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Rhythmic priming of grammaticality judgments in children: Duration matters

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ABSTRACT

Research has shown that regular rhythmic primes improve grammaticality judgments of subsequently presented sentences compared with irregular rhythmic primes. In the theoretical framework of dynamic attending, regular rhythmic primes are suggested to act as driving rhythms to entrain neural oscillations. These entrained oscillations then sustain once the prime has finished, engendering a state of global enhanced activation that facilitates the processing of subsequent sentences. Up to now, this global rhythmic priming effect has largely been shown with primes that are approximately 30 s or more. To investigate whether shorter primes also facilitate grammaticality judgments, two experiments were run on two groups of children aged 7 to 9 years (*Ms* = 8.67 and 8.58 years, respectively). Prime durations were 8 and 16 s in Experiment 1, and they were 16 and 32 s in Experiment 2. Rhythmic priming was observed in Experiment 2 for 32-s primes, as observed previously. Furthermore, positive correlations were found between reading age and performance level after regular primes for both 8-s and 16-s primes in Experiment 1 and for 32-s primes in Experiment 2. In addition, the benefit of the regular primes increased with chronological age for the 32-s primes in Experiment 2. The findings suggest that (at least) 32-s primes are optimal in global rhythmic priming studies when testing children in the current age range and that results may be modulated by chronological age and reading age. Results are discussed

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in relation to dynamic attending theory, neural oscillation strength, developmental considerations, and implications for rhythmic stimulation in language rehabilitation.

Introduction

Accumulating evidence suggests that the neural mechanisms underlying temporal processing and temporal attention are similar for music and speech rhythm (Fujii & Wan, 2014; Tierney & Kraus, 2014). Rhythm in music is generally regular and stable, providing a highly predictive rhythmic context (London, 2012; McAuley, 2010). Rhythm in speech is less regular but still facilitates temporal prediction of upcoming elements, especially in relation to stress prominence of accented and unaccented syllables (Arvaniti, 2009; Pitt & Samuel, 1990). An influential theory explaining how the brain tracks music and speech rhythms is based on dynamic attending. The dynamic attending theory (DAT) suggests that external stimuli with rhythmic regularities are represented in the brain via the entrainment of endogenous neural oscillations at multiple hierarchical levels. This synchronization facilitates temporal prediction of upcoming events, notably by enhancing temporal attention to expected points in time (Jones, 1976, 2016, 2019; Jones & Boltz, 1989). Because both music and speech appear to be tracked in the brain via similar neural mechanisms, research has begun to exploit the strongly regular temporal structure of music to enhance the processing of the less regular speech signal. The current study investigated this issue by focusing on whether regular rhythmic primes can influence syntactic processing of speech in children.

Research has shown that music and language share cognitive resources for structural integration (Fiveash, McArthur, & Thompson, 2018; Fiveash & Pammer, 2014; Fiveash, Thompson, Badcock, & McArthur, 2018; Patel, 2008; Slevc, Rosenberg, & Patel, 2009), and relations have been observed between music rhythm and language grammar processing capacities (Gordon, Jacobs, Schuele, & McAuley, 2015). For example, Gordon, Shivers, et al. (2015) found that rhythm perception skills were related to grammatical production skills in typically developing 6-year-old children. Furthermore, 10- and 11-year-old children with music training showed an early left anterior negativity response to violations of language structure (grammatical errors), whereas this response was not observed in children who were not musically trained, likely because their automatic language syntax skills were still developing (Jentschke & Koelsch, 2009). In addition to long-term benefits of music rhythm for language processing (see Schön & Tillmann, 2015), short-term effects have been investigated within the rhythmic priming paradigm, focusing specifically on whether regular rhythmic primes can facilitate subsequent grammaticality judgments in speech (Canette et al., 2020; Chern, Tillmann, Vaughan, & Gordon, 2018; Przybylski et al., 2013).

The rhythmic priming paradigm draws on the premise of DAT that oscillatory neural activity is entrained to temporal regularities in the environment and actively supports the distribution of attention in time via temporal predictions. Neural entrainment, therefore, is suggested to reflect more than a mere accumulation of separate passive responses to acoustic energy in external stimuli (Large, 2008; Tal et al., 2017). In line with oscillator dynamics (Large & Jones, 1999), the entrained neural oscillations are proactive and self-sustaining and can continue even when the external stimulus has stopped. The continuation of self-sustaining oscillations triggered by a rhythmic context results in the hypothesis that a transient rhythmic prime can influence subsequent perception. Indeed, studies testing predictions of the DAT have shown that attention is enhanced at specific points in time when an event is expected to occur based on a prior entrained sequence (e.g., Barnes & Jones, 2000; Jones, Kidd, & Wetzel, 1981; Large & Jones, 1999). The effect of sustained neural oscillations and temporal attention to the subsequent processing of speech stimuli has been tested using either a one-to-one mapping of a prime (or cue) matched to one specific sentence that follows or a more global priming approach. The one-to-one mapping approach has shown enhanced processing of phonemes (Cason, Astésano, &

Schön, 2015; Cason & Schön, 2012) and words (Gould, McKibben, Ekstrand, Lorentz, & Borowsky, 2016; Gould, Mickleborough, Ekstrand, Lorentz, & Borowsky, 2017) and even enhanced neural entrainment to the following sentence (Falk, Lanzilotti, & Schön, 2017; Gordon, Schön, Magne, Astesano, & Besson, 2010). The focus of the more global rhythmic priming paradigms, including the one presented here, has been on morphosyntactic processing following regular rhythmic primes (in comparison with different baseline conditions).

In global rhythmic priming paradigms, participants are presented with longer rhythmic primes followed by a set of naturally spoken sentences. Regular rhythmic primes are assumed to entrain brain oscillations globally at the beat level (and related hierarchical meter levels). This entrainment then favors a state of enhanced activation, which boosts subsequent sentence processing by the promotion of an attentional temporal window consistent with linguistic units in the naturally spoken speech signal. Early studies using long rhythmic primes (3 min) in patient populations have shown benefits to subsequent grammatical speech processing. Rhythmic primes restored the P600 component to syntactic violations in patients with basal ganglia lesions (Kotz, Gunter, & Wonneberger, 2005) who have been previously reported to not show this component (Frisch, Kotz, von Cramon, & Friederici, 2003; Kotz, Frish, von Cramon, & Friederici, 2003). Similarly, rhythmic march primes restored the P600 to subsequently presented sentences in a patient with Parkinson's disease (Kotz & Gunter, 2015).

Based on the promising results of rhythmic priming in adults, studies began to investigate whether rhythmic priming also enhanced grammaticality judgments in children who are still developing their syntactic processing skills, using shorter primes and shorter blocks of sentences. Przybylski et al. (2013) presented regular and irregular 32-s primes, each followed by six grammatically correct and incorrect sentences, to French children with developmental language disorder (DLD; previously called specific language impairment; see Bishop, Snowling, Thompson, & Greenhalgh, 2017), children with dyslexia, and their chronological age- and reading age-matched controls. All groups showed enhanced sensitivity to syntactic violations after a regular rhythmic prime compared with an irregular rhythmic prime, and this effect was particularly strong for children with DLD. To investigate whether this effect was based on a facilitative influence of the regular primes and was not simply a detrimental effect of the irregular primes, Bedoin, Brisseau, Molinier, Roch, and Tillmann (2016) presented children with DLD and age-matched controls with the same 32-s regular prime compared with an environmental sound scene without temporal regularities. Grammaticality judgments were improved after the regular primes, suggesting that the previously reported relative facilitation effect (comparing regular primes with irregular primes) is at least partly due to the boosting effect of the regular prime.

