

Rhythm and Syntax Processing in School-Age Children

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Scholars debate whether musical and linguistic abilities are associated or independent. In the present study, we examined whether musical rhythm skills predict receptive grammar proficiency in childhood. In Experiment 1, 7- to 17-year-old children ($N = 68$) were tested on their grammar and rhythm abilities. In the grammar-comprehension task, children heard short sentences with subject-relative (e.g., “Boys *that help girls* are nice”) or object-relative (e.g., “Boys *that girls help* are nice”) clauses, and determined the gender of the individual performing the action. In the rhythm-discrimination test, children heard two short rhythmic sequences on each trial and decided if they were the same or different. Children with better performance on the rhythm task exhibited higher scores on the grammar test, even after holding constant age, gender, music training, and maternal education. In Experiment 2, we replicated this finding with another group of same-age children ($N = 96$) while further controlling for working memory. Our data reveal, for the first time, an association between receptive grammar and rhythm perception in typically developing children. This finding is consistent with the view that music and language share neural resources for rule-based temporal processing.

Keywords: rhythm, syntax, music, language, children

Behavioral studies often report associations between music and speech. In childhood, music aptitude is correlated with phonological (Anvari, Trainor, Woodside, & Levy, 2002; Moritz, Yampolsky, Papadelis, Thomson, & Wolf, 2013) and pronunciation (Milovanov et al., 2009) skills. Although one study reported that pitch perception was correlated positively with phonological awareness (Anvari et al., 2002), musical rhythm skills (e.g., rhythm discrimination or reproduction) are more often predictive of speech perception (Carr, White-Schwoch, Tierney, Strait, & Kraus, 2014; Moritz et al., 2013; Ozernov-Palchik, Wolf, & Patel, 2018; Politimou, Dalla Bella, Farrugia, & Franco, 2019; Swaminathan & Schellenberg, 2017, 2019). For example, a recent study found that rhythm perception and production best accounted for phonological

awareness in 4-year-olds (Politimou et al., 2019). By contrast, impaired rhythm abilities are associated with deficits in phonological awareness. For example, children with SLI (specific language impairment) or developmental dyslexia exhibit poor performance on tasks that require them to detect rhythmic timing or amplitude rise—cues that are essential to speech perception (Corriveau, Pasquini, & Goswami, 2007; Corriveau & Goswami, 2009; Goswami, Gerson, & Astruc, 2010; Huss, Verney, Fosker, Mead, & Goswami, 2011).

In some instances, children assigned randomly to music lessons exhibit enhanced performance on auditory tasks that require discrimination and detection of subtle phonetic features in speech (Degé & Schwarzer, 2011; Flaunacco et al., 2015; François, Grau-Sánchez, Duarte, & Rodriguez-Fornells, 2015; Moreno et al., 2009). For example, children who received two years of music classes performed better on a test of speech-segmentation ability than other children who received two years of painting class (François, Chobert, Besson, & Schön, 2013). Similarly, children with dyslexia who received seven months of music training outperformed their counterparts who received painting training on phonemic blending (i.e., hearing /c/-/a/-/t/ and producing “cat”) or rhythm reproduction tasks (Flaunacco et al., 2015). These findings raise the possibility that music training causes improvements in speech processing, as some scholars have theorized (Kraus & Chandrasekaran, 2010; Patel, 2011). According to Patel (2011), the particular characteristics of the music-learning process are demanding but enjoyable, leading to enhanced listening skills that transfer to speech perception. The perspective of Kraus is similar but focused on encoding sound in the brainstem, which becomes more faithful and accurate with music training, such that it enhances the perception of speech (Kraus & Chandrasekaran, 2010).

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Although both scholars focus on transfer from music to speech, they also believe that enhanced speech perception has cascading effects that positively influence language use more broadly (e.g., reading).

Despite numerous reports of associations between music and speech perception (for review, see Schellenberg & Weiss, 2013), only recently have scholars turned their attention to plausible connections between musical ability and language skills beyond simple listening (or acoustic) processes in childhood (Gordon, Jacobs, Schuele, & McAuley, 2015; Gordon, Shivers, et al., 2015; Politimou et al., 2019). For example, Gordon, Shivers, et al. (2015) tested 6-year-old children and reported a positive association between rhythm-discrimination ability and expressive grammar (i.e., producing morpho-syntactically well-formed words/phrases). Notably, the association remained evident even after controlling for IQ, musical experiences, and socioeconomic status, which suggests that similar underlying mechanisms influence both rhythm and expressive grammar.

