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No influence of regular rhythmic priming on grammaticality judgment and sentence comprehension in English-speaking children

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ABSTRACT

A growing body of research has demonstrated the association between music and language, particularly between rhythm and grammar skills in children. A compelling piece of evidence for the influence of music on language comes from findings that a brief exposure to regular musical rhythm improved subsequent syntactic language performance in children. Nevertheless, those observations were made on one particular task, i.e., grammaticality judgment, mostly with French-speaking children. Here, we sought to corroborate and extend the rhythmic priming effect with English-speaking children aged 7 to 12 years who underwent two different syntactic tasks on spoken sentences: one involving judgment on morphosyntactic well-formedness (grammaticality judgment) and the other requiring noun–verb relation analysis (sentence comprehension), both following either regular or irregular rhythmic priming. Half of the children were administered synthetic speech stimuli (Experiment 1), and the other half were presented with natural speech (Experiment 2). Across the two experiments, we did not find any rhythmic priming effect; children's performance on both the grammaticality judgment and sentence comprehension tasks was comparable irrespective of the regularity in prior rhythms. These results imply that the positive influence of regular rhythmic priming on syntactic processing

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may be confined to specific language or age populations, warranting further investigation.

Introduction

Music and language are two forms of auditory communication unique to humans. Researchers have investigated the relationship between music and language to gain insight into behavioral and neurofunctional characteristics shared by both domains (Patel, 2008). Among various domains of music and language, there is growing evidence for the relationship between musical rhythm and linguistic syntax in children (Gordon et al., 2015; Lee et al., 2020; Swaminathan & Schellenberg, 2019). For example, Lee et al. (2020) found, in a large cohort of children aged 7 to 17 years, that the ability to discriminate between two rhythmic patterns was predictive of performance on identifying the grammatical agent of spoken sentences after controlling for age, socioeconomic status, and auditory short-term memory. A recent study extended this result to an adult population whose syntactic analysis performance was associated not only with rhythm discrimination but also with motoric rhythm skills such as tapping to an auditory metronome (Kim, Kovar, et al., 2023).

In addition to these correlational observations, the rhythm–syntax connection has been demonstrated by findings that children's syntactic language processing was affected by prior (passive) listening to a metrically regular rhythm, that is, a sequence of regularly arranged acoustic intervals that induces a sense of beat. More specifically, priming with regular rhythm for 32 s yielded better performance on a subsequent grammaticality judgment task than priming with metrically irregular rhythm (Chern et al., 2018; Ladányi et al., 2021; Przybylski et al., 2013), environmental sound (Bedoin et al., 2016), or silence (Ladányi et al., 2021). This so-called "rhythmic priming" effect was initially reported in French-speaking children aged 6 to 12 years (Bedoin et al., 2016; Canette, Lalitte, et al., 2020; Fiveash et al., 2020; Przybylski et al., 2013) and then was replicated in French-speaking adults (Canette, Bedoin, et al., 2020) as well as in English-speaking children (aged 5–8 years; Chern et al., 2018) and Hungarian-speaking children (aged 5–7 years; Ladányi et al., 2021). Importantly, the facilitatory effect of regular rhythmic priming was not observed when nongrammatical tasks such as picture naming and arithmetic operations were used (Chern et al., 2018; Ladányi et al., 2021), indicating that the rhythmic priming effect does not just confer a domain-general cognitive advantage. Together with previous cross-sectional findings, the influence of regular rhythm on language suggests cooptation of neurobiological resources for processing regular temporal structures, pervasive in both music and language (Heard & Lee, 2020; Kotz et al., 2009; Schön & Tillmann, 2015).

Despite the emerging evidence, there remain two limitations. First, most of the previous work has focused on French speakers, and there has been only one English study with 5- to 8-year-olds (Chern et al., 2018). Second, the rhythmic priming effect has been demonstrated solely using a grammaticality judgment task.