Rhythmic priming has also been observed in different languages and within training paradigms (all using ~30-s primes followed by six sentences or short tasks). Recent research using the same primes as in Przybylski et al. (2013) has replicated the rhythmic priming effect in English children (Chern et al., 2018) and Hungarian children (Ladányi, Lukacs, & Gervain, submitted for publication). Chern et al. (2018) included two nonlinguistic control tasks (math and visuospatial), and Ladányi et al. (submitted for publication) included a picture-naming task and a nonverbal Stroop task. In both studies, a benefit of the regular prime was observed only for grammaticality judgments and not for the control tasks, suggesting that the regular prime had a specific benefit for subsequent sentence processing and was not merely a general effect of enhanced arousal. Rhythmic primes have also been implemented within morphosyntax training sessions proposed to cochlear-implanted deaf children to investigate whether presenting a regular rhythmic prime (~30 s) compared with an environmental sound baseline before sets of training items enhanced the long-term benefits of training (Bedoin et al., 2018). A larger improvement in performance for grammaticality judgments and nonword repetition was recorded in posttraining sessions when morphosyntactic exercises had been preceded by rhythmic primes rather than by baseline primes. These results suggest that rhythmic priming in the short-term context of morphosyntactic exercises could also have beneficial long-term effects on language processing. Rhythmic priming, therefore, appears to be a valuable tool to enhance grammaticality judgments in speech, and rhythmic primes of approximately 30 s appear to work well in this context.

To understand the strengths and limits of the priming effect, one question is how long the prime needs to be for the entrainment and synchronization of neural oscillations to sustain and facilitate subsequent language processing. Notably, the rhythmic primes used in previous studies all have been at least 30 s. Long rhythmic primes (3 min) appeared to benefit the subsequent processing of 24 sentences (Kotz et al., 2005) and 48 sentences (Kotz & Gunter, 2015) in adult patients. The other rhythmic priming studies outlined above all have used 32-s rhythmic primes followed by six sentences in children aged approximately 6 to 10 years (Bedoin et al., 2016; Chern et al., 2018; Ladányi et al., submitted for publication; Przybylski et al., 2013). Therefore, it is unknown whether shorter rhythmic primes could also facilitate grammaticality judgments in sentence processing and whether the duration of the primes and their potential benefit might depend on children's chronological or reading age.

The current study was designed with two main aims. The first aim was to replicate previous rhythmic priming effects with 32-s primes and to investigate whether shorter prime durations can also influence subsequent grammaticality judgments. Participants were presented with 8-s and 16-s rhythmic primes in Experiment 1 and with 16-s and 32-s rhythmic primes in Experiment 2. In both experiments, rhythmic primes (regular or irregular) were followed by six sentences (grammatical or ungrammatical) as in previous rhythmic priming experiments (e.g., Przybylski et al., 2013). We aimed to replicate the benefit of the regular rhythmic prime for 32-s primes, and to test whether this benefit extended at least to the 16-s primes or even the 8-s primes.

Our second aim was a first attempt to address whether the sensitivity to rhythmic primes might depend on chronological age (CA) and reading age (RA). Based on previous age ranges in similar research, we tested children from 7 to 9 years of age because children in this age range are still developing their syntactic processing skills (Friederici, 2006; Hahne, Eckstein, & Friederici, 2004). We assessed each child's RA, based on an RA measure administered after the experiment, and recorded each child's CA. We predicted that older children and children with higher RAs would benefit more strongly from the prime regularity, resulting in enhanced grammaticality judgments after regular primes compared with irregular primes. This prediction was based on evidence that rhythmic processing skills improve with age (Bonacina, Krizman, White-Schwoch, Nicol, & Kraus, 2019; Drake, Jones, & Baruch, 2000; Ireland, Parker, Foster, & Penhune, 2018; McAuley, Jones, Holub, Johnston, & Miller, 2006) and documented links between reading skills and rhythmic processing skills (Bekius, Cope, & Grube, 2016; Dellatolas, Watier, Le Normand, Lubart, & Chevrie-Muller, 2009; Moreno et al., 2009; Taub & Lazarus, 2012).

We ran two separate experiments for the following reasons. First, shorter experiments (~20 min) were preferable to maintain attention within the current age group. Second, we wanted to investigate effects of duration across two different groups of children (drawn from the same participant pool) to analyze the potential CA and RA effects. Third, we wanted to isolate the effects of individual prime durations as much as possible; running two experiments allowed us to observe whether a different pattern occurred depending on whether a 16-s prime was presented in the second part or the first part of an experimental session. In addition to the manipulation of duration and the investigation of CA and RA, the current study is the first to analyze correct response times (RTs) as well as *d* prime (*d*') and accuracy in grammaticality judgments following the primes. In the following, we first present the method common for the two experiments, followed by the presentation of Experiment 1 and Experiment 2.

Common method

Design

Experiments 1 and 2 were based on a 2 (Prime Duration: short or long) $\times$ 2 (Prime Regularity: regular or irregular) $\times$ 2 (Sentences: grammatical or ungrammatical) within-participant design. As in gating paradigms, which introduce increasingly large segments of information (e.g., Walley, Michela, & Wood, 1995), short primes were presented in the first part of each experiment, and long primes were presented in the second part of each experiment. Each experiment contained 16 blocks (8 short and 8 long blocks), with each block consisting of one prime rhythm followed by six sentences (three grammatical and three ungrammatical sentences, randomly ordered). Rhythmic primes were pseudorandomized so that two primes of the same type (regular or irregular) were presented in succession (e.g., AA BB AA BB) and the same individual prime was not played twice in a row. Individual (regular and irregular) rhythms were played once in the short condition and once in the long condition, so that participants heard the same rhythms twice throughout the experiment. The starting rhythm (regular or irregular) and sentence list (List A or List B; see below) were counterbalanced across participants. See Fig. 1 for a schematic representation of the paradigm.

Stimuli

Rhythms

Four regular rhythms were created by a musicologist (R1, R2, R3, and R4). Regular rhythms had a 4/4 meter with a tempo of 120 beats per minute, corresponding to an inter-beat interval (IBI) of 500 ms or 2 Hz, and were created with several percussion instruments and electronic sounds based on MIDI (Musical Instrument Digital Interface) VST (Virtual Studio Technology) instrument timbres (i.e., bass drum, snare drum, tom-tom, and cymbal) to increase acoustic complexity and musicality. The shortest (8-s) rhythm contained one cycle of 16 beats. The 16-s and 32-s rhythms contained two and four cycles of the short rhythm, respectively. At the end of each rhythm, the first beat of the cycle was played again to create a feeling of completion, including a small reverberation effect that added about 1 s to the rhythm, resulting in total durations of 9 s, 17 s, and 33 s, respectively. Nevertheless, for clarity, we refer to the rhythms as 8-s, 16-s, and 32-s rhythms. The irregular rhythms contained the same acoustic information as the regular rhythms (event duration, total duration, and instruments were identical), but the acoustic events were redistributed in time to create highly irregular sequences with no underlying meter or pulse (thereby leading to four items: I1, I2, I3, and I4). Sequences were exported in 16-bit, 48,000-Hz mono wav files and normalized in loudness (−3 dB).