For adults, some evidence points to interactions between rhythm and syntactic processing when these processes operate in parallel during language comprehension. For example, words that unfold metrically over time (i.e., with a beat) facilitate comprehension of sentences that are syntactically complex or ambiguous (Roncaglia-Denissen, Schmidt-Kassow, & Kotz, 2013; Schmidt-Kassow & Kotz, 2008). By contrast, processing of word sequences with irregular rhythmic patterns is more effortful (Bohn, Knaus, Wiese, & Domahs, 2013). Priming with external rhythmic cues (e.g., march music) also leads to enhanced performance on tests of syntax (Bedoin, Brisseau, Molinier, Roch, & Tillmann, 2016; Canette et al., 2020; Chern, Tillmann, Vaughan, & Gordon, 2018; Kotz & Gunter, 2015; Przybylski et al., 2013).

In the present study, we tested school-age children. Our goal was to examine the possibility of a connection between proficiency on a task that measured receptive grammar, and the ability to perceive, remember, and discriminate musical rhythms. Basic syntactic abilities are acquired early in life (Corrêa, 1995; Kidd & Bavin, 2002; Labelle, 1990), such that older, school-age children tend to be fluent in commanding multiclausal sentences (Nippold, 2009). Nevertheless, syntactic skills continue to improve throughout the adolescent period (Frizelle, Thompson, McDonald, & Bishop, 2018; Hartshorne, Tenenbaum, & Pinker, 2018; Loban, 1976). Notably, in a recent study based on a large amount of data ($N > 600,000$), Hartshorne et al. (2018) estimated that grammar-learning abilities improved until approximately 17 years of age. Although syntactic competency is thought to remain stable throughout adulthood (Chomsky, 2014; Herschensohn, 2009; Nowak, Komarova, & Niyogi, 2001), there are individual differences in syntactic ability among adults (Dąbrowska, 2012a, 2012b, 2018, 2019; Dąbrowska & Street, 2006). In a recent study, Dąbrowska (2018) demonstrated that grammar competency among adults depended on differences in IQ, education, and exposure to print. There are similarly marked individual differences in children's syntactic ability (Nippold, 2009; Nippold, Mansfield, & Billow, 2007; Spencer, Clegg, & Stackhouse, 2012). In the present study, we held constant extraneous individual differences (i.e., confounding variables) to ensure that any observed associations between rhythm and grammar were not artifacts. We hypothesized that this association would emerge because central auditory pro-

cessing is required for rapid and efficient temporal analysis of musical and linguistic structures.

To test this hypothesis, we administered short tests of rhythm and grammar, which were tailored for testing outside of the laboratory (i.e., in a children's museum). In the rhythm test, children compared pairs of rhythm sequences that required same/different judgments. In the grammar test, children were asked to indicate the gender of a noun that was linked to an "action" verb in a sentence with either a subject- or object-relative embedded clause. For example, consider the following two sentences, which comprise the same six words:

"Kings that help queens are nice"

"Kings that queens help are nice"

Whereas the first sentence has an embedded clause that relates to the subject of the action, the second sentence has an embedded clause that relates to the object of the action (*Kings* in both instances). Such object-relative (OR) clauses are syntactically more complex than subject-relative (SR) clauses, a consequence of the order (or temporal) rearrangement of the same words presented serially. Half of these SR and OR sentences were further manipulated in acoustic clarity by applying a vocoding-filter (Experiment 1) or by adding multitalker babble (Experiment 2). The clarity manipulation would allow us to explore a potential interaction between sensory (acoustic) and linguistic (syntactic) challenges (Wingfield, McCoy, Peelle, Tun, & Cox, 2006). Although all of the degraded sentences were intelligible, such acoustic manipulations could still render difficulty in syntactic access.

Experiment 1

The study protocol used here and in Experiment 2 was approved by the Institutional Review Board at the Ohio State University (IRB #: 2012B0213; Language studies in the labs in Life POD at the Center of Science and Industry).

Method

A priori power analysis conducted with G*Power 3.1 (Faul, Erdfelder, Buchner, & Lang, 2009) indicated that a sample of 63 participants was required to reach 85% certainty of detecting a medium-sized association ($f^2 \geq .15$; Cohen, 1988) between rhythm and grammar with six other variables held constant, $\alpha = .05$. Our goal was to ensure that the sample was at least this large, and our arrangement with the museum did not allow for turning away children after this goal was reached.

Participants. Ninety-eight native English-speaking children, with reported normal speech, language, and hearing, were recruited from the visitor population at a local museum. Only five children were bilingual, and one was trilingual. The children ranged in age from 7 to 17 years, which ensured marked individual differences in grammar and rhythm skills. Parental consent and child assent were obtained prior to the beginning of the experiment. Some children ($N = 26$) were subsequently excluded from the sample for significantly below-chance (i.e., worse than guessing) levels of performance on the grammar test (i.e., in any of 4 conditions), which likely arose due to misunderstanding directions or swapping button responses. Another three children did not want

to complete the task, and one child was excluded for concurrently receiving speech therapy. Thus, the final sample comprised 68 children (35 girls), whose mean age was 11.3 years ($SD = 2.7$).

