each of the rhythm and language measures were tested and are reported in the online Supplementary Material (Data S3).

In order to rule out alternative explanations[2] for the above results, the relations between rhythm and the two language measures were examined while separately controlling for each of three variables: non-verbal IQ (PTONI scores), Musical Experience, and a proxy for socioeconomic status (Parent Education); see Table 2. Significant positive partial correlations remained between rhythm measures and the SPELT-3 after controlling for these variables. However, with respect to the weaker relation between rhythm and phonological awareness, an ANCOVA that included the PTONI score as a covariate revealed that the difference in BBA complex rhythm discrimination between high and low scorers on the CTOPP was non-significant, $F(1, 22) = 1.52$, $p = .23$.

[2] Because suitable age-norming was available for only the language measures but not rhythm measures, an additional set of follow-up correlations was conducted while co-varying Age. Correlations were still significant between SPELT-3 and the following: BBA d' simple ($r(22) = .54$, $p = .007$), BBA d' complex ($r(22) = .63$, $p = .001$), PMMA ($r(22) = .46$, $p = .025$), and Rhythm Composite ($r(22) = .70$, $p < .001$).

Table 2 *Results of planned correlations between rhythm and language measures*

Correlations tested	Zero-order correlations	Partial correlation controlling Non-verbal IQ	Partial correlation controlling Music Experience	Partial correlation controlling Parent Education
BBA *d'* simple vs. SPELT-3	0.59**	0.58**	0.56**	0.62**
BBA *d'* complex vs. SPELT-3	0.63**	0.63**	0.62**	0.64**
PMMA vs. SPELT-3	0.51**	0.53**	0.49*	0.50*
Rhythm composite vs. SPELT-3	0.73***	0.72***	0.71***	0.73***
BBA *d'* simple vs. CTOPP	0.25			
BBA *d'* complex vs. CTOPP	0.35	0.17		
PMMA vs. CTOPP	0.05			
Rhythm composite vs. CTOPP	0.25			

*$p < .05$; **$p < .01$; *** $p < .001$.

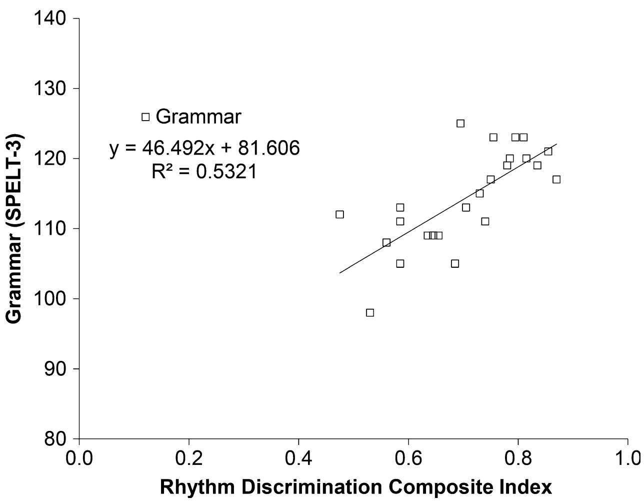

Figure 4 *Scatterplot showing the relationship between the Rhythm Discrimination Composite index and the grammar measure (SPELT-3).*

Additional analyses were conducted to determine whether the significant rhythm–grammar relations reported above were influenced by phonological awareness, in view of prior results showing an association between grammatical deficits and weaknesses in phonological awareness (Criddle & Durkin, 2001; Hulme & Snowling, 2009). To this end, correlations were re-tested between the SPELT-3 and each of the rhythm measures while co-varying CTOPP scores. Correlations were still significant when controlling for CTOPP between the SPELT-3 and BBA simple rhythms ($r(22) = .56$, $p = .005$), SPELT-3 and BBA complex rhythms ($r(22) = .58$, $p = .003$), SPELT-3 and PMMA ($r(22) = .52$, $p = .009$), and SPELT-3 and Rhythm Composite ($r(22) = .70$, $p < .001$). Thus, the relation between the rhythm perception measures and the use of morphemes in speech cannot be attributed to differences in phonological awareness skills.