Sentences

Two lists (A and B) of 96 French sentences spoken naturally by a native French female speaker were used. Each list contained 48 grammatical and 48 ungrammatical sentences. Sentences that were grammatical in List A were ungrammatical in List B. Sentences of List A and List B were matched on

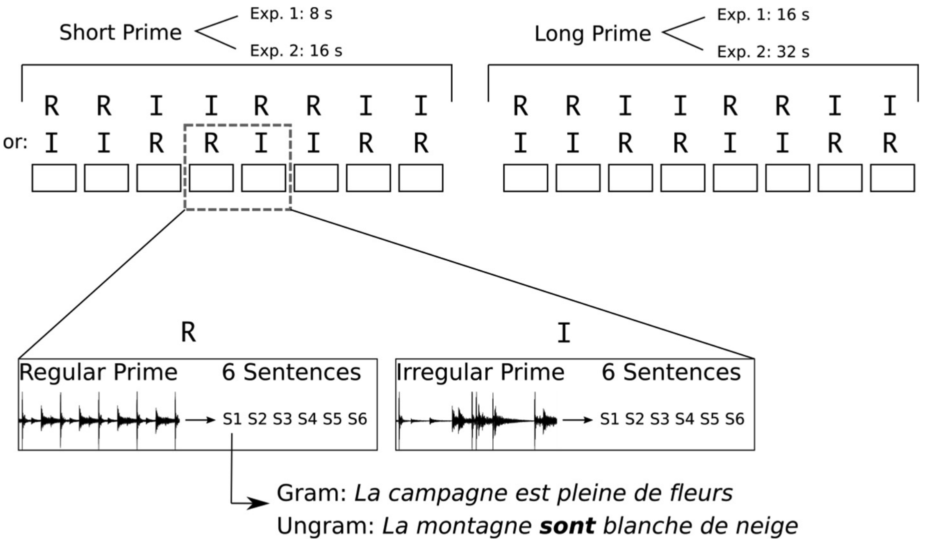

Fig. 1. Method for Experiments 1 and 2. Short primes were presented in the first part of the experiment, and long primes were presented in the second part of the experiment. Example sentences translate to *The countryside is full of flowers* (grammatical) and *The* [singular] *mountain are white with snow* (ungrammatical)—an example of a number error. Note that three of the six sentences in each block were grammatical and three were ungrammatical. After each sentence, children indicated whether they thought that the sentence was grammatical or ungrammatical. Exp. 1/2, Experiment 1/2; R, regular prime; I, irregular prime; S1/2/3/4/5/6, Sentence 1/2/3/4/5/6; Gram, grammatical sentence; Ungram, ungrammatical sentence.

a number of lexical properties such as the number of words and number of syllables, the lexical frequency, and the grammatical type of the open-class words. Eight types of grammatical errors were created by a French linguist: errors of number, person, gender, tense, auxiliary, morphology, position, and past participle. Error words were distributed in different positions throughout the sentences so that they could not be predicted. All sentences and error types can be seen in the online supplementary material. The three ungrammatical sentences of a block always included three different error types, and the lexical properties of grammatical and ungrammatical sentences were matched within each block to control for differences between sentence structures within blocks. The sentences were matched for peak intensity by rescaling them by their maximum absolute amplitude value.

Procedure

Children were tested 2 at a time in a quiet classroom. Common instructions were provided, whereby children were told that they would listen to music and then hear some sentences. They were shown pictures of two dragons: one that always said correct sentences (clever dragon) and one that was confused and always made mistakes (confused dragon). It was reinforced that the confused dragon would make French errors rather than errors of meaning. After a (grammatical) example sentence, children were taken to separate computers to begin the experiment. Children performed the experiment separately on different MacBook Pro laptops facing opposite directions and on opposite sides of the room. One experimenter stayed with 1 child and a second experimenter stayed with the other child throughout the experiment to ensure adherence to the task and quiet behavior and to initiate each trial.

During the experiment, a fixation cross was presented on the screen during the rhythmic primes, and children were encouraged to listen carefully. While the sentences were playing, the two dragons appeared on the screen. Children responded using the keyboard to indicate whether the clever dragon or the confused dragon spoke each sentence. If children responded before the sentence finished, the dragons disappeared but the sentence continued. Once children had responded, a question mark appeared on the screen, and the experimenter started the next trial by pressing a button when children were concentrating and ready to continue. It was ensured that children rested their hands on the keys to record RTs, and all unused keys were covered with cardboard. After the first part of the experiment with the shorter primes, children were told that for the next part of the experiment the music would be a bit longer but that they would continue with the same task. Stimuli were presented through headphones at a comfortable listening level. The experiments were run with MATLAB (Version 2018a) and Psychtoolbox (Version 3.0.14). To avoid sampling bias between schools or participants, Experiments 1 and 2 were alternately tested during each testing day.

At the end of the experiment, children were tested separately on a classical French age-normed measure of reading (i.e., *Test de l'Alouette;* Lefavrais, 1967). Children needed to read out loud (within 3 min) a text for which no efficient semantic prediction was possible to avoid guessing. Their score was calculated by taking into account reading speed and mistakes made, which were referenced to normed values providing a measure of RA in French. Children were encouraged and told that they did a good job at the end of the reading test regardless of their performance.

Analysis

Sensitivity analysis

In accordance with signal detection theory (Stanislaw & Todorov, 1999), *d'* values were calculated by subtracting the *z*-score of the false alarm rate (i.e., there was no grammatical error but the participant responded *ungrammatical*) from the *z*-score of the hit rate (i.e., there was an error and the participant responded *ungrammatical*) as a measure of sensitivity to the signal. A *d'* of 0 (zero) suggests that the participant could not distinguish the signal (a grammatical error) from noise (no grammatical error). Extreme hit and false alarm rates of 1 and 0 were corrected to 0.99 and 0.01, respectively, for the calculations. A measure of response bias *c* was also calculated by taking the sum of the *z*-scores of hits and false alarms multiplied by −0.50. Positive values suggest a bias to respond *grammatical,* and negative values suggest a bias to respond *ungrammatical.*

For each experiment, d' and response bias c were calculated for all sentences following the four priming conditions: regular short, irregular short, regular long, and irregular long. A 2×2 analysis of variance (ANOVA) with prime regularity (regular or irregular) and duration (short or long) as within-participant factors was performed on d' and c values, respectively. Correlations between d' and response bias c with RA and CA are also reported. Interaction effects were investigated with paired-samples t tests (two-sided) using Cohen's d effect sizes that take into account paired-samples correlations. Effect sizes from ANOVAs are reported with partial eta squared (η_p^2).

Response time calculation

RTs for correct responses were calculated from the end of the sentence for grammatical sentences and from the end of the syllable that introduced the grammatical error for ungrammatical sentences. Negative RTs were excluded for the ungrammatical sentences because the participant would not yet have heard the error. Negative RTs were not removed for grammatical sentences because it was possible to predict that there was no error by the end of the sound file. Individual RTs deviating more than 3 standard deviations from the participant's average RT (calculated separately for grammatical and ungrammatical sentences) were removed to exclude any particularly early or late responses.

Linear mixed models: Accuracy and RT

Accuracy and RT were analyzed using the *lme4* package for linear mixed models (Bates, Mächler, Bolker, & Walker, 2015) in R (R Core Team, 2018). Linear mixed models were used to allow us to investigate the effects of interest on a trial-by-trial basis while controlling for random effects of participant and sentence. They also allowed us to investigate more closely the effects of RA and CA on performance across trials. Trial-by-trial accuracy data, therefore, were included to complement the d' analysis.