The current behavioral study was designed to address these issues. To this end, we recruited English-speaking children aged 7 to 12 years who performed two different syntactic tasks—grammaticality judgment and sentence comprehension—following priming with either a regular or irregular musical rhythm sequence. In the grammaticality judgment task, children listened to a series of sentences with or without a morphosyntactic error and decided whether each sentence was grammatical or ungrammatical. In the sentence comprehension task, children were asked to indicate the gender of the person performing an action in a series of sentences containing either a subject-relative (SR) or object-relative (OR) center-embedded clause (Table 1). An OR clause is thought to be syntactically more complex than an SR clause, yielding poorer comprehension in both children (Lee et al., 2020; Montgomery et al., 2016) and adults (Kim, Happe, et al., 2023; King & Just, 1991).

Based on the previous findings, we expected that children would show better performance after being primed with a regular rhythm compared with an irregular rhythm in both language tasks. In

Table 1
Sentence examples for the sentence comprehension task

Sentence type	Examples	Correct answer
Subject relative	The boy that reaches the girl is small.	Male
	The queen that touches the king is strong.	Female
Object relative	The boy that the girl reaches is small	Female
	The queen that the king touches is strong.	Male

Note. The relative clause is underlined.

addition, in the sentence comprehension task, we expected to find a more robust effect of regular rhythmic priming on the syntactically more complex OR sentences compared with SR sentences (e.g., Kim, Happe, et al., 2023).

Method

Participants

In total, 18 children aged 7;3 (years;months) to 11;8 years participated in Experiment 1 (6 girls; M_{age} = 9;3 years, *SD* = 1;4), and another 16 children aged 7;2 to 12;1 years participated in Experiment 2 (9 girls; M_{age} = 9;5 years, *SD* = 1;6). Parents reported that children spoke English as their primary language, had normal vision and hearing, and had no history of cognitive, speech, language, or neurological disorders. In Experiment 1, one child completed only the sentence comprehension task and another child completed only the grammaticality judgment task, resulting in 17 participants' data for each language task. We later excluded one more participant whose parent reported a history of attention-deficit/hyperactivity disorder, resulting in a total of 16 participants for Experiment 1. Parents and children provided written informed consent and verbal assent, respectively, to participate in the study. Thus, our final sample for each language task consisted of 16 children in both experiments, which was our target sample size, predetermined by the sample size of Chern et al. (2018). The experimental protocols were approved by the University of Texas at Dallas Institutional Review Board (IRB-21-109).

Stimuli

For metrically regular and irregular rhythm primes, we used two 32-s musical rhythm sequences from Przybylski et al. (2013). In the regular rhythm sequence, the inter-tone intervals of two instruments were metrically organized such that one could easily find a beat/meter with an inter-beat interval of 500 ms. The irregular rhythm sequence had a rhythmic pattern that was far less aligned with the underlying metrical grid, making it difficult to extract a beat/meter (see Przybylski et al., 2013, for more detailed description).

In Experiment 1, auditory sentence stimuli were synthesized using Google text-to-speech with the speaker voice set to an American English-speaking male, which provided well-controlled but still naturally sounding speech (see Supplementary Material 1 in the online supplementary material). For the grammaticality judgment task, sentence materials comprised 36 sentences adapted from Chern et al. (2018). Each sentence had an ungrammatical variant with either a subject–verb agreement error (e.g., "Every year, the animal eats (*eat*) grass in the big pasture.") or a tense error (e.g., "Yesterday, the children hummed (*hum*) a song on the playground.") in the verb clause. Seven of the 36 original sentences were slightly modified given that morphosyntactic errors of those sentences were difficult to discern in synthetic speech. Each sentence was presented only once in either a grammatical or ungrammatical form for each participant. In Experiment 2, the auditory stimuli were replaced with the original natural speech stimuli recorded by a female speaker (see Chern et al., 2018, for more details).

