Rhythm and Syntax Processing in School-Age Children

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We thank Jessica Grahn and Reyna Gordon for sharing materials for the rhythm test. We also thank Ian Goldthwaite, Allison Byrer, Kate Corbeil, Katherine Miller, Korrin Perry, and Aiesha Polakampalli, Christina Roup, Laura Wagner, Cynthia Clopper, Kathryn Campbell-Kibler for their supports. Special thanks to the parents and children who participated in our study.

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** Data are available upon request

Research Highlights

• School-age children's receptive grammar was predicted by their ability to perceive and remember rhythmic sequences, even when individual differences in demographic background, music training, and working memory were held constant.

• The rhythm-grammar association was replicated across two experiments with large samples (*N*s = 68 and 96).

• Despite large differences in music and language proficiency, younger *and* older children exhibited the association between rhythm and grammar.

• The connection between rhythm and grammar became stronger with age.

Abstract

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, 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, grammar, music, language, children

Rhythm and Syntax Processing in School-Age Children

Behavioral studies often report associations between music and speech. In childhood, music aptitude is correlated with phonological (Anvari et al., 2002; Moritz et al., 2013) and pronunciation (Milovanov et al., 2009) skills. Although one study reported that pitch perception is correlated positively with phonological awareness (Anvari et al., 2002), musical *rhythm* skills (e.g., rhythm discrimination or reproduction) are more often predictive of better speech perception (Carr et al., 2014; Moritz et al., 2013; Ozernov-Palchik et al., 2018; Politimou et al., 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 et al., 2007; Corriveau & Goswami, 2009; Goswami et al., 2010; Huss et al., 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; Flaugnacco et al., 2015; François et al., 2015; Moreno et al., 2009). For example, children who received 2 years of music class better performed on speech-segmentation ability than other children who received 2 years of painting class (François et al., 2013). Similarly, children with dyslexia who received 7 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 (Flaugnacco 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). Although both scholars focus on transfer from music to *speech*, they 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, et al., 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 et al., 2013; Schmidt-Kassow & Kotz, 2008). By contrast, processing of word sequences with irregular rhythmic patterns is more effortful (Bohn et al., 2013). Priming with external rhythmic cues (e.g., march music) also leads to enhanced performance on tests of syntax (Bedoin et al., 2016; Canette et al., 2019; Chern et al., 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 multi-clausal sentences (Nippold, 2009). Nevertheless, syntactic skills continue to improve throughout the adolescent period (Frizelle et al., 2018; Hartshorne et al., 2018; Loban, 1976). Notably, in a recent estimation on a large amount of data ($N > 600{,}000$), Hartshorne et al. (2018) demonstrated 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 et al., 2001), there are individual differences in syntactic ability among adults (Dąbrowska, 2012b, 2012a, 2018, 2019; Dąbrowska & Street, 2006). In a recent study, Dabrowska (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, 2007,2009, Spencer et al., 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 processing 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 stimulus sentences were further manipulated in acoustic clarity by applying a vocoding-filter (Experiment 1) or by adding multi-talker babble (Experiment 2). The clarity manipulation would allow us to explore a potential interaction between sensory (acoustic) and linguistic (syntactic) challenges (Wingfield et al., 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 et al., 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 five 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 et al., 2010), 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 five-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 a subject-relative (SR) clause or object-relative (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 et al., 2000; Fishman Kim E. et al., 1997; Lee et al., 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 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 et al., 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), *p*s < .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, $F(1, 67) = 132.11$, $p < .001$, $\eta^2_p = .664$, confirmed that children were more accurate with SR than OR sentences. Similarly, a main effect of acoustic clarity, $F(1, 67) = 13.02$, $p = .001$, $\eta^2_p = .163$, 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, $F(1, 67) = 50.21$, $p < 0.001$, $\eta^2_p = .428$, 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, *p*s > .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, *p*s < .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 multi-level mixed-effects model (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 (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, 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 (Hansen et al., 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 six other variables held constant, alpha = .05.