Accuracy. Because the accuracy data were binomial (correct or incorrect), a mixed-effects logistic regression was run using the *glmer* command in R (generalized linear mixed model [GLMM] family = binomial, link = logit). The model was fitted with the maximum likelihood method using a Laplace approximation. For significance testing of fixed effects, the *anova* function (using Type III Wald chi-square tests) from the *car* package (Fox & Weisberg, 2011) was used. The base model included the fixed effects of prime regularity and duration (and their interaction) to investigate effects of the independent variables. Different combinations of random effects were modeled to find the best compromise between having a maximal-effects random structure and a converging model (see Baayen, Davidson, & Bates, 2008; Barr, Levy, Scheepers, & Tily, 2013). The best-performing model (based on a likelihood ratio test using the *anova* function in R and the Akaike information criterion) included random intercepts for participant and sentences as well as by-sentence slopes depending on sentence list presented to participants (List A or List B), as suggested in Baayen et al. (2008). See (1):

$$\begin{aligned}&\text{Model1} <\text{- glmer(Correct} \sim \text{PrimeRegularity} * \text{Duration} + (1 \mid \text{Participant})\\&\quad + (1 + \text{SentList} \mid \text{SentNum}), \text{data} = \text{data}, \text{family} = \text{binomial(link=“logit”))}.\end{aligned} \tag{1}$$

To investigate whether prime regularity and duration affected grammatical and ungrammatical sentence judgments differently, grammaticality and its interactions were included in Model 2 [see (2)]. For each of the two experiments, there were no interactions between grammaticality and prime regularity and/or duration, so grammaticality was removed from subsequent models:

$$\begin{aligned}&\text{Model2} <\text{- glmer(Correct} \sim \text{PrimeRegularity} * \text{Duration} * \text{Grammaticality}\\&\quad + (1 \mid \text{Participant}) + (1 + \text{SentList} \mid \text{SentNum}), \text{data} = \text{data}, \text{family} = \text{binomial(link=“logit”))}.\end{aligned} \tag{2}$$

To investigate the effects of CA and RA, these variables (z-score scaled and centered using the *scale* function in R) were added to the base model [see (3) and (4)] in two separate models because we were interested in the direct effect of each continuous variable rather than their interaction:

$$\text{Model3} <\text{- glmer(Correct} \sim \text{PrimeRegularity} * \text{Duration} * \text{RAScaled} + (1 \mid \text{Participant}) + (1 + \text{SentList} \mid \text{SentNum}), \text{data} = \text{data}, \text{family} = \text{binomial(link="logit"))} \tag{3}$$

$$\text{Model4} <\text{- glmer(Correct} \sim \text{PrimeRegularity} * \text{Duration} * \text{CAScaled} + (1 \mid \text{Participant}) + (1 + \text{SentList} \mid \text{SentNum}), \text{data} = \text{data}, \text{family} = \text{binomial(link="logit"))}. \tag{4}$$

Response time data. Because RTs for ungrammatical sentences were measured from the end of the error syllable and RTs for grammatical sentences were measured from the end of the sentence, this introduced an artificial bimodal distribution (with faster RTs for grammatical items than for ungrammatical items) and allowed for negative RT values for grammatical sentences (because participants were able to predict that there was no error before the end of the sound file). Therefore, these data did not fit a gamma or inverse Gaussian distribution to use with GLMER (as suggested in Lo & Andrews, 2015, for adult RT data), and so we ran a linear mixed-effects model, maintaining grammaticality as a fixed effect.

Our base model for RT [see (5)] included the fixed effects of prime regularity, duration, grammaticality, and all interactions. We again compared all different random-effects structures to find the balance between maximal random effects and convergence of the model (Baayen et al., 2008). The full random-effects structure (when random slopes for both independent variables were included) did not converge for the data of Experiment 2, so for comparison between the two experiments and the accuracy models we included the same random-effects structure as in the accuracy model (random intercepts for participants and sentences as well as by-sentence slopes depending on sentence list presented to participants: List A or List B):

$$\text{Model5} <\text{- lmer(RT} \sim \text{PrimeRegularity} * \text{Duration} * \text{Grammaticality} + (1 \mid \text{Participant}) + (1 + \text{SentList} \mid \text{SentNum}), \text{data} = \text{data}). \tag{5}$$

We then added RA [see (6)] and CA [see (7)] separately, as in the accuracy analyses:

$$\text{Model6} <\text{- lmer(RT} \sim \text{PrimeRegularity} * \text{Duration} * \text{Grammaticality} * \text{RAScaled} + (1 \mid \text{Participant}) + (1 + \text{SentList} \mid \text{SentNum}), \text{data} = \text{data}) \tag{6}$$

$$\text{Model 7} <\text{- lmer(RT} \sim \text{PrimeRegularity} * \text{Duration} * \text{Grammaticality} * \text{CAScaled} + (1 \mid \text{Participant}) + (1 + \text{SentList} \mid \text{SentNum}), \text{data} = \text{data}). \tag{7}$$

For all models, significant effects were compared using the *emmeans* package (Version 1.4.3.01; (Lenth, 2019). This package determines whether there are significant differences between conditions based on the estimates and standard errors within the model. Reported *p* values were adjusted using the Tukey method for a family of estimates (implemented via *emmeans;* (Lenth, 2019). For interactions including continuous variables (RA and CA), *emtrends* (part of the *emmeans* package) was used to determine whether there were significant trends in performance depending on the continuous variable as a function of the categorical variables

Experiment 1

Method

Participants

A total of 36 children (16 girls and 20 boys) aged 7 to 9 years from two different private schools participated in Experiment 1. Of these children, 4 had an RA that was 18 months or more inferior to their CA, which is considered being at risk for dyslexia (Lefavrais, 1967). Therefore, these children were removed from the analysis. For the remaining 32 participants, the mean CA was 104 months

(SD = 6.19, range = 90–111), the mean RA was 116 months (SD = 17.87, range = 88–171), and the difference between RA and CA averaged + 12 months (SD = 14.55, range = –6 to +61). Note that 1 participant did not have any RA information because this child did not bring glasses and, therefore, could not read the text. The experiment was run in accordance with the Declaration of Helsinki, all data were anonymized, and parents of all children provided written informed consent prior to the experiment.

Data analyses

Regarding RT removal, incorrect responses averaged 15.8% (SD = 10.47) across all conditions and participants. Removed RTs ± 3 standard deviations from each individual's mean RT averaged 1.76% (SD = 0.97).

Results

D prime and response bias c

There was a nonsignificant trend for *d'* values to be higher after 16-s primes than after 8-s primes, $F(1, 31) = 3.82$, $p = 0.06$, $\eta^2_p = 0.11$ (see Fig. 2), but there was no main effect of prime regularity ($p = 0.88$) and no interaction between prime regularity and duration ($p = 0.66$). There were no significant effects for response bias *c* (see Supplementary Table 1; all *p* values > 0.64). RA correlated positively with *d'* judgments after regular rhythmic primes for durations of both 8 s, $r(30) = 0.37$, $p = 0.039$, and 16 s, $r(30) = 0.36$, $p = 0.046$, but not after irregular rhythmic primes for durations of 8 s, $r(30) = 0.24$, $p = 0.19$, or 16 s, $r(30) = 0.11$, $p = 0.55$. See Fig. 3. CA did not correlate with any of the conditions (all *p* values > 0.13), nor did response bias *c* (all *p* values > 0.13).

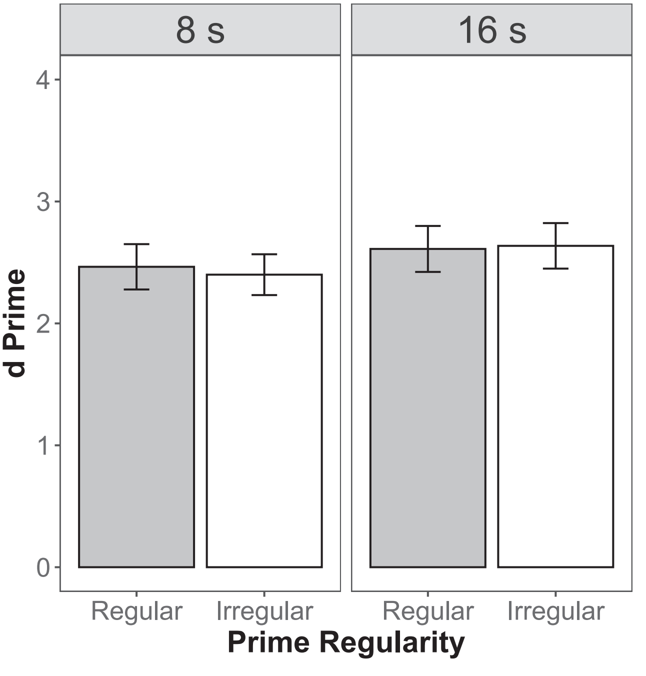

Fig. 2. Sensitivity to grammaticality judgments after regular and irregular rhythms in the 8-s and 16-s conditions for all participants. There was no significant main effect of prime regularity. Error bars represent 1 standard error on either side of the mean.