We also measured demographic variables, including age, gender, music training, and maternal education (as a proxy for socioeconomic status, or SES). Because these demographic variables are known to be associated with children's language skills (Barbu et al., 2015; Hoff, 2003; Tabri, Chacra, & Pring, 2011), they served as covariates when we examined whether musical-rhythm sensitivity predicts receptive-grammar proficiency. Duration of music training was calculated as the square root of total period of training (i.e., total years), which was summed for children who had learned more than one musical instrument, as in previous research (e.g., Swaminathan & Schellenberg, 2017). Lastly, maternal education was measured on a 5-point scale (1 = high school diploma or less, 2 = associate's degree, 3 = bachelor's degree, 4 = master's degree, and 5 = doctorate).

Stimuli. In the grammar test, stimuli comprised sentences uttered by a native American-English speaking female. Ten "base" sentences varied in syntax and acoustic clarity (Figure 1A). For the syntactic manipulation, each of the sentences was center-embedded with an SR clause or an OR clause. Sentences with SR and OR clauses consisted of identical words, the only difference being the position of two words in each sentence. Each sentence also contained a male and a female noun, but only one of them performed the action of the sentence (e.g., "hug," Figure 1A). The gender of the characters was counterbalanced, as was the presence of SR and OR clauses. For the acoustic manipulation, sentences

were processed by a 15-channel vocoder that reduced spectral details, hampering acoustic clarity. Although sound quality was substantially degraded, sentences were still intelligible, as would be expected (Eisenberg, Shannon, Martinez, Wygonski, & Boothroyd, 2000; Fishman, Shannon, & Slattery, 1997; Lee, Min, Wingfield, Grossman, & Peelle, 2016). The stimuli comprised 40 sentences in total, 10 in each of four conditions: SR and OR in clear and vocoded formats. A second set of 40 sentences was created to counterbalance gender fully with the syntactic and acoustic manipulations. The two sets were alternated from one child to the next. The sentence stimuli were equalized in mean RMS (root-mean-square) intensity.

In the rhythm test, 20 rhythm sequences were chosen from Grahn and Brett (2009), with the original pure tones (sine waves) replaced by woodblock sounds. The new rhythm stimuli (.wav files; 44.100 kHz; stereo) were obtained from the instrument source in Ableton Live music production software (www.ableton.com). Sound intensity was equalized based upon mean RMS. Half of the rhythms consisted of seven sounds; the other half had eight (Figure 1B). All sequences were structured so that the woodblock sounds' onsets were aligned with four beats (i.e., not syncopated), in order to provide a strong sense of meter. The standard and comparison rhythms varied on "different" trials, but even then they had the same number of woodblock sounds.

Procedure. All children were administered the grammar and rhythm tests, which were programmed on Open Sesame 3.1.6 and run on desktop computers (Dell OptiPlex 7040). Both tests took approximately 10 min. Sound stimuli were presented binaurally through Bose Quiet Comfort 15 Acoustic Noise Canceling headphones. A parent completed a background questionnaire regarding the child's age, gender, language/music background, maternal education, and any history of speech or language deficits and/or therapy. The grammar test was always administered before the rhythm test to avoid the potential influence of musical-rhythm activity on subsequent grammar performance. For both tasks, accuracy and response times (RTs) were recorded.

Children were first familiarized with the grammar task by undergoing 14 practice trials. On each trial, they were instructed to indicate the gender of the actor by pressing either the "male" (left arrow) or "female" (right arrow) key as quickly and accurately as possible (Figure 1A). During sentence presentation, children were instructed to view the fixation cross on the monitor (Dell Professional P2417H 23.8" Screen LED-Lit) located approximately 50 cm in front of the child, and to hover their right-hand fingers over the left and right arrows on the keyboard. During practice, there was no restriction on response time, and children received feedback after each response. During the actual test session that followed, children were encouraged to respond within 3 s and instructed to proceed to the next trial if no response was made during this window. No feedback was given, but noncontingent verbal encouragement was provided.

After a short break, children took the rhythm test (Figure 1C), which had 20 trials. On each trial, children heard a pair of rhythm sequences (Grahn & Brett, 2009) presented concurrently with visual images of cartoon characters adapted from Gordon, Shivers, et al. (2015). Five practice trials with feedback were administered first to familiarize children with the test. On each trial, children heard a rhythmic "standard" sequence while viewing a single cartoon character playing drums. After a short delay (1500 ms, a