Participants. Children were recruited as in Experiment 1. Although we tested 136 children, 40 were excluded for the following 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 multi-talker babble that consisted of three male and three female talkers (adapted from Sperry et al., 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, $F(1, 95) = 102.85$, $p < 0.001$, $\eta^2_p = .520$, 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, $F(1, 95) = 69.25$, $p < 0.001$, $\eta^2_p = .422$, with faster RTs for SR than for OR sentences, as well as a main effect of clarity, $F(1, 95) = 11.88$, $p = .001$, $\eta^2_p = .111$, 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, *p*s < .001. Performance was correlated across the two conditions, $r = .263$, $N = 96$, $p = .010$, but better for the 8-sound than for the 7-sound rhythms, $t(95) = 3.50$, $p = .001$, $\eta^2_p = .114$. RTs were also faster for 8-sound rhythms, $t(95) = 3.51$, $p = .001$, $\eta^2_p = .115$, 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 (LME) 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 replicated 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, *p*s > .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 (Schellenberg and 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 pre-existing 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 an positive influence of music training on speech perception (Boebinger et al., 2015; Ruggles et al., 2014; Swaminathan & Schellenberg, 2017, 2019) and reading comprehension (Swaminathan et al., 2018; Swaminathan & Schellenberg, 2019). 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 et al., 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 on-line 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 et al., 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 et al., 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 multi-talker 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 multi-talker 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 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 were simultaneously varied. 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).

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*(2), 111–130. https://doi.org/10.1016/S0022-0965(02)00124-8

Barbu, S., Nardy, A., Chevrot, J.-P., Guellaï, B., Glas, L., Juhel, J., & Lemasson, A. (2015). Sex Differences in Language Across Early Childhood: Family Socioeconomic Status does not Impact Boys and Girls Equally. *Frontiers in Psychology*, *6*. https://doi.org/10.3389/fpsyg.2015.01874

Bedoin, N., Brisseau, L., Molinier, P., Roch, D., & Tillmann, B. (2016). Temporally Regular Musical Primes Facilitate Subsequent Syntax Processing in Children with Specific Language Impairment. *Frontiers in Neuroscience*, *10*. https://doi.org/10.3389/fnins.2016.00245

Bhatara, A., Yeung, H. H., & Nazzi, T. (2015). Foreign language learning in French speakers is associated with rhythm perception, but not with melody perception. *Journal of Experimental Psychology. Human Perception and Performance*, *41*(2), 277–282. https://doi.org/10.1037/a0038736

Boebinger, D., Evans, S., Rosen, S., Lima, C. F., Manly, T., & Scott, S. K. (2015). Musicians and non-musicians are equally adept at perceiving masked speech. *The Journal of the Acoustical Society of America*, *137*(1), 378–387. https://doi.org/10.1121/1.4904537

Bohn, K., Knaus, J., Wiese, R., & Domahs, U. (2013). The influence of rhythmic (ir)regularities on speech processing: Evidence from an ERP study on German phrases. *Neuropsychologia*, *51*(4), 760–771. https://doi.org/10.1016/j.neuropsychologia.2013.01.006

Brown, H. D. (1971). Children's Comprehension of Relativized English Sentences. *Child Development*, *42*(6), 1923–1936. https://doi.org/10.2307/1127595

Canette, L.-H., Fiveash, A., Krzonowski, J., Corneyllie, A., Lalitte, P., Thompson, D., Trainor, L., Bedoin, N., & Tillmann, B. (2019). Regular rhythmic primes boost P600 in grammatical error processing in dyslexic adults and matched controls. *Neuropsychologia*, 107324. https://doi.org/10.1016/j.neuropsychologia.2019.107324

Carr, K. W., White-Schwoch, T., Tierney, A. T., Strait, D. L., & Kraus, N. (2014). Beat synchronization predicts neural speech encoding and reading readiness in preschoolers. *Proceedings of the National Academy of Sciences*, *111*(40), 14559–14564. https://doi.org/10.1073/pnas.1406219111

Chern, A., Tillmann, B., Vaughan, C., & Gordon, R. L. (2018). New evidence of a rhythmic priming effect that enhances grammaticality judgments in children. *Journal of Experimental Child Psychology*, *173*, 371–379. https://doi.org/10.1016/j.jecp.2018.04.007

Chomsky, N. (2014). *Aspects of the Theory of Syntax*. MIT Press.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed). Hillsdale, N.J.