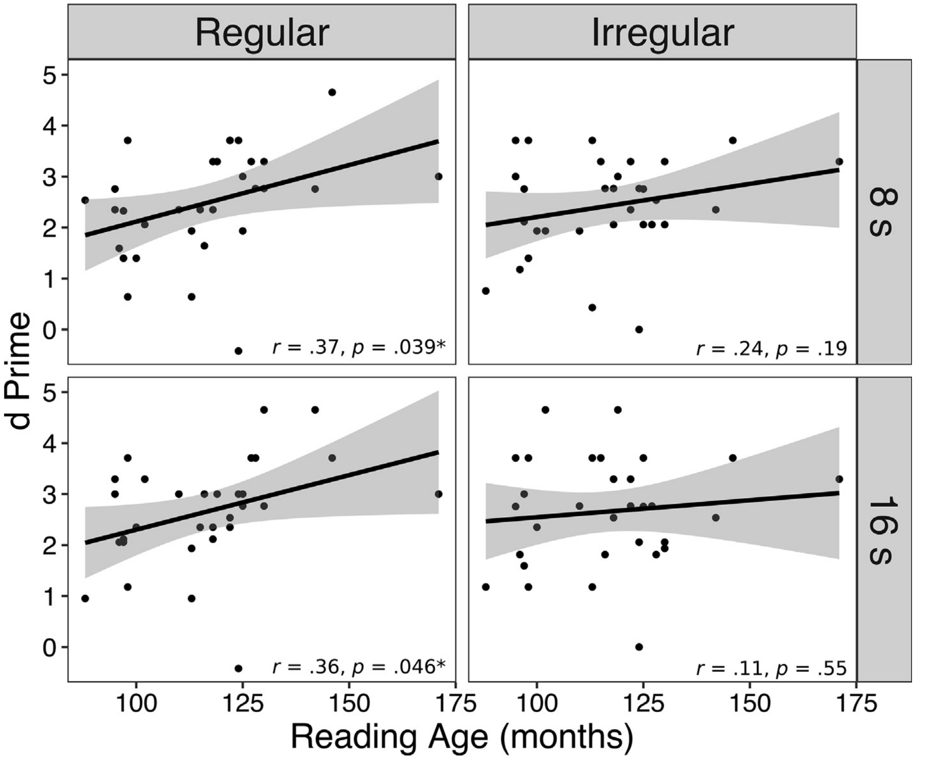

Fig. 3. Correlations between reading age in months and d' values across prime regularity and duration ($df = 30$). Significant p values are marked with an asterisk (*). The regression line is fitted with a linear model in R for illustrative purposes. Shaded error bars are based on standard error of the mean.

Accuracy

Model 1 (main effects only). The main effect of duration was marginal, $\chi^2(1, N = 32) = 3.73$, $p = 0.053$, with participants performing better overall for 16-s primes than for 8-s primes. There was no main effect of prime regularity, $\chi^2(1, N = 32) = 0.14$, $p = 0.71$, and no interaction between prime regularity and duration, $\chi^2(1, N = 32) = 0.01$, $p = 0.91$.

Model 2 (including grammaticality). With grammaticality included in the model, the main effect of duration was significant, $\chi^2(1, N = 32) = 4.79$, $p = 0.03$, and there was a main effect of grammaticality, $\chi^2(1, N = 32) = 24.31$, $p < 0.001$, with participants being more accurate for grammatical sentences than for ungrammatical sentences. There were no other significant effects (all p values > 0.24).

Model 3 (RA added). The main effects of duration, $\chi^2(1, N = 32) = 3.50$, $p = 0.06$, and RA, $\chi^2(1, N = 32) = 3.21$, $p = 0.07$, were marginal, with a trend for children with higher RAs to perform better overall. No other effects were significant (all p values > 0.14).

Model 4 (CA added). There was a main effect of CA, $\chi^2(1, N = 32) = 4.87$, $p = 0.03$, with participants performing more accurately with age. There was no main effect of duration, $\chi^2(1, N = 32) = 2.94$, $p = 0.09$, and no other significant effects (all p values > 0.21).

Correct response times

Model 5 (main effects only). There were main effects of grammaticality, $\chi^2(1, N = 32) = 487.40$, $p < 0.001$, and duration, $\chi^2(1, N = 32) = 18.76$, $p < 0.001$, which showed that participants were faster to detect grammatical sentences compared with ungrammatical sentences and were faster in the 16-s condition compared with the 8-s condition, in line with the accuracy data. All other effects were non-significant (all p values > 0.39).

Model 6 (RA added). The significant main effects of grammaticality $\chi^2(1, N = 32) = 458.93$, $p < 0.001$, and duration, $\chi^2(1, N = 32) = 20.09$, $p < 0.001$, were confirmed. There were no other significant effects (all p values > 0.20).

Model 7 (CA added). The significant main effects of grammaticality, $\chi^2(1, N = 32) = 500.31$, $p < 0.001$, and duration, $\chi^2(1, N = 32) = 17.66$, $p < 0.001$, were confirmed. There was also a Duration × CA interaction, $\chi^2(1, N = 32) = 7.63$, $p = 0.006$, and a Grammaticality × CA interaction, $\chi^2(1, N = 32) = 8.00$, $p = 0.005$. The Duration × CA interaction suggested, although not significantly, that participants were generally slower with increased CA for the 8-s primes (trend = 74.64, *SE* = 84.6, *t*-ratio = 0.88, $p = 0.38$), but not for the 16-s primes (trend = −5.46, *SE* = 84.6, *t*-ratio = − 0.07, $p = 0.95$). The Grammaticality × CA interaction suggested, again not significantly, that RTs were slower with increasing age for grammatical sentences (trend = 75.36, *SE* = 84.2, *t*-ratio = 0.90, $p = 0.38$), but not for ungrammatical sentences (trend = −6.18, *SE* = 85.0, *t*-ratio = −0.07, $p = 0.94$).

Discussion

Across all children, there was no benefit of regular rhythmic primes compared with irregular rhythmic primes at either 8-s or 16-s durations for *d'*, accuracy, or RT. There was also no influence of prime regularity or duration on bias to respond *grammatical* or *ungrammatical*, as measured by response bias *c*. However, significant positive correlations between RA and *d'* after regular (but not irregular) primes with both durations suggest that the regular primes had a greater influence on children with higher RAs compared with lower RAs. Thus, it appears that regularity in rhythms boosted performance level with increased RA, whereas performance level after irregular primes was not modulated by RA. This finding suggests that children who have a higher reading ability might benefit more strongly from regular primes compared with children who have a lower reading ability at these shorter durations. Based on previous findings showing potential links between children's rhythmic processing capacities and reading capacities (e.g., Bekius et al., 2016; Dellatolas et al., 2009; Flaugnacco et al., 2014), one could argue that children with lower RAs were less able to synchronize with the rhythms than children with higher RAs, especially presented over short durations such as the primes used in the current experiment. This possibility is discussed together with the findings of Experiment 2 in the General Discussion.

Experiment 2

Method

Participants

A total of 36 different children (18 girls and 18 boys) aged 7 to 9 years from two different private schools participated in Experiment 2. Of these participants, 1 had an RA more than 18 months inferior to that child's CA and so was removed from the analysis. For the remaining 35 participants, the mean CA was 103 months (*SD* = 5.59, range = 91–112), the mean RA was 109 months (*SD* = 16.30, range = 85–166), and the difference between RA and CA averaged +6 months (*SD* = 16.71, range = −15 to +59). The experiment was run in accordance with the Declaration of Helsinki, data were anonymized, and parents of all children provided written informed consent prior to the experiment.