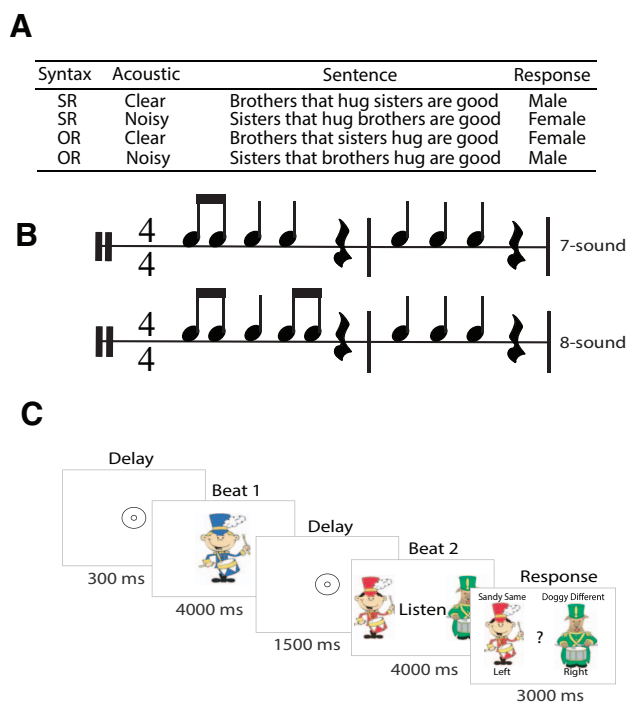


Figure 1. (A) Examples of sentence conditions from the grammar test. (B) Examples of a 7-sound and 8-sound rhythm in the rhythm test. (C) Schematic illustration of the rhythm test. See the online article for the color version of this figure.

comparison rhythm sequence was presented with side-by-side pictures of two cartoon characters, one being the same as the character who had just appeared, the other being new. In other words, the cartoon characters provided a visual analogue for children's "same" or "different" responses. During familiarization, there was no restriction on response time, and feedback was given following each response. For the test session, children were encouraged to answer within 3 s and no feedback was provided except for noncontingent verbal encouragement. Trials were fully randomized across participants.

Results and Discussion

Scores measuring performance accuracy on the grammar and rhythm tasks were converted to d' scores for statistical analyses. Because perfect performance leads to an indeterminate d' , hit and false-alarm rates were modified slightly by adding 0.5 to the numerator and 1.0 to the denominator. This transformation has no effect on the rank order of scores (Thorpe, Trehub, Morrongiello, & Bull, 1988).

Figures 2A and 2B illustrate descriptive statistics for the grammar task, separately for accuracy and RTs. Mean levels of performance accuracy were significantly above chance levels ($d' = 0$) in each of the four conditions (Bonferroni-Holm corrected for four tests), $ps < .05$. A two-way analysis of variance (ANOVA) was used to analyze effects of syntax (SR or OR) and acoustic clarity (clear or vocoded) as repeated measures. For accuracy, a main effect of syntax, $F(1, 67) = 132.11$, $p < .001$, $\eta_p^2 = .664$,

confirmed that children were more accurate with SR than OR sentences. Similarly, a main effect of acoustic clarity, $F(1, 67) = 13.02$, $p = .001$, $\eta_p^2 = .163$, indicated higher accuracy for clear than for vocoded speech. There was no two-way interaction, $F < 1$. For RTs, there was a main effect of syntax, $F(1, 67) = 50.21$, $p < .001$, $\eta_p^2 = .428$, with performance on SR trials being faster than it was on OR trials. There was no main effect of acoustic clarity and no two-way interaction, $ps > .1$. Further analyses were restricted to performance accuracy.

Figures 2C and 2D illustrate descriptive statistics for the rhythm test. Accuracy was similar for sequences that had seven- or eight-sound rhythm, $p > .1$, correlated across conditions, $r = .464$, $N = 68$, $p < .001$, and substantially better than chance in both conditions, $ps < .001$. Similarly, RTs did not differ reliably across conditions, $p > .1$, but they were correlated across conditions, $r = .377$, $N = 68$, $p = .002$. Further analyses considered performance accuracy collapsed across the two conditions.

A linear mixed-effects regression (using the LMER framework via lme4 package in R, Version 3.4) was used to predict d' scores in the four sentence conditions as a function of performance accuracy (d') on the rhythm test. Covariates (fixed effects) included syntax (SR/OR), clarity (clear/vocoded), age ($M = 11.13$ years, $SD = 2.7$), duration of music training ($M = 1.9$ years, $SD = 2.8$), maternal education ($M = 2.7$, $SD = 1.0$), and gender (Male/Female). Intercepts for subjects were included as random effects. Syntax and clarity were included as random slopes. The results revealed that age was the most significant predictor of grammatical ability, as one would expect, with rhythm being the second-best predictor, in line with the expected pattern of higher levels predicting better grammar performance (see Table 1).

In sum, as children improved on the rhythm task, they also improved on the grammar task. Although this finding was evident when maternal education, age, duration of music training, and gender were held constant, one potentially important though missing covariate was a measure of short-term or working memory. In Experiment 2, we attempted to replicate and extend the findings of Experiment 1 by adding a brief test of working memory.

Experiment 2

Time constraints of testing in a museum setting precluded the possibility of administering a comprehensive measure of general cognitive ability, such as IQ. We therefore opted to measure one aspect of general cognition that might best account for performance on the grammar and rhythm tests: auditory working memory. On same-different tasks of musical ability, performance tends to be associated with scores on nonmusical tests of auditory memory (Hausen, Torppa, Salmela, Vainio, & Särkämö, 2013).