Corrêa, L. M. S. (1995). An alternative assessment of children's comprehension of relative clauses. *Journal of Psycholinguistic Research*, *24*(3), 183–203. https://doi.org/10.1007/BF02145355

Corriveau, K. H., & Goswami, U. (2009). Rhythmic motor entrainment in children with speech and language impairments: Tapping to the beat. *Cortex*, *45*(1), 119–130. https://doi.org/10.1016/j.cortex.2007.09.008

Corriveau, K., Pasquini, E., & Goswami, U. (2007). Basic Auditory Processing Skills and Specific Language Impairment: A New Look at an Old Hypothesis. *Journal of Speech, Language, and Hearing Research*, *50*(3), 647–666. https://doi.org/10.1044/1092-4388(2007/046)

Dąbrowska, E. (2012a). Different speakers, different grammars: Individual differences in native language attainment. *Linguistic Approaches to Bilingualism*, *2*(3), 219–253. https://doi.org/10.1075/lab.2.3.01dab

Dąbrowska, E. (2012b). Explaining individual differences in linguistic proficiency. *Linguistic Approaches to Bilingualism*, *2*(3), 324–335. https://doi.org/10.1075/lab.2.3.16dab

Dąbrowska, E. (2018). Experience, aptitude and individual differences in native language ultimate attainment. *Cognition*, *178*, 222–235. https://doi.org/10.1016/j.cognition.2018.05.018

Dąbrowska, E. (2019). Experience, Aptitude, and Individual Differences in Linguistic Attainment: A Comparison of Native and Nonnative Speakers. *Language Learning*, *69*(S1), 72–100. https://doi.org/10.1111/lang.12323

Dąbrowska, E., & Street, J. (2006). Individual differences in language attainment: Comprehension of passive sentences by native and non-native English speakers. *Language Sciences*, *28*(6), 604–615. https://doi.org/10.1016/j.langsci.2005.11.014

de Villiers, J. G., Tager Flusberg, H. B., Hakuta, K., & Cohen, M. (1979). Children’s comprehension of relative clauses. *Journal of Psycholinguistic Research*, *8*(5), 499–518. https://doi.org/10.1007/BF01067332

Degé, F., & Schwarzer, G. (2011). The effect of a music program on phonological awareness in preschoolers. *Auditory Cognitive Neuroscience*, *2*, 124. https://doi.org/10.3389/fpsyg.2011.00124

Eisenberg, L. S., Shannon, R. V., Schaefer Martinez, A., Wygonski, J., & Boothroyd, A. (2000). Speech recognition with reduced spectral cues as a function of age. *The Journal of the Acoustical Society of America*, *107*(5), 2704–2710. https://doi.org/10.1121/1.428656

Faul, F., Erdfelder, E., Buchner, A., & Lang, A.-G. (2009). Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. *Behavior Research Methods*, *41*(4), 1149–1160. https://doi.org/10.3758/BRM.41.4.1149

Fishman Kim E., Shannon Robert V., & Slattery William H. (1997). Speech Recognition as a Function of the Number of Electrodes Used in the SPEAK Cochlear Implant Speech Processor. *Journal* *of Speech, Language, and Hearing Research*, *40*(5), 1201–1215. https://doi.org/10.1044/jslhr.4005.1201

Flaugnacco, E., Lopez, L., Terribili, C., Montico, M., Zoia, S., & Schön, D. (2015). Music Training Increases Phonological Awareness and Reading Skills in Developmental Dyslexia: A Randomized Control Trial. *PLOS ONE*, *10*(9), e0138715. https://doi.org/10.1371/journal.pone.0138715

François, C., Chobert, J., Besson, M., & Schön, D. (2013). Music Training for the Development of Speech Segmentation. *Cerebral Cortex*, *23*(9), 2038–2043. https://doi.org/10.1093/cercor/bhs180

François, C., Grau-Sánchez, J., Duarte, E., & Rodriguez-Fornells, A. (2015). Musical training as an alternative and effective method for neuro-education and neuro-rehabilitation. *Frontiers in Psychology*, *6*. https://doi.org/10.3389/fpsyg.2015.00475

Frizelle, P., Thompson, P. A., Mcdonald, D., & Bishop, D. V. M. (2018). Growth in syntactic complexity between four years and adulthood: Evidence from a narrative task. *Journal of Child Language*, *45*(5), 1174–1197. https://doi.org/10.1017/S0305000918000144

Gordon, R. L., Jacobs, M. S., Schuele, C. M., & McAuley, J. D. (2015). Perspectives on the rhythm–grammar link and its implications for typical and atypical language development. *Annals of the New York Academy of Sciences*, *1337*(1), 16–25. https://doi.org/10.1111/nyas.12683

Gordon, R. L., Shivers, C. M., Wieland, E. A., Kotz, S. A., Yoder, P. J., & Devin McAuley, J. (2015). Musical rhythm discrimination explains individual differences in grammar skills in children. *Developmental Science*, *18*(4), 635–644. https://doi.org/10.1111/desc.12230