Finally, boys and girls did not differ in either their Rhythm composite scores, $t(23) = 1.26$, $p = .22$, or morpho-syntactic ability, $t(23) = 1.06$, $p = .30$. However, to consider the possibility that correlations between rhythm and morpho-syntactic competence might possibly be driven by a sex difference, despite the lack of a overall difference between boys and girls on the rhythm and grammar measures, we ran separate correlations for boys and girls, and Rhythm Composite was found to be correlated reliably with SPELT-3 for both sexes while controlling IQ (girls, $r(9) = .77$, $p = .006$; boys, $r(10) = .66$, $p = .019$).

In sum, rhythm discrimination ability showed a strong positive relationship with grammar production independent of IQ, socioeconomic status, music experience, or phonological awareness. Combining the two rhythm measures into a composite rhythm index accounted for 48% ($r(20) =.70$, $p < .001$) of the variance in scores on the morpho-syntactic measure after partialling out the contributions of IQ, Parent Education, and Musical Experience. In contrast, only weak evidence was found for a relation between rhythm ability and phonological awareness. Although high scorers on the phonological awareness measure discriminated complex rhythms better than low scorers, this difference was non-significant when controlling for non-verbal IQ.

Discussion

The present study examined the relationship between rhythmic, syntactic and phonological abilities of 6-year-olds with typical language development. The results revealed a robust relation between rhythm discrimination and syntactic abilities. Both simple and complex rhythm discrimination on the BBA and scores on the PMMA were each reliably associated with morpho-syntactic competence. A composite score combining the BBA and PMMA measures accounted for 48% of the variance in grammar skill performance after controlling for non-verbal IQ, socioeconomic status and musical activities. With respect to phonological ability, we did not find consistent correlations between any of the rhythm measures and phonological awareness, and the variance in phonological awareness skills did not influence the relation between grammar and rhythm.

It is important to note that the grammar and rhythm tests in this experiment are very different in their task demands and stimuli. The grammar assessment (SPELT-3) is a speech production task in which children are asked to describe or answer questions about people in a series of photographs; it assesses competence in using morpho-syntactic structures. The two rhythm tests are perceptual tasks that require children to make same/different judgments about tone sequences that vary in rhythm, but are constant in pitch. Hence we have found evidence for an association between rhythm perception and grammar production that is not accounted for by individual differences in cognitive ability. Children who have stronger musical rhythm discrimination skills may also be more sensitive in general to speech rhythm variations that mark grammatical events, and thus have built up better morpho-syntactic competence during language development. This finding supports a domain-general role for basic rhythm perception in language acquisition (see Brandt, Gebrian & Slevc, 2012, for a discussion of the directionality of music–speech influence). The association between rhythm perception and grammar production could reflect the retrieval of morphemes and implementation of syntactic rules by brain circuitry shared by speech production and perception of timing (Kotz & Schwartze, 2010; Herdener, Humbel, Esposito, Habermeyer, Cattapan-Ludewig & Seifritz, 2014; Donnay, Rankin, Lopez-Gonzalez, Jiradejvong & Limb, 2014).

It is possible that the BBA complex rhythms and the phonological tasks from the CTOPP both engage higher-level auditory working memory mechanisms, associated with IQ. Moreover, previous results examining the relation between rhythm and phonological skills are mixed. For example, Anvari and colleagues (2002) observed an association between rhythm and phonological awareness in 4-year-olds but not 5-year-olds. One possible explanation for this developmental trend is that rhythm skills may be part of the auditory skillset that works to bootstrap early phonological acquisition in very young, but not older, children. This is consistent with our findings of only a weak relation between rhythm discrimination and phonological awareness in 6-year-olds, whose phonological development is already well under way.