Method

Our inclusion of a measure of working memory as a covariate could decrease the size of the partial association between rhythm and grammar. Thus, we used G*Power 3.1 (Faul et al., 2009) to determine that a sample of 92 participants was required to be 85% certain of detecting a small- to medium-sized association ($f^2 \geq .10$, Cohen, 1988), with seven other variables held constant, $\alpha = .05$.

Participants. Children were recruited as in Experiment 1. Although we tested 136 children, 40 were excluded for the fol-

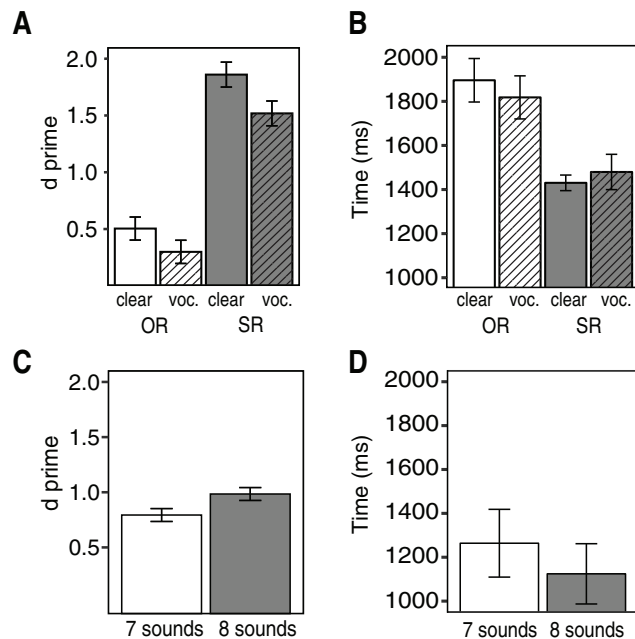


Figure 2. Descriptive statistics for Experiment 1: (A) Mean d' in the four conditions of the grammar test (voc. = vocoded; OR = object-relative; SR = subject-relative); (B) Mean response times in the four conditions of the grammar test; (C) Mean d' in the two conditions of the rhythm test; (D) Mean response times in the two conditions of the rhythm test. Error bars are standard errors calculated using method from Loftus and Masson (1994).

Table 1
Results From the Linear Mixed-Effects Model Predicting Performance on the Grammar Test in Experiment 1

Variable	Estimate	Std. Error	<i>t</i> score	<i>p</i> value
Syntax (SR)	1.287	0.111	11.580	<.001
Acoustic clarity (voc.)	-0.273	0.077	-3.530	<.001
Age	0.147	0.03	4.987	<.001
Gender (M)	0.052	0.154	0.337	.737
Maternal education	0.102	0.083	1.231	.222
Music training	0.047	0.035	1.357	.179
Rhythm discrimination	0.272	0.097	2.793	.007

Note. SR = subject-relative; voc. = vocoded; M = male.

lowing reasons: 32 performed significantly below chance levels in at least one condition of the grammar test, 4 did not complete the task, and 4 had speech problems or language delays. Thus, the final sample comprised 96 children (56 females), whose mean age was 11.1 years ($SD = 2.7$). Only two children were bilingual. Two of the 96 caregivers did not provide information about maternal education. These missing values were replaced by the mean.

Stimuli and measures. The stimuli were the same as in Experiment 1 with one exception. For the grammar test, instead of degrading the speech signal itself (via vocoding), the original sentences were presented in a background of multitalker babble that consisted of three male and three female talkers (adapted from Sperry, Wiley, & Chial, 1997). MATLAB code was used to combine the babble with each sentence at a signal-to-noise ratio (SNR) of 2 dB. In pilot testing, this SNR manipulation rendered a degree of difficulty comparable to the vocoding manipulation of Experiment 1. An additional buffer of 0.5 s babble was included before and after each sentence. The intensity (mean RMS) of all stimuli was equated.

For our test of auditory working memory, we adapted Sternberg's (1966) paradigm. On each trial, a group of three or four novel synthetic sounds was presented followed by a probe sound. Participants indicated whether the probe sound was old (i.e., presented in the group) or new. An example is provided at the following link: <https://www.youtube.com/watch?v=9TwDVn5n8Zw>.

Results and Discussion

As in Experiment 1, performance accuracy was indexed with d' scores, including performance on the test of working memory. Figures 3A and 3B show descriptive statistics across the four different conditions of the grammar test. As in Experiment 1, performance was above chance levels in all four conditions, $ps < .005$. A two-way ANOVA revealed a main effect of syntax, $F(1, 95) = 102.85, p < .001, \eta_p^2 = .520$, with higher accuracy for SR than for OR sentences. Neither acoustic clarity, $F < 1$, nor the interaction between syntax and clarity, $p > .1$, was significant. For the ANOVA on RTs, there was again a main effect of syntax, $F(1, 95) = 69.25, p < .001, \eta_p^2 = .422$, with faster RTs for SR than for OR sentences, as well as a main effect of clarity, $F(1, 95) = 11.88, p = .001, \eta_p^2 = .111$, with faster RTs for sentences presented in quiet than in babble. There was no interaction between syntax and clarity, $F < 1$. In other words, background babble slowed down responding, but it did not make the children less accurate.