Goswami, U., Gerson, D., & Astruc, L. (2010). Amplitude envelope perception, phonology and prosodic sensitivity in children with developmental dyslexia. *Reading and Writing*, *23*(8), 995–1019. https://doi.org/10.1007/s11145-009-9186-6

Grahn, J. A., & Brett, M. (2009). Impairment of beat-based rhythm discrimination in Parkinson's disease. *Cortex*, *45*(1), 54–61. https://doi.org/10.1016/j.cortex.2008.01.005

Hartshorne, J. K., Tenenbaum, J. B., & Pinker, S. (2018). A critical period for second language acquisition: Evidence from 2/3 million English speakers. *Cognition*, *177*, 263–277. https://doi.org/10.1016/j.cognition.2018.04.007

Hausen, M., Torppa, R., Salmela, V. R., Vainio, M., & Särkämö, T. (2013). Music and speech prosody: A common rhythm. *Frontiers in Psychology*, *4*. https://doi.org/10.3389/fpsyg.2013.00566

Heard, M., & Lee, Y. S. (2020). Shared neural resources of rhythm and syntax: An ALE meta-analysis. *Neuropsychologia*, *137*, 107284. https://doi.org/10.1016/j.neuropsychologia.2019.107284

Herschensohn, J. (2009). Fundamental and gradient differences in language development. *Studies in Second Language Acquisition*, *31*(2), 259–289. Scopus. https://doi.org/10.1017/S0272263109090305

Hoff, E. (2003). The Specificity of Environmental Influence: Socioeconomic Status Affects Early Vocabulary Development Via Maternal Speech. *Child Development*, *74*(5), 1368–1378. https://doi.org/10.1111/1467-8624.00612

Huss, M., Verney, J. P., Fosker, T., Mead, N., & Goswami, U. (2011). Music, rhythm, rise time perception and developmental dyslexia: Perception of musical meter predicts reading and phonology. *Cortex*, *47*(6), 674–689. https://doi.org/10.1016/j.cortex.2010.07.010

Jones, M. R. (1976). Time, our lost dimension: Toward a new theory of perception, attention, and memory. *Psychological Review*, *83*(5), 323–355. https://doi.org/10.1037/0033-295X.83.5.323

Jones, M. R., & Boltz, M. (1989). Dynamic attending and responses to time. *Psychological Review*, *96*(3), 459–491. https://doi.org/10.1037/0033-295X.96.3.459

Kidd, E., & Bavin, E. L. (2002). English-Speaking Children's Comprehension of Relative Clauses: Evidence for General-Cognitive and Language-Specific Constraints on Development. *Journal of Psycholinguistic Research*, *31*(6), 599–617. https://doi.org/10.1023/A:1021265021141

Kotz, S. A., & Gunter, T. C. (2015). Can rhythmic auditory cuing remediate language-related deficits in Parkinson's disease? *Annals of the New York Academy of Sciences*, *1337*(1), 62–68. https://doi.org/10.1111/nyas.12657

Kraus, N., & Chandrasekaran, B. (2010). Music training for the development of auditory skills. *Nature Reviews Neuroscience*, *11*(8), 599–605. https://doi.org/10.1038/nrn2882

Labelle, M. (1990). Predication, WH-Movement, and the Development of Relative Clauses. *Language Acquisition*, *1*(1), 95–119. https://doi.org/10.1207/s15327817la0101_4

Lee, Y.-S., Min, N. E., Wingfield, A., Grossman, M., & Peelle, J. E. (2016). Acoustic richness modulates the neural networks supporting intelligible speech processing. *Hearing Research*, *333*, 108–117. https://doi.org/10.1016/j.heares.2015.12.008

Loban, W. (1976). *Language Development: Kindergarten through Grade Twelve. NCTE Committee on Research Report No. 18*. https://eric.ed.gov/?id=ED128818

Loftus, G. R., & Masson, M. E. (1994). Using confidence intervals in within-subject designs. *Psychonomic Bulletin & Review*, *1*(4), 476–490. https://doi.org/10.3758/BF03210951

Moreno, S., Marques, C., Santos, A., Santos, M., Castro, S. L., & Besson, M. (2009). Musical Training Influences Linguistic Abilities in 8-Year-Old Children: More Evidence for Brain Plasticity. *Cerebral Cortex*, *19*(3), 712–723. https://doi.org/10.1093/cercor/bhn120

Moritz, C., Yampolsky, S., Papadelis, G., Thomson, J., & Wolf, M. (2013). Links between early rhythm skills, musical training, and phonological awareness. *Reading and Writing*, *26*(5), 739–769. https://doi.org/10.1007/s11145-012-9389-0