Data analyses

All data analyses were performed as in Experiment 1.

Regarding RT removal, incorrect responses averaged 12.9% of trials across participants (*SD* = 8.06). Removed RTs ± 3 standard deviations from each individual's mean RT averaged 1.40% (*SD* = 0.83).

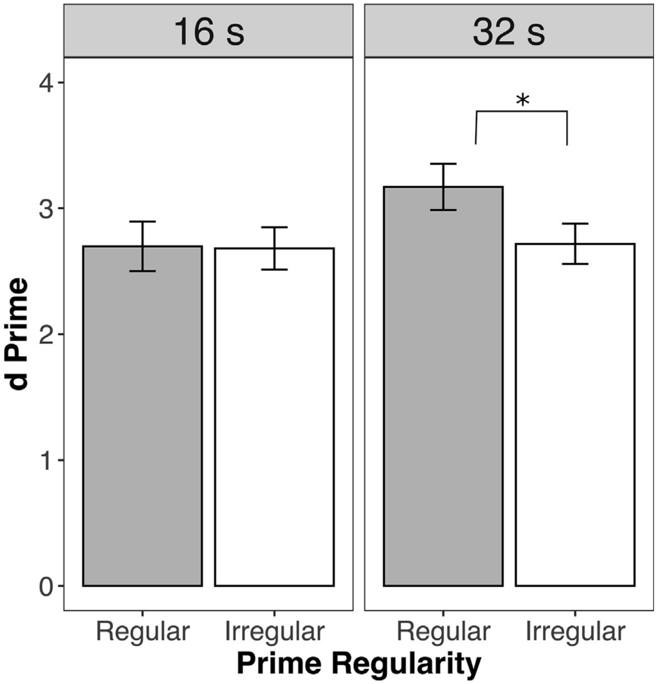

Fig. 4. Sensitivity to grammaticality judgments after regular and irregular primes in the 16-s and 32-s conditions for all participants. Significant contrast is marked with an asterisk (*$p < 0.05$). Error bars represent one standard error either side of the mean.

Results

D prime and response bias c

For *d'*, the main effect of prime fell short of significance, $F(1, 34) = 3.53$, $p = 0.07$, $\eta_p^2 = 0.09$, but indicated a nonsignificant trend for higher *d'* after regular primes than after irregular primes. The main effect of duration was significant, $F(1, 34) = 4.19$, $p = 0.048$, $\eta_p^2 = 0.11$, with better performance after 32-s primes compared with 16-s primes, but there was no Prime Regularity × Duration interaction, $F(1, 34) = 1.72$, $p = 0.20$, even though Fig. 4 shows an interactive pattern. Based on this observation and our strong hypothesis of a priming effect with 32-s primes based on previous work, we tested for prime effects at each duration. For 32-s primes, *d'* values were significantly higher after regular primes than after irregular primes, $t(34) = 2.19$, $p = 0.036$, $d = 0.33$, whereas for 16-s durations, performance did not differ depending on prime regularity ($p = 0.94$). There were no significant effects for response bias *c* (see Supplementary Table 1; all *p* values > 0.40).

RA positively correlated with *d'* after 32-s regular primes, $r(34) = 0.33$, $p = 0.050$, but not after 16-s regular primes, $r(34) = 0.28$, $p = 0.11$, or after irregular primes at either 16 s, $r(34) = 0.27$, $p = 0.11$, or 32 s, $r(34) = 0.08$, $p = 0.67$. See Fig. 5. CA did not correlate with any of the conditions (all *p* values > 0.28), nor did response bias *c* (all *p* values > 0.24).

Accuracy

Model 1 (main effects only). The main effect of duration was significant, $\chi^2(1, N = 35) = 7.36$, $p = 0.007$, with better performance after the 32-s primes compared with the 16-s primes. The interaction between prime regularity and duration fell just short of significance, $\chi^2(1, N = 35) = 3.79$, $p = 0.051$, and there was no main effect of prime regularity, $\chi^2(1, N = 35) = 1.30$, $p = 0.25$. Based on the marginal interaction and theoretical hypotheses, we ran paired contrasts between regular and irregular primes

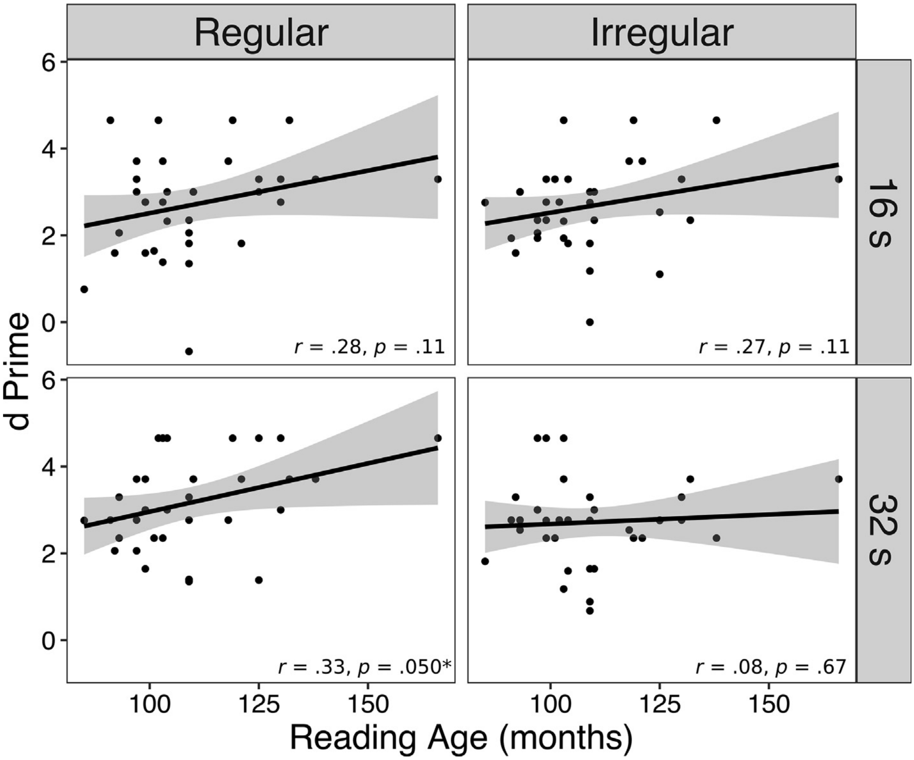

Fig. 5. Correlations between reading age (in months) and *d'* depending on prime regularity and duration. Significant correlation is marked with an asterisk. The regression line is fitted with a linear model in R for illustrative purposes. Shaded error bars are based on standard error of the mean.

for each duration, which showed that accuracy after regular primes was higher than after irregular primes in the 32-s condition (estimate = 0.37, *SE* = 0.18, *z*-ratio = 2.09, $p = 0.037$), but there was no difference in the 16-s condition (estimate = −0.10, *SE* = 0.16, *z*-ratio = −0.60, $p = 0.55$), supporting the *d'* analysis.

Model 2 (grammaticality added). Including grammaticality in the model gave a main effect of grammaticality, $\chi^2(1, N = 35) = 25.16$, $p < 0.001$, with better performance for grammatical sentences, and confirmed the significant main effect of duration, $\chi^2(1, N = 35) = 5.46$, $p = 0.02$, and the marginally significant interaction between prime regularity and duration, $\chi^2(1, N = 35) = 3.20$, $p = 0.07$. No other effects were significant (all *p* values > 0.29).