Figures 3C and 3D provide descriptive statistics for performance on the rhythm test. For accuracy, performance was much higher than chance levels in both conditions, $ps < .001$. Performance was correlated across the two conditions, $r = .263, N = 96, p = .010$, but better for 8-sound than for 7-sound rhythms, $t(95) = 3.50, p = .001, \eta_p^2 = .114$. RTs were also faster for 8-sound rhythms, $t(95) = 3.51, p = .001, \eta_p^2 = .115$, which were nevertheless correlated with 7-sound rhythms, $r = .394, N = 96, p < .001$.

For the test of auditory working memory, the children responded correctly on an average of 75.4% ($SD = 14.0$) of the trials, such that the mean d' score was substantially better than chance, $p < .001$. Scores were correlated with mean performance on the grammar test, $r = .296, N = 96, p = .003$, but not with performance on the rhythm test, $p > .4$. When age was held constant, the association between working memory and grammar disappeared, $p > .4$.

As in Experiment 1, the linear mixed-effects regression was conducted to predict d' in the four sentence conditions as a function of accuracy (d') on the rhythm test. Other variables for fixed effects were syntax (SR/OR), clarity (clear/vocoded), age, rhythm, auditory working memory ($M = 1.38, SD = 0.38$), duration of music training ($M = 1.2$ years, $SD = 2.1$), maternal education ($M = 2.7, SD = 1.1$), and gender (Male/Female). Intercepts for subjects were included as random effects, as were the slopes of the syntax and clarity manipulations. Results are summarized in Table 2. After controlling for all other variables, performance on the grammar test improved dramatically with age, and significantly with rhythm scores. In short, the findings repli-

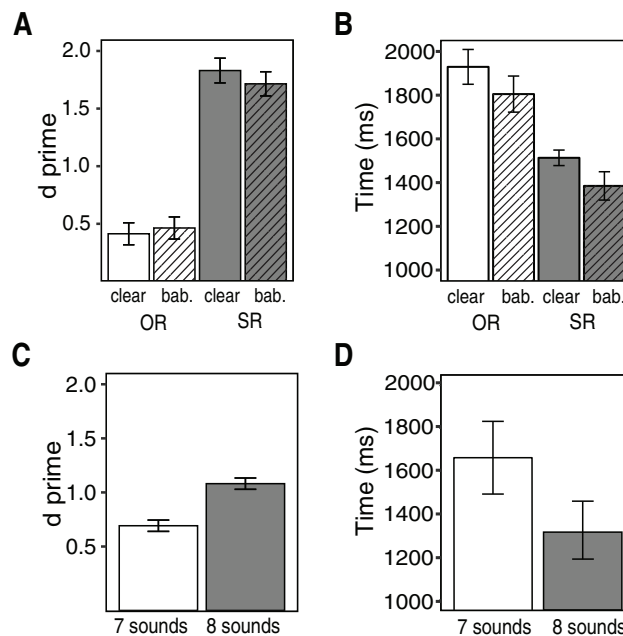


Figure 3. Descriptive statistics for Experiment 2: (A) Mean d' in the four conditions of the grammar test (bab. = babble; OR = object-relative; SR = subject-relative); (B) Mean response times in the four conditions of the grammar test; (C) Mean d' in the two conditions of the rhythm test; (D) Mean response times in the two conditions of the rhythm test. Error bars are standard errors calculated using method from Loftus and Masson (1994).

Table 2
Results From the Linear Mixed-Effects Model Predicting Performance on the Grammar Test in Experiment 2

Variable	Estimate	Std. Error	<i>t</i> score	<i>p</i> value
Syntax (SR)	1.334	0.131	10.195	<.001
Acoustic clarity (babble)	-0.033	0.066	-0.495	.622
Age	0.162	0.027	5.978	<.001
Gender (M)	0.145	0.136	1.065	.737
Maternal education	-0.011	0.061	-0.182	.856
Music training	-0.026	0.033	-0.782	.436
Rhythm discrimination	0.211	0.097	2.168	.033
Working memory	0.039	0.086	0.450	.654

Note. SR = subject-relative; M = male.

cated the association between rhythm and grammar found in Experiment 1, but with auditory working memory held constant as well.