The association observed between rhythm perception and morpho-syntactic production in typically developing 6-year-old children provides support for the hypothesized link between musical rhythm skills and syntactic processing. This coincides with data in adults showing that syntax can be modulated by temporally predictable input (Schmidt-Kassow & Kotz, 2008; Schmidt-Kassow & Kotz, 2009b). Interestingly, Przybylski, Bedoin, Krifi-Papoz, Herbillon, Roch, Leculier, Kotz and Tillmann (2013) tested the influence of the rhythmic regularity of musical primes and found that it facilitated detection of syntactic violations of target sentences in children with grammatical deficits, children with dyslexia, and typically developing controls. Taken together, these data provide both trait-like evidence (i.e. the present correlations between rhythm and grammar skills in American English-speaking children) and state-like evidence (rhythm modulates online syntactic processing in German and French) of a relation between rhythm and grammar. In addition, other studies of grammatical abilities in typically developing children that have not included a rhythm measure may therefore be missing an important source of variance.

In previous work, correlations between syntactic skills and rhythm were not explicitly examined in children with typical development; moreover, to our knowledge only one prior study has examined an association between syntactic and rhythm abilities in atypical development (Weinert, 1992). That study showed that 6-year-old German children with Specific Language Impairment (SLI, which is usually characterized by a grammatical deficit) were impaired in using prosodic cues to learn morpho-syntactic rules, and furthermore, this deficit co-varied with performance on a rhythmic discrimination task with musical stimuli. The subset of children that did well on the rhythm discrimination task was also better at grammar judgments and at reproducing prosody-rich sentences.

The present findings are in accordance with previous literature suggesting a key role of rhythm for the grammatical aspect of language development, in consideration of previously observed weaker performance on tasks that require tapping (Corriveau & Goswami, 2009), prosodic discrimination (Weinert, 1992; Wells & Peppé, 2003; Fisher *et al.*, 2007), and perception of rise time cues (Corriveau *et al.*, 2007) in children with SLI. Though the present study did not include a measure of speech rhythm, future studies on children both with typical and with atypical language development should incorporate prosody/speech rhythm (e.g. Domahs, Lohmann, Moritz & Kauschke, 2013) to examine its relationship to musical rhythm skills (Hausen *et al.*, 2013) and syntactic acquisition.

More broadly, the current results are consistent with the body of literature showing an overlap of neural resources for language and music processing (e.g. Patel, 2008), as well as a transfer from musical training to language skills (Patel, 2011; Kraus & Chandrasekaran, 2010; Besson, Chobert & Marie, 2011). We hypothesize that associations between timing and syntax arise from a shared subcortical network of brain areas including the basal ganglia (Kotz & Schwartze, 2010), which are likely affected in children with grammatical deficits (Ullman & Pierpont, 2005), and are crucial for timing and beat perception (Grahn & McAuley, 2009; Schwartze, Rothermich, Schmidt-Kassow & Kotz, 2011). The present study adds to this literature by demonstrating that individual differences in rhythm discrimination ability can account for substantial variance in grammar skills in children with typical language development. One mechanism that might explain the association between syntax and rhythm is suggested by the Dynamic Attending theory (Jones & Boltz, 1989; Large & Jones, 1999), which states that when a person listens to rhythmically organized stimuli, such as music, speech, or song (Gordon *et al.*, 2011), brain rhythms synchronize with auditory input and generate temporal expectancies for future events by directing attention to specific points in time. These rhythmic fluctuations in temporal attention may create scaffolding for the acquisition of important speech features such as morphemes. According to a related theory, the Temporal Sampling Framework (Goswami, 2011), phase-locking of neural oscillations at a hierarchy of different frequencies is responsible for encoding the speech signal, and a deficit in these mechanisms at the syllable level is hypothesized to play a causal role in both dyslexia and other related language impairments.

In conclusion, we have shown that individual differences in rhythm perception ability of typically developing 6-year-old children account for a significant portion of the variance in grammar skills. The finding of a robust association between rhythm perception and syntax supports a theoretical framework whereby rhythm serves to guide the temporal allocation of attention to speech in a manner that bolsters acquisition of language structure (Kotz & Schwartze, 2010). Further research is needed to determine the underlying brain bases of this relation between rhythm and grammar in both children with typical and those with atypical language development.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Data S1. Example of stimuli from the Simple rhythm condition on the Beat-Based Advantage assessment.

Data S2. Example of stimuli from the Complex rhythm condition on the Beat-Based Advantage assessment.

Data S3. Correlations tested between Music experience and language and rhythm measures.