For the sentence comprehension task, 12 base sentences were constructed using a word pool that consisted of one-syllable words with age-of-acquisition estimates of 6;1 years or younger (Brysbaert

et al., 2017), neighborhood density less than 21, high word frequency (>24,000; Davies & Gardner, 2010), and high imageability (>4; Cortese & Fugett, 2004). Each sentence contained an SR or OR center-embedded clause in which one of two gendered nouns was linked to an action verb (Table 1). Note that the syntactic structure was solely determined by switching the temporal order of two phrases (i.e., a noun phrase or a verb phrase) within the relative clause. Each base sentence was used to create four sentences that varied in sentence type (i.e., SR or OR) and gender of the agent (i.e., female or male). The auditory stimuli consisted of 48 sentences in total, synthetically generated using the text-to-speech synthesizer. In Experiment 2, a female native English speaker recorded sentences in a soundproof booth.

Procedure

Children underwent the experimental tasks in a dimly lit soundproof booth. The experiment was run using MATLAB R2021 (MathWorks, Natick, MA, USA) equipped with Psychtoolbox-3. All auditory stimuli were presented through a Logitech Z207 speaker. Prior to performing the main experiment, children completed a set of rhythm and working memory tasks that would be used for future studies (hence, these pilot data are not reported). Half of the children completed the grammaticality judgment task first, and the other half completed the sentence comprehension task first. Children took intermittent breaks between the tasks upon their request. The entire experiment lasted up to 2 h.

In the grammaticality judgment task, children were instructed on how to play a game with two fox cartoon characters, one of whom looked confused and the other of whom looked confident. Participants were told that the two foxes would have the same voice, but the confused one would always say his words wrong (i.e., ungrammatical), whereas the confident fox would always say his words right (i.e., grammatical). Participants were asked to listen to each sentence and identify which fox was saying it by pressing the left (“ungrammatical”) or right (“grammatical”) arrow key. The confused and confident fox characters were shown on the left and right sides of the screen, respectively, to indicate response choices. Children were first familiarized with two auditory sentences and concurrent text presented in both grammatical and ungrammatical forms. Then they performed four practice trials without visual sentence presentation. Feedback was provided during the practice.

In the sentence comprehension task, children were instructed on how to play a story game with a male (Experiment 1) or female (Experiment 2) cartoon character, who would tell them short stories about boys and girls. They were asked to indicate which gender was performing an action by pressing the left (“male”) or right (“female”) arrow key. The storytelling character holding a picture of a boy on the left and a girl on the right side of the screen was displayed to indicate response choices. After verbal instruction on the task with six auditory sentences along with the corresponding text on the screen, children completed two practice trials with the auditory sentences and concurrent text and four additional trials without text, provided with feedback.

Following the practice, children were informed that they would first listen to an elephant character on the screen playing the drums (either regular or irregular rhythms) prior to performing the task. While listening, they were asked to relax and have some rest. For both tasks, there was no feedback during the main task. Children were presented with blocks of six sentences (grammaticality judgment; three grammatical and three ungrammatical) or eight sentences (sentence comprehension; four SR and four OR). Each block was preceded by a 32-s rhythm prime, triggered by an experimenter when children were ready. The first sentence of each block was presented 3 s after rhythmic priming. There was a 2-s interval between a button response and the onset of the next sentence, with no time constraint to make a response. In Experiment 2, a 0- to 500-ms jitter was included in addition to the 3-s interval between the offset of a rhythm and the onset of the first sentence, as well as between the button response and the next sentence, to prevent potential influence of phase locking between rhythm and sentence sounds. In each language task, regular and irregular rhythm primes were alternated three times across the six blocks (Fig. 1A). The sentence items were separated into two lists for the regular and irregular prime conditions, respectively. The order of rhythmic priming, the list assignment, and the order of two language tasks were fully counterbalanced across children.