In a final analysis, we collapsed the data sets from Experiments 1 and 2 in order to look at developmental trends more closely. Of particular interest was whether the association between rhythm and grammar would become weaker or stronger with age. We used multiple regression to predict performance on the grammar task (aggregated across the four conditions) as a function of age, rhythm, and the interaction between age and rhythm (variables centered). Additional control variables included gender (dummy coded), maternal education, music training, and a dummy variable that accounted for differences between the two experiments. The model explained 40.3% of the variance in grammar performance, $R = .637$, $F(7, 156) = 15.05$, $p < .001$ (adjusted $R^2 = .376$). Significant contributions were made by age, $\beta = .532$, $t(156) = 8.24$, $p < .001$, rhythm, $\beta = .239$, $t(156) = 3.62$, $p < .001$, and the interaction between age and rhythm, $\beta = .148$, $t(156) = 2.35$, $p = .020$. All control variables were nonsignificant, $ps > .1$. In short, performance on the grammar task was better among older children and among children with better performance on the rhythm task. The positive slope for the interaction term indicated that the association between rhythm and grammar became stronger as age increased.

To test for possible interactions between age and variance in performance due to the syntactic manipulation, we correlated age with the difference between performance in the subject- and object-relative conditions. The association was negative but very weak, $r = -.143$, $N = 164$, $p = .034$ (one-tailed; a positive association would be uninterpretable). In other words, we found weak evidence that the performance advantage for subject- over object-relative sentences decreased as children became older and more masterful with English grammar.

General Discussion

In two experiments, we explored the possibility of an association between musical rhythm skills and receptive grammar in school-age children. In Experiment 1, rhythm discrimination predicted the comprehension of syntactically complex sentences (i.e., with embedded clauses), and this positive association remained significant after accounting for individual differences in age, gender, music experience, and maternal education. This finding was replicated in Experiment 2 while further

controlling for individual differences in working memory. After collapsing both data sets, we found that the rhythm–grammar link became stronger as children grew older. These data further corroborate the association between rhythm and grammar in typically developing children, and provide support for the prevailing notion that shared neural resources are involved in some aspects of music and language processing (Heard & Lee, 2020).

Despite ample documentation of a positive association between musical expertise and speech perception (see Schellenberg & Weiss, 2013, for review), it is less common to find links between music and higher-order language processes, such as grammar or reading. In one previous study, cited earlier, the 6-year-olds' rhythm discrimination ability predicted their use of expressive syntax (Gordon, Shivers, et al., 2015). Our results extend this finding by documenting an association between rhythm abilities and receptive grammar among children who varied substantially in age. In both studies, there was no association between music training and grammar proficiency when rhythm abilities were held constant, which raises the possibility that the link may be mediated by preexisting neural traits. This interpretation is inconsistent with proposals that music training benefits speech and language skills (Kraus & Chandrasekaran, 2010; Patel, 2011), but consistent with other studies that failed to find a positive influence of music training on speech perception (Boebinger et al., 2015; Ruggles, Freyman, & Oxenham, 2014; Swaminathan & Schellenberg, 2017, 2019) and reading comprehension (Swaminathan & Schellenberg, 2019; Swaminathan, Schellenberg, & Venkatesan, 2018). One possibility is that the discrepancy may be due to the differences in the way that music training was measured, although Swaminathan and her colleagues reported the same finding when they coded music training in four different ways (Swaminathan & Schellenberg, 2017, 2019; Swaminathan et al., 2018). Indeed, links between music training and language abilities may be epiphenomenal (Schellenberg, 2015), such that they disappear when individual differences in musical aptitude or general cognitive ability are held constant.

Although our findings are consistent with those of Gordon, Shivers, et al. (2015), there are notable differences between the two studies. The earlier study measured the use of morpho-syntactic operations in expressive grammar, whereas we used a receptive grammar test that required listeners to cope rapidly with syntactic complexities while listening to a series of short sentences. Although SR and OR sentences involved temporal interruption due to the center-embedded clause, OR sentences were more challenging than SR sentences due to the noncanonical ordering of the words, as evidenced by less accurate and slower performance. Although most children use sentences with relative clauses well before they enter school (Brown, 1971; Corrêa, 1995; de Villiers, Tager Flusberg, Hakuta, & Cohen, 1979; Kidd & Bavin, 2002; Labelle, 1990; Sheldon, 1976, 1977), our data confirm that full mastery of these types of sentences develops throughout the school-age period. With such large developmental differences between 7 and 17 years of age, however, it would be ideal to replicate the present results with even larger samples of children. Nevertheless, our findings are in line with those from a large and multinational online sample, which documented that grammar development continued throughout

most of adolescence, plateauing at approximately 17 years of age (Hartshorne et al., 2018).