Nippold, Marilyn A. (2009). School-Age Children Talk About Chess: Does Knowledge Drive Syntactic Complexity? *Journal of Speech, Language, and Hearing Research*, *52*(4), 856–871. https://doi.org/10.1044/1092-4388(2009/08-0094)

Nippold, Marilyn A., Mansfield, Tracy C., & Billow, Jesse L. (2007). Peer Conflict Explanations in Children, Adolescents, and Adults: Examining the Development of Complex Syntax. *American Journal of Speech-Language Pathology*, *16*(2), 179–188. https://doi.org/10.1044/1058-0360(2007/022)

Nowak, M. A., Komarova, N. L., & Niyogi, P. (2001). Evolution of Universal Grammar. *Science*, *291*(5501), 114–118. https://doi.org/10.1126/science.291.5501.114

Ozernov-Palchik, O., Wolf, M., & Patel, A. D. (2018). Relationships between early literacy and nonlinguistic rhythmic processes in kindergarteners. *Journal of Experimental Child Psychology*, *167*, 354–368. https://doi.org/10.1016/j.jecp.2017.11.009

Patel, A. D. (2011). Why would musical training benefit the neural encoding of speech? The OPERA hypothesis. *Auditory Cognitive Neuroscience*, *2*, 142. https://doi.org/10.3389/fpsyg.2011.00142

Patscheke, H., Degé, F., & Schwarzer, G. (2019). The effects of training in rhythm and pitch on phonological awareness in four- to six-year-old children. *Psychology of Music*, *47*(3), 376–391. https://doi.org/10.1177/0305735618756763

Politimou, N., Dalla Bella, S., Farrugia, N., & Franco, F. (2019). Born to Speak and Sing: Musical Predictors of Language Development in Pre-schoolers. *Frontiers in Psychology*, *10*. https://doi.org/10.3389/fpsyg.2019.00948

Przybylski, L., Bedoin, N., Krifi-Papoz, S., Herbillon, V., Roch, D., Léculier, L., Kotz, S. A., & Tillmann, B. (2013). Rhythmic auditory stimulation influences syntactic processing in children with developmental language disorders. *Neuropsychology*, *27*(1), 121–131. https://doi.org/10.1037/a0031277

Roncaglia-Denissen, M. P., Schmidt-Kassow, M., & Kotz, S. A. (2013). Speech Rhythm Facilitates Syntactic Ambiguity Resolution: ERP Evidence. *PLOS ONE*, *8*(2), e56000. https://doi.org/10.1371/journal.pone.0056000

Ruggles, D. R., Freyman, R. L., & Oxenham, A. J. (2014). Influence of Musical Training on Understanding Voiced and Whispered Speech in Noise. *PLOS ONE*, *9*(1), e86980. https://doi.org/10.1371/journal.pone.0086980

Schellenberg, E. G. (2015). Music training and speech perception: A gene–environment interaction. *Annals of the New York Academy of Sciences*, *1337*(1), 170–177. https://doi.org/10.1111/nyas.12627

Schellenberg, E. G., & Weiss, M. W. (2013). Music and cognitive abilities. In *The psychology of music, 3rd ed* (pp. 499–550). Elsevier Academic Press. https://doi.org/10.1016/B978-0-12-381460-9.00012-2

Schmidt-Kassow, M., & Kotz, S. A. (2008). Entrainment of syntactic processing? ERP-responses to predictable time intervals during syntactic reanalysis. *Brain Research*, *1226*, 144–155. https://doi.org/10.1016/j.brainres.2008.06.017

Sheldon, A. (1976). *The Acquisition of Relative Clauses in French and English: Implications for Language Learning Universals*. https://eric.ed.gov/?id=ED132846

Sheldon, A. (1977). On strategies for processing relative clauses: A comparison of children and adults. *Journal of Psycholinguistic Research*, *6*(4), 305–318. https://doi.org/10.1007/BF01068301

Spencer, S., Clegg, J., & Stackhouse, J. (2012). Language and disadvantage: A comparison of the language abilities of adolescents from two different socioeconomic areas. *International Journal of Language & Communication Disorders*, *47*(3), 274–284. https://doi.org/10.1111/j.1460-6984.2011.00104.x

Sternberg, S. (1966). High-speed scanning in human memory. *Science*, *153*(3736), 652–654. https://doi.org/10.1126/science.153.3736.652

Swaminathan, S., & Schellenberg, E. G. (2017). Musical competence and phoneme perception in a foreign language. *Psychonomic Bulletin & Review*, 1–6. https://doi.org/10.3758/s13423-017-1244-5