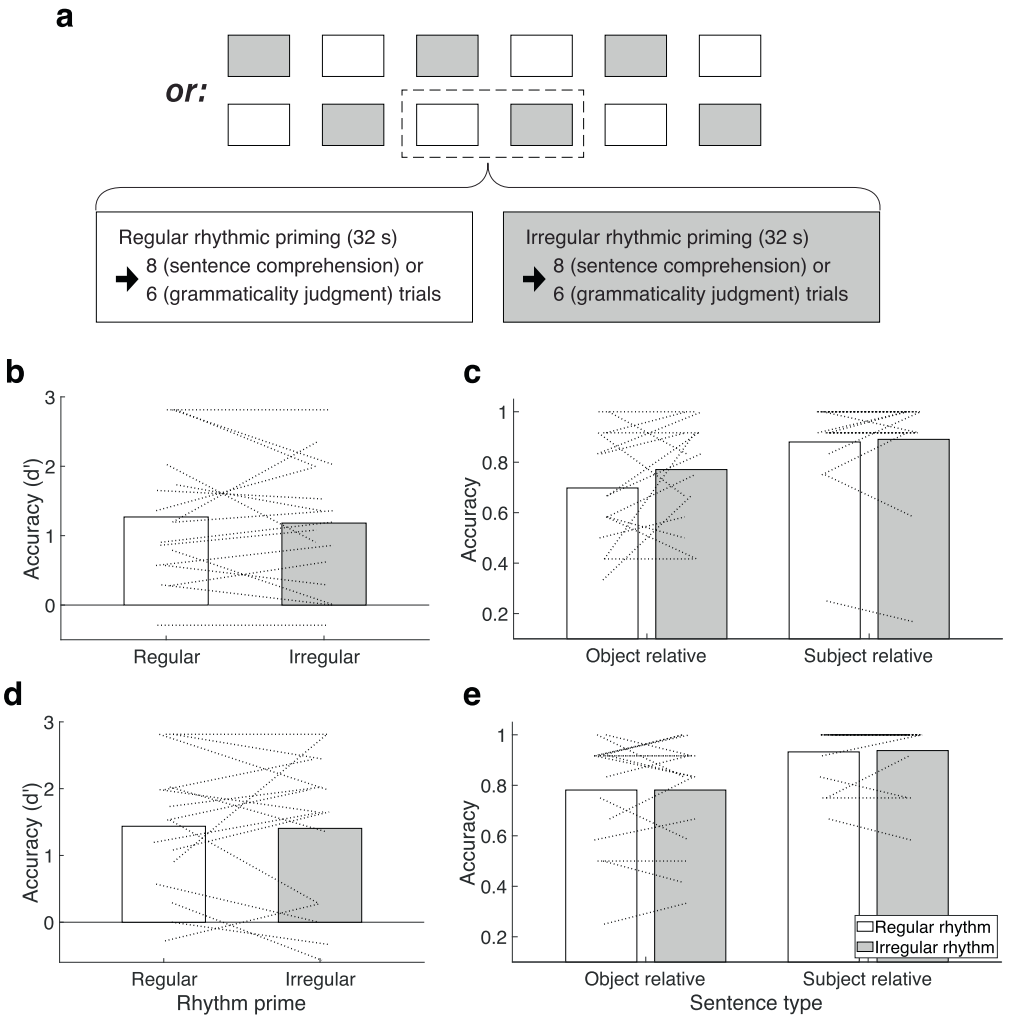

Fig. 1. (A) A schematic of the experimental procedure. Participants underwent a total of six experimental blocks per task. (B–E) Bar graphs showing task accuracy in Experiment 1 (B, C) and Experiment 2 (D, E). (B, D) The accuracy of grammaticality judgment across the two rhythmic priming conditions. (C, E) The accuracy of sentence comprehension across object-relative and subject-relative sentences in the two rhythmic priming conditions. Dotted lines denote individual participants' data.

Results

Experiment 1

Grammaticality judgment

The mean accuracies for grammatical and ungrammatical sentences were 69.4% and 72.2% for the regular rhythmic priming condition and were 70.8% and 68.1% for the irregular rhythmic priming condition, respectively. We calculated a *d*-prime (d') score for each of the two rhythmic priming conditions by subtracting the *z*-score of a false alarm rate (1 − accuracy for ungrammatical sentences) from that of a hit rate (accuracy for grammatical sentences). The hit and false alarm rates of 0 and 1 were adjusted to avoid an indefinite d' score. The d' data were analyzed using a paired *t* test between

two rhythmic priming conditions. The result showed that grammaticality judgment performance was slightly better after listening to regular rhythm (M = 1.25, SD = 0.96) compared with irregular rhythm (M = 1.16, SD = 0.91), but the difference was far from significance, $t(15) = 0.56$, p = .579, Cohen's d = .14 (Fig. 1B).