Model 3 (RA added). With RA included in the model, the Prime Regularity × Duration interaction reached significance, $\chi^2(1, N = 35) = 3.95$, $p = 0.047$. In addition, there was a significant main effect of RA, $\chi^2(1, N = 35) = 3.96$, $p = 0.046$, indicating increased performance with increased RA. Finally, the significant main effect of duration, $\chi^2(1, N = 35) = 7.47$, $p = 0.006$, was confirmed. No other effects were significant (all *p* values > 0.20).

Model 4 (CA added). With CA included in the model, the Prime Regularity × Duration interaction, $\chi^2(1, N = 35) = 4.35$, $p = 0.04$, was significant, and the main effect of duration was confirmed, $\chi^2(1, N = 35) = 7.94$, $p = 0.005$. There was also a Prime Regularity × Duration × CA interaction, $\chi^2(1, N = 35) = 4.85$, $p = 0.03$. The trend analysis showed that there was a significant trend for performance to increase with

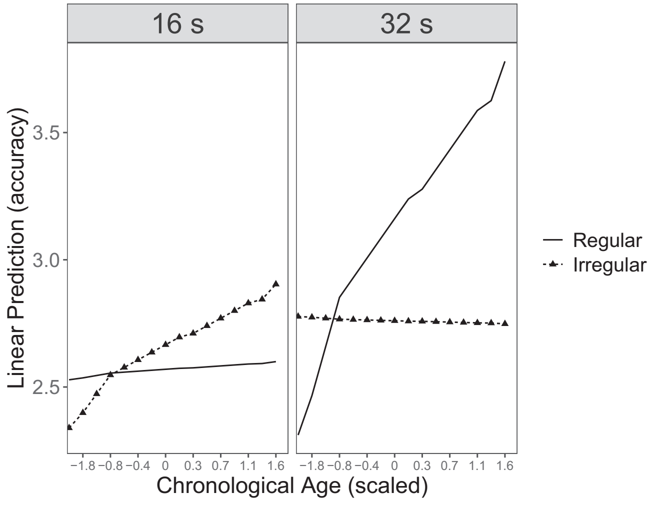

Fig. 6. Visual representation of the Prime Regularity × Duration × Chronological Age interaction. Linear prediction is based on model parameters of accuracy data. For the 32-s duration for regular rhythmic primes, the trend over chronological age was significant ($p = 0.04$).

increasing CA in the 32-s regular condition (trend = 0.38, $SE = 0.19$, z-ratio = 2.02, $p = 0.04$). The other trends were not significant: 32-s irregular (trend = −0.01, $p = 0.94$), 16-s regular (trend = 0.02, $p = 0.93$), and 16-s irregular (trend = 0.14, $p = 0.42$). See Fig. 6. No other effects were significant (all p values > 0.20).

Correct response times

Model 5 (main effects only). A significant main effect of duration, $\chi^2(1, N = 35) = 9.89$, $p = 0.002$, showed that RTs were faster in the 32-s conditions compared with the 16-s conditions, and a significant main effect of grammaticality, $\chi^2(1, N = 35) = 339.52$, $p < 0.001$, showed that RTs were faster for grammatical sentences compared with ungrammatical sentences. No other effects were significant (all p values > 0.23).

Model 6 (RA added). The main effects of duration, $\chi^2(1, N = 35) = 9.95$, $p = 0.002$, and grammaticality, $\chi^2(1, N = 35) = 346.38$, $p < 0.001$, were significant again. There was a significant Prime Regularity × RA interaction, $\chi^2(1, N = 35) = 4.81$, $p = 0.03$, which was further modulated by grammaticality, as reflected in a significant Prime Regularity × RA × Grammaticality interaction, $\chi^2(1, N = 35) = 5.11$, $p = 0.02$ (Fig. 7). For grammatical items, the trends of regular and irregular conditions did not differ, and although both were decreasing with RA, the trends were not significant (regular: trend = −81.2, $p = 0.28$; irregular: trend = −79.6, $p = 0.29$). For ungrammatical items, the trend analysis showed a significant trend for ungrammatical responses to be faster with increasing RAs in the irregular prime condition (trend = −160.6, $SE = 74.9$, t-ratio = −2.14, $p = 0.04$), but not in the regular condition even though in the same direction (trend = −54.7, $p = 0.47$). Therefore, it appears that the interactions between RA and prime regularity were related to faster RTs for ungrammatical sentences after regular primes compared with irregular primes for children with low RAs. As shown in Fig. 7, children with lower RAs were faster to respond after regular primes compared with irregular primes (for ungrammatical items). With increasing RAs, the difference between regular and irregular equalized and then a slight reversal of the effect can be seen.

Model 7 (CA added). The significant main effects of duration, $\chi^2(1, N = 35) = 10.10$, $p = 0.001$, and grammaticality, $\chi^2(1, N = 35) = 339.47$, $p < 0.001$, were confirmed. No other effects were significant (all p values > 0.22).

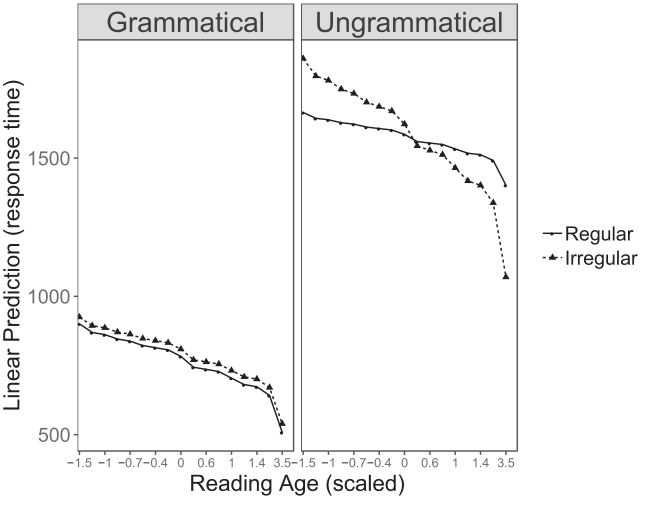

Fig. 7. Visual representation of Model 6 (response times) to show the interaction between prime regularity and reading age depending on grammaticality. For the 32-s duration for irregular rhythmic primes, the trend over reading age was significant (p = 0.04).

Age comparison across experiments

We ran further analyses to investigate whether there were age-related differences in our two experiment samples. Independent-samples t tests showed that there were no significant differences in CA, $t(65)$ = 0.64, p = 0.52, or RA, $t(64)$ = 1.62, p = 0.11, between Experiments 1 and 2.

Discussion

Experiment 2 replicated the rhythmic priming effect in typically developing French children aged 7 to 9 years. For d' and accuracy analyses, the rhythmic priming effect was observed only for the 32-s primes but not for the 16-s primes. After 32-s regular primes, RA correlated with sensitivity to grammaticality judgments (d') and CA correlated with accuracy. Note that the d' effect was not accompanied by an observed response bias, suggesting that the primes did not bias the children to respond in a particular way but rather the regular primes boosted sensitivity to grammatical errors. Both RA and CA, therefore, appear to modulate the rhythmic priming effect, particularly with 32-s primes.

RT analyses also revealed some interesting trends with RA that were not modulated by prime duration; namely, children with lower RAs were particularly slow to respond to ungrammatical sentences after irregular primes, and as RA increased, RT improved and joined the RT level after the regular primes, which were faster even at younger RAs. Put differently, the RT analyses suggest for children with younger RAs that the RT to ungrammatical items benefits from the regular primes, leading to faster RT in comparison with the irregular primes. These findings are discussed further in the General Discussion.