Swaminathan, S., & Schellenberg, E. G. (2019). Musical ability, music training, and language ability in childhood. *Journal of Experimental Psychology. Learning, Memory, and Cognition*. https://doi.org/10.1037/xlm0000798

Swaminathan, S., Schellenberg, E. G., & Venkatesan, K. (2018). Explaining the association between music training and reading in adults. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *44*(6), 992–999. https://doi.org/10.1037/xlm0000493

Tabri, D., Chacra, K. M. S. A., & Pring, T. (2010). Speech perception in noise by monolingual, bilingual and trilingual listeners. *International Journal of Language & Communication Disorders*, *0*(0), 1–12. https://doi.org/10.3109/13682822.2010.519372

Thorpe, L. A., Trehub, S. E., Morrongiello, B. A., & Bull, D. (1988). Perceptual grouping by infants and preschool children. *Developmental Psychology*, *24*(4), 484–491. https://doi.org/10.1037/0012-1649.24.4.484

Wingfield, A., McCoy, S. L., Peelle, J. E., Tun, P. A., & Cox, L. C. (2006). Effects of adult aging and hearing loss on comprehension of rapid speech varying in syntactic complexity. *Journal of the American Academy of Audiology*, *17*(7), 487–497.

Table 1.

Results from the Linear Mixed-Effects Model Predicting Performance on the Grammar Test in Experiment 1.

Predictor Variable	Estimate	SE	*t*-score	*p*-value
Syntax (SR)	1.287	0.111	11.58	<.001
Acoustic Clarity (voc.)	-0.273	0.077	-3.53	<.001
Age	0.147	0.030	4.987	< .001
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

Table 2

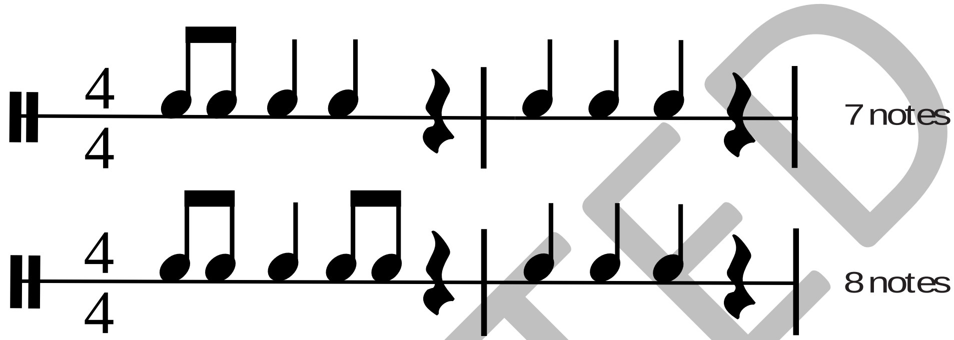
Results from the Linear Mixed-Effects Model Predicting Performance on the Grammar Test in Experiment 2.

Predictor Variable	Estimate	SE	*t*-score	*p*-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
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

A)

Syntax	Acoustic	Sentence	Response
SR	Clear	Brothers that hug sisters are good	Male
SR	Noisy	Sisters that hug brothers are good	Female
OR	Clear	Brothers that sisters hug are good	Female
OR	Noisy	Sisters that hug brothers are good	Male

B)



C)

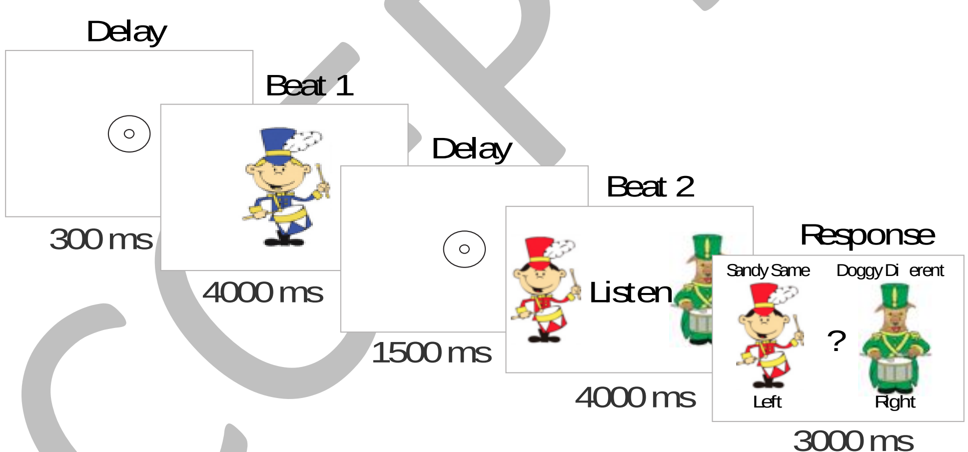


Figure 1. (A) Examples of sentence conditions from the grammar test. B) Examples of a 7-sound and 8-sound rhythm in the rhythm test. C) Schematic illustration of the rhythm test.