Sentence comprehension

The binary (i.e., correct or incorrect) accuracy data were analyzed by a mixed effects logistic regression model using the *glmer* function of the "lme4" package (Bates et al., 2015), including sentence type (SR or OR), rhythm type (regular or irregular), and sentence type × rhythm type interaction as fixed factors and participant as a random intercept. As expected, we found a robust main effect of sentence type (b = .60, SE = .11, z = 5.58, p < .001), indicating that children performed better on SR sentences (M = 88.5%, SD = 19.9) than on OR sentences (M = 73.4%, SD = 19.0) (Fig. 1C). However, there was neither a main effect of either rhythm type (b = −.14, SE = .11, z = −1.36, p = .175) nor interaction (b = .09, SE = .11, z = 0.81, p = .418).

Experiment 2

Results from Experiment 1 yielded no significant effects of rhythmic priming across the two tasks. A potential reason for this could be the use of synthetic stimuli. That is, even though the text-to-speech synthesizer provided natural-sounding speech quality, this may still sound less intelligible than natural human speech, particularly in children (Reynolds & Fucci, 1998). In addition, synthetic speech may lack critical acoustic characteristics (e.g., prosody) that possibly mediate the connection between rhythm and syntax in natural speech.

To examine these possibilities, we recruited another 16 English-speaking children aged 7;2 to 12;1 years in Experiment 2. For the grammaticality judgment task, we used the original natural speech stimuli from Chern et al. (2018). For the comprehension task, we used newly recorded sentences spoken by a native English speaker. In addition, we included a 0- to 500-ms jitter between the offset of rhythmic priming and the onset of sentences to prevent potential influence of phase locking between rhythm and sentence sounds.

Grammaticality judgment

The mean accuracies for grammatical and ungrammatical sentences were 79.9% and 68.1% for the regular priming condition and were 77.1% and 68.8% for the irregular priming condition, respectively. A paired t test on d' data indicated no significant difference in grammaticality judgment performance between regular priming (M = 1.44, SD = 0.98) and irregular priming (M = 1.41, SD = 1.12) conditions, $t(15) = 0.16$, p = .873, Cohen's d = .03 (Fig. 1D). To assess the influence of the experiment parameters on the results, we collapsed data from both Experiments 1 and 2 and analyzed the d' using a mixed analysis of variance (ANOVA) with a within-participant factor of rhythm and a between-participant factor of experiment. Again, we found no significant effects (ps > .511). To rule out possible order and/or fatigue effects, we performed another paired t test by including only the children who first completed the grammaticality judgment task across Experiments 1 and 2, which yielded no effect, $t(15) = -.17$, p = .866, Cohen's d = −.04.

Given the replication failure, we also performed a Bayes factor (BF) analysis using the *ttestBF* function of the "BayesFactor" package (Rouder et al., 2009) to quantify the evidence toward the null hypothesis. The BFs were 0.22 and 0.19 for Experiments 1 and 2, respectively, both indicative of substantial evidence for the null model according to the guideline proposed by Jeffreys (1961).

Sentence comprehension

A mixed effects logistic regression analysis revealed a significant main effect of sentence type (SR: M = 93.5%, SD = .11.8; OR: M = 93.5%, SD = 11.8; b = .80, SE = .13, z = 6.27, p < .001), but no effect of rhythm (b = −.02, SE = .13, z = −.18, p = .854) or interaction (b = .07, SE = .12, z = 0.56, p = .576) (Fig. 1E). The collapsed accuracy data from both Experiments 1 and 2 yielded no significant effect of rhythmic priming (b = −.02, SE = .13, z = −.18, p = .854). Interestingly, when we included in the model only the children who first completed the sentence comprehension task across Experiments

1 and 2, we found a significant effect of rhythmic priming ($b = -.25$, $SE = .13$, $z = -1.97$, $p = .049$), indicating that children performed better after "irregular" rhythmic priming compared with "regular" rhythmic priming. Together, we found no evidence for a regular rhythmic priming effect on sentence comprehension.