In a recent study of 6- to 9-year-old children (Swaminathan & Schellenberg, 2019), performance on a test of receptive grammar was correlated positively with performance on a test of rhythm discrimination, a finding that corroborates the present results. Moreover, as in the present study, the association remained evident after holding constant SES and general cognitive ability. Claims of a special link between rhythm and grammar require evidence of discriminant validity, however, which their data only partly supported. On the one hand, rhythm discrimination was better than melody discrimination at predicting receptive grammar and speech perception. On the other hand, scores on a test of memory for music matched rhythm abilities in predictive power. These results raise the possibility that the “special” status of rhythm in predicting language abilities may emerge primarily when it is compared directly with melody perception, a result that is now common in studies of adults (Bhatara, Yeung, & Nazzi, 2015; Hausen et al., 2013; Swaminathan & Schellenberg, 2017). Among children, however, things may be less clear-cut. Indeed, studies of very young children have reported that melody is better than rhythm at predicting grammar (Politimou et al., 2019), and that training in melody is superior to training in rhythm at improving phonological awareness (Patscheke, Degé, & Schwarzer, 2019). In short, a complete developmental account of associations between music and language will require researchers to include multiple measures in both domains.

One particularly positive aspect of the present study was its relatively large samples of children compared to previous research. In the study by Gordon, Jacobs, et al. (2015), only 25 children were tested, whereas we had a total of 164 children across two experiments. A notable limitation of the present study was that we did not include full-scale IQ to measure general cognitive ability, due to the time constraint imposed by testing in the museum (i.e., < 25–30 min). Rather, in Experiment 2, we administered a brief test of auditory working memory. Another potential limitation was that the experiment was conducted in an open laboratory space where other experiments were sometimes conducted simultaneously. Although our auditory stimuli were delivered via noise-canceling headphones, the children may still have been distracted periodically in the open environment. Such distraction may have led to a higher exclusion rate than anticipated due to misunderstanding of the task, and/or loss of interest in both auditory experiments. In any event, the cross-experiment replication and large samples provide clear evidence of a link between rhythm and receptive grammar among school-age children, thereby extending evidence of a link with expressive grammar in 6-year-olds (Gordon, Shivers, et al., 2015).

In addition to varying the degree of syntactic complexity, we varied the acoustic clarity of the speech stimuli using two strategies. In Experiment 1, we removed some of the spectral details using a 15-channel vocoder, whereas in Experiment 2, we added multitalker babble as background noise to mask the speech energetically. The vocoded speech was challenging for our child listeners, who were less accurate with vocoded than with clear speech. By contrast, the multitalker babble had no effect on accuracy, but it led to slower responding. Although we attempted to equate the perceptual difficulty between the two

types of manipulation, we failed to do so in the sense that they had differential effects on accuracy, but succeeded in the sense that both manipulations affected the processing time required to complete the task. As noted in the introduction, our rationale for including acoustic clarity in the stimuli design was to explore children’s language comprehension when both syntactic complexity and acoustic clarity varied simultaneously. Indeed, noise is detrimental to the comprehension of syntactically complex sentences, such as those with object-relative clauses for older adults (Wingfield et al., 2006). For our children, vocoded object-relative sentences were the most difficult to comprehend in Experiment 1, but the effects of syntax and clarity were additive rather than interactive.

Tierney and Kraus (2015) suggest that different tests of rhythm involve different aspects of cognitive and sensory processes (e.g., working memory, sensory-motor integration, etc.). The rhythm-discrimination test that we used allowed us to measure children’s auditory sensitivity to moment-by-moment temporal dynamics in musical sequences. Why would such sensitivity predict children’s ability to comprehend syntactically and sequentially complex sentences? One likely possibility is that the neural mechanism responsible for analyzing temporal structures extends to both musical and linguistic events. That is, certain aspects of music and language processes, such as the rhythm and syntactic tasks explored here, are mediated by common temporal-processing mechanisms.

Emerging evidence demonstrates that temporal structures of sentences affect syntactic analysis. As noted, individuals perform better on a syntactic task when constituent words of a sentence are presented metrically with a regular beat (Roncaglia-Denissen et al., 2013). They also display a concomitantly reduced P600 EEG amplitude, a hallmark of syntactic processing in response to metrical sentences, which suggests that the established meter made syntactic processing less effortful. Syntactic processing is also influenced by external rhythms that are independent of the intrinsic temporal structure of given sentences. Specifically, Przybylski et al. (2013) demonstrated that children are better at detecting morphosyntactic violations after listening to 32 s of rhythmically regular rather than irregular musical sequences. This finding was subsequently extended to a design that compared priming with regular beats to arrhythmic environmental sounds (Bedoin et al., 2016). Evidence of discriminant validity comes from results showing that regular-beat priming improves grammar performance but not mathematical ability (Chern et al., 2018).

According to dynamic attending theory (Jones, 1976; Jones & Boltz, 1989), neural oscillations for syntactic operations become more efficient when a regular rhythm serves as a prime. The observed phenomena could nonetheless be independent of attentional modulation; rather, temporal processing could be enhanced via the sensorimotor network. Future research is warranted to elucidate further the detailed neurofunctional and neuroanatomical mechanisms that explain the link between rhythm and grammar. In any case, our data provide behavioral support for the prevailing notion that similar or identical neural mechanisms are used for rule-based temporal processing in language and music (Heard & Lee, 2020).

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