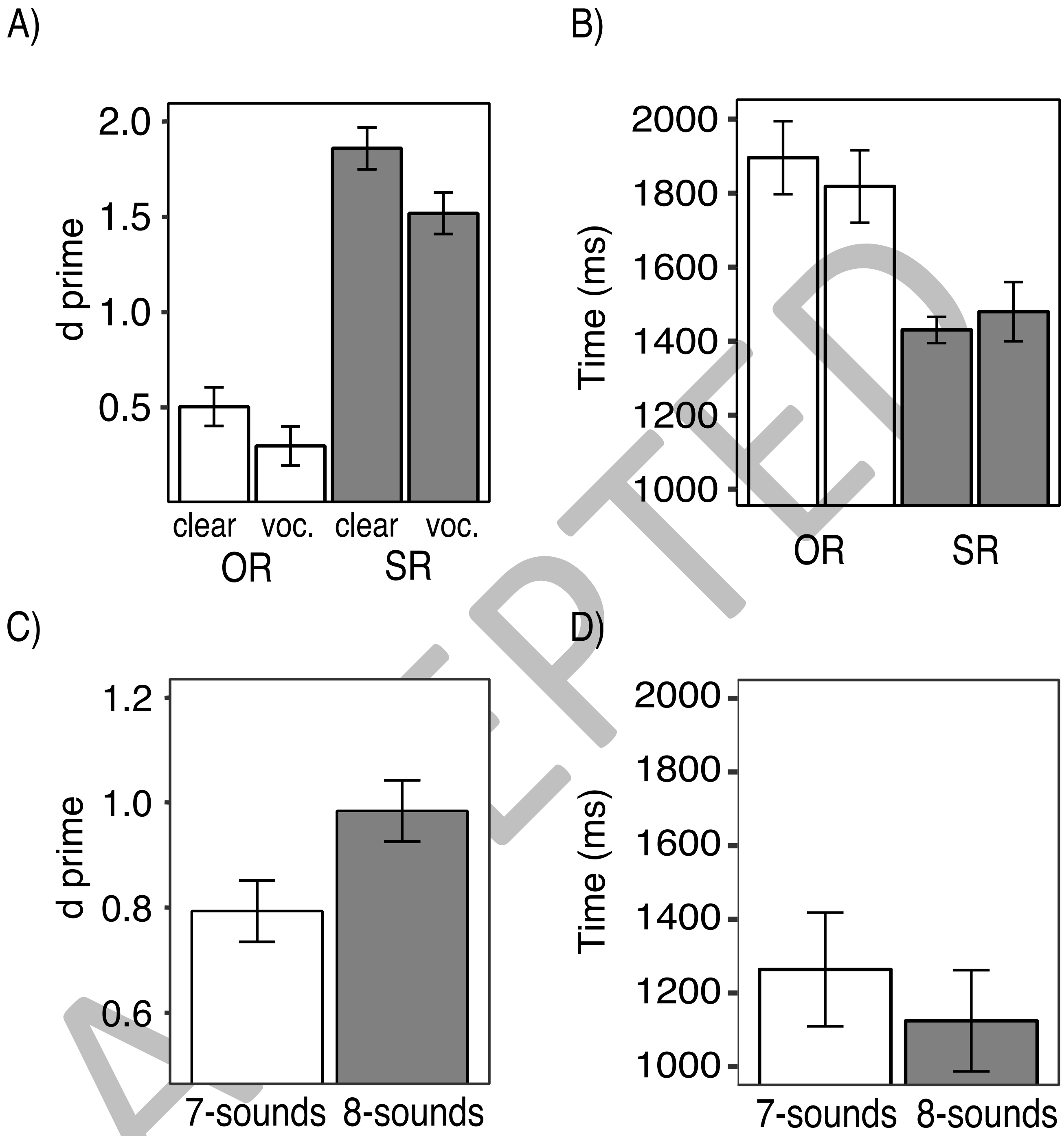


Figure 2. Descriptive statistics for Experiment 1: A) Mean *d'* in the four conditions of the grammar test (voc. = vocoded; OR = object-relative; SR = subject-relative); B) Mean response times in the four conditions of the grammar test; C) Mean *d'* in the two conditions of the rhythm test; D) Mean response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