Age differences

Given that we had a broad age range, we explored whether children's age differentially affected the rhythm–syntax association by performing correlation analyses between participant age and the accuracy difference between the regular and irregular rhythmic priming conditions. The rhythmic priming effect was not dependent on age for grammaticality judgment ($R = -.06$, $p = .731$) or sentence comprehension (OR: $R = -.17$, $p = .348$; SR: $R = .25$, $p = .170$).

Discussion

Metrically regular rhythm has been shown to yield better performance on a subsequent language task involving grammaticality judgment. Although this finding was consistent in the literature, it was largely based on French-speaking children in a particular grammar task, necessitating replication and extension with different grammar tasks and more diverse populations. Although our sample size ($N = 16$) was based on the one existing rhythmic priming study with English-speaking children (Chern et al., 2018) and our sentence stimuli for the grammaticality judgment task were similar (Experiment 1) or identical (Experiment 2) to those in the previous study, we failed to replicate the regular rhythmic priming effect. For both experiments, the effect size of regular rhythmic priming on grammaticality judgment (Experiment 1: Cohen's $d = .14$; Experiment 2: Cohen's $d = .03$) was markedly smaller than that (Cohen's $d = .57$) of Chern et al. (2018). One looming difference between our study and theirs was the age of children: 7 to 12 years versus 5 to 8 years. Hence, one possible explanation might be that there is a minimal effect of "regular" rhythmic priming when English-speaking children during late childhood perform the grammaticality judgment task. This null finding is, however, contradictory to previous studies with French speakers reporting significant enhancement of grammaticality judgment through regular rhythmic priming in children aged 6 to 12 years (e.g., Przybylski et al., 2013) as well as in young adults (Canette, Bedoin, et al., 2020). Given that the regular rhythmic priming effect has been reported mostly in French and in only a few other languages (i.e., English and Hungarian), it is difficult to conclude whether the replication failure is due to differences in age or language. Further research is warranted to better understand how regular rhythmic priming aids subsequent grammaticality judgment with more diverse populations in terms of language and age.

In addition, the regular rhythmic priming effect was not extended to a different grammar task requiring analysis of noun–verb relations in sentences with an SR or OR center-embedded clause. Intriguingly, however, there was a significant effect of "irregular" rhythmic priming when potential order and/or fatigue effects were considered by analyzing only those who completed the sentence comprehension task first before performing the grammaticality judgment task. This observation resembles a previous finding that comprehension of syntactically ambiguous sentences was enhanced after performing an incongruent Stroop task, that is, indicating an ink color (e.g., blue ink) of a color word incongruent with the ink color (e.g., "RED") (Hsu & Novick, 2016). Indeed, it has been shown that the Stroop effect was reduced after irregular rhythmic priming in Hungarian-speaking children (Ladányi et al., 2021). Similarly, children might have benefitted from irregular rhythmic priming by engaging cognitive control during sentence comprehension. In any case, the current results are not in line with the extant evidence.

Conclusion

We failed to observe any positive impact of regular rhythmic priming on either grammaticality judgment or sentence comprehension with English-speaking children of a broader age range (7–12 years). These results suggest that the impact of prior rhythmic priming on syntactic processing might

be age and/or language specific. Further research is needed to better characterize the rhythmic priming phenomena.

Data availability

Data will be made available on request.

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Author contributions

Conceptualization: H-W.K. and Y.S.L.; methodology: H-W.K. and Y.S.L.; investigation: H-W.K. and K.E.M.; formal analysis and visualization: H-W.K.; writing–original draft: H-W.K.; writing–review & editing: H-W.K., K.E.M., and Y.S.L.; supervision: Y.S.L.

Appendix A. Supplementary material

Supplementary material to this article can be found online at https://doi.org/10.1016/j.jecp.2023.105760.

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