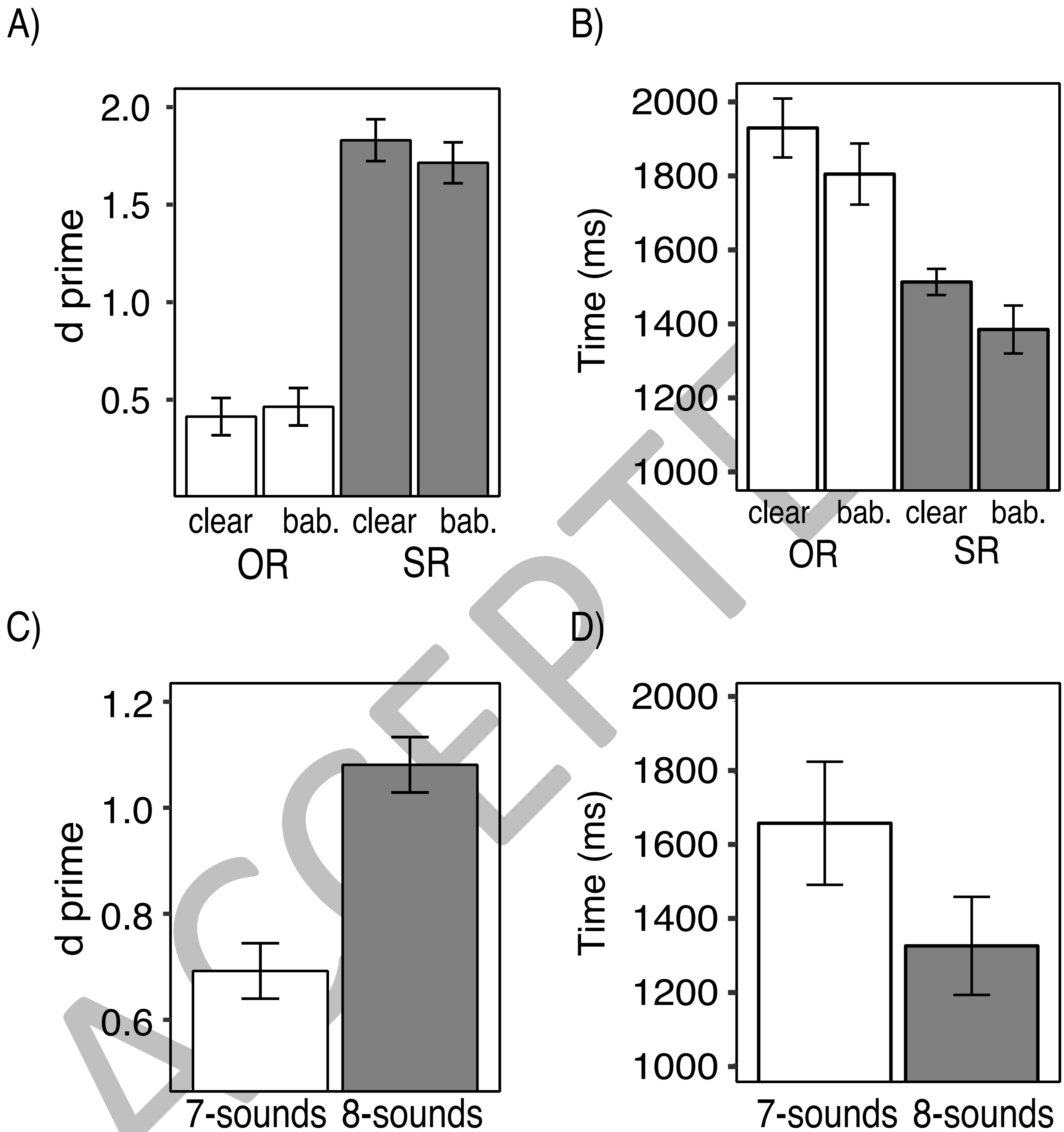


Figure 3. Descriptive statistics for Experiment 2: A) Mean *d'* in the four conditions of the grammar test (bab. = babble; OR = object-relative; SR = subject-relative); B) Mean response times in the four conditions of the grammar test; C) Mean *d'* in the two conditions of the rhythm test; D) Mean response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