General discussion

The current study was designed to (a) investigate the prime duration necessary to facilitate subsequent grammaticality judgments in children, and (b) make a first attempt to investigate differences depending on CA and RA on the rhythmic priming effect. To this end, two different groups of children aged 7 to 9 years were presented with 8-s and 16-s primes (Experiment 1) or with 16-s and 32-s primes (Experiment 2), followed by six sentences (as in Bedoin et al., 2016; Chern et al., 2018; Ladányi et al., submitted for publication; Przybylski et al., 2013). Replicating this previous research, 32-s regular primes facilitated grammaticality judgments (both sensitivity and accuracy) compared with irregular primes. Across all children, the shorter primes in Experiment 1 (8 s and 16 s) and Experiment 2 (16 s) did not show a rhythmic priming effect for sensitivity or accuracy to grammaticality judgments. However, RA and CA appeared to modulate the rhythmic priming effect, with increased benefits of the regular rhythmic primes for older children and children with higher RAs. Performance after regular rhythmic primes was correlated with RA for both 8-s and 16-s primes in Experiment 1 and with 32-s primes in Experiment 2, suggesting that regular primes were more effective with increased RA. In the 32-s condition of Experiment 2, accuracy after regular primes increased with CA, and children with low RAs appeared to be specifically faster after regular primes (in comparison with irregular primes) across both durations. These results are discussed below in relation to applications of rhythmic priming and developmental rhythm and language processing within a DAT framework.

The main finding from the current study is that longer primes (here, 32 s) were more effective than shorter primes (i.e., 8 s and 16 s) at enhancing grammaticality judgments in children. The hypothesis behind global rhythmic priming paradigms is that the neural oscillations entrained by the regular rhythmic primes sustain over time, resulting in a state of enhanced activation that persists across the subsequent sentences, boosting perception and processing of the natural prosodic contours within subsequent sentences. According to Jones (2019), strong driven oscillations can continue in their intrinsic period even when the original stimulus has stopped and new rhythms are encountered, making them more stable and resistant to change (e.g., from a probe tone or a new sentence) (p. 71). In the current paradigm, this continuation could result in persistent global oscillatory energy that maintains across the phase reset incurred by each incoming sentence. Weak driven oscillations, on the other hand, are more likely to be entirely "captured" by a new rhythm or event. Oscillations are suggested to become stronger depending on the regularity and strength of the external (driving) rhythm (Jones, 2019). It is likely that the longer regular recurring input of the 32-s rhythms was required to sufficiently entrain endogenous oscillations that were strong enough to persist across the six subsequent sentences. Therefore, the current results suggest that at the group level, for children in this age range, 8-s and 16-s primes are not long enough to entrain neural oscillations that are strong enough to concretely affect subsequent grammaticality judgments across a number of subsequent naturally spoken sentences. However, it appears that other factors, including RA and CA, can enhance the strength of the prime effect by potentially enhancing the strength of the entrained oscillations.

Influence of reading age

Across both experiments, correlations were observed between RA and sensitivity to grammatical errors after regular (but not irregular) primes. These correlations were particularly evident for 8-s and 16-s primes in Experiment 1 as well as for 32-s primes in Experiment 2. Such correlations are particularly interesting for the shorter primes because they suggest that shorter rhythmic primes may benefit children with higher RAs. Children with higher RAs might be better and more quickly able to attend and entrain to the rhythms with shorter durations, resulting in stronger oscillations that were able to persist across the subsequent sentences. This suggestion is supported by previously reported correlational research that shows connections between rhythmic abilities and reading skills in typically developing children and adolescents (Bonacina, Krizman, White-Schwoch, & Kraus, 2018; Douglas & Willatts, 1994; González-Trujillo, Defior, & Gutiérrez-Palma, 2014; Gordon, Shivers, et al., 2015; Rautenberg, 2015; Tierney & Kraus, 2013; Wigley, Fletcher, & Davidson, 2009), correlations between length of music training and reading comprehension in 6- to 9-year-old children (Corrigall & Trainor, 2011), and benefits of rhythmic music training on reading skills in 7- and 8-year-old children compared with control groups (Moreno et al., 2009; Rautenberg, 2015; see also Flaugnacco et al., 2015, for enhanced reading skills in 8- to 11-year-old dyslexic children after music training compared with painting training). Note also that children with lower RAs appeared to respond faster after the regular primes than after the irregular primes (for which RTs decreased with RAs to reach the speed observed after regular primes), as measured by the more sensitive measure of RT.

Connections between language skills and rhythmic processing are also predicted by the *temporal sampling framework* (TSF) of developmental dyslexia (Goswami, 2011), which suggests that impairments in phonological processing (and subsequently reading skills) are based on impaired tracking of the speech envelope. The TSF predicts that children who are poor readers may also have difficulties in processing musical rhythm. Supporting this hypothesis, correlations have been observed between rhythmic processing tasks and various measures of reading across both typically developing children and children with dyslexia (paced tapping: Thomson & Goswami, 2008; metrical same–different task: Huss, Verney, Fosker, Mead, & Goswami, 2011; rhythm reproduction: Flaugnacco et al., 2014) and children with DLD (paced tapping; Corriveau & Goswami, 2009). Children with higher RAs in our study may also have had better rhythm processing skills, allowing for better synchronization with the rhythms, and a benefit of the rhythmic primes despite their short duration. This possibility now needs to be investigated experimentally by measuring rhythm perception and production skills in subsequent experiments to observe whether greater rhythmic ability is associated with a stronger effect of the regular rhythmic prime on subsequent grammaticality judgments and whether this benefit can be seen with shorter primes for children with better rhythm skills. Relatedly, it would be interesting to investigate whether children in a rhythmic training group show an increased rhythmic priming effect from pretraining to posttraining compared with a control group. Such work would suggest that long-term rhythmic training can also influence short-term effects of musical rhythm and could be useful for rehabilitation and training.

Influence of chronological age

Experiment 2 revealed that the effect of the 32-s rhythmic primes was stronger with increasing age. Previous developmental research has shown that beat synchronization ability increases with age (Drake et al., 2000; Drewing, Aschersleben, & Li, 2006; Ireland et al., 2018; McAuley et al., 2006; Savion-Lemieux, Bailey, & Penhune, 2009; Tryfon et al., 2017), as does the ability to synchronize to multiple hierarchical levels (Drake et al., 2000). Therefore, it is possible that the older children in Experiment 2 were better able to synchronize with the rhythms and to extract the beat than the younger children, enhancing the effect of the rhythmic prime on subsequent sentence processing. Effects of *sentence envelope* priming have also been shown for older children (M_{age} = 11;0 [years; months]) but not for younger children (M_{age} = 7;7) (Ríos-López, Molnar, Lizarazu, & Lallier, 2017). It should be noted that the effect of the 32-s primes emerged across all children in Experiment 2, confirming rhythmic priming effects of 32-s primes for young children in French (6;6–12;11: Przybylski et al., 2013), English (5;6–8;7: Chern et al., 2018), and Hungarian (5;0–7;0: Ladányi et al., submitted for publication). The trend for increased accuracy with increased CA after 32-s primes may have emerged in Experiment 2 because the rhythmic primes were more difficult to synchronize with for younger children than for older children. Indeed, the aging hypothesis as stated by Jones (2019) suggests that the strength of endogenous oscillations to external rhythmic stimuli increases with age, with weaker driven oscillations in younger children. Future research could aim to boost synchronization capacity in younger children by adding a motor component to the experiment (e.g., short-term rhythmic or audio-motor training: Cason et al., 2015; tapping along to the regular rhythm: Morillon & Baillet, 2017; Tierney & Kraus, 2014), which could result in stronger entrainment to the rhythms and a potentially stronger effect of the rhythmic prime even with shorter prime durations.

One might also argue that the metrical complexity and tempo of the rhythmic primes were not optimal for the younger participants. Drake et al. (2000) tested 4-, 6-, 8-, and 10-year-old French-speaking children (and adults) and reported that the younger children were less flexible in the tempos they could tap to, synchronize with, and discriminate (a similar pattern can be observed for English-speaking children in McAuley et al., 2006). The 4-year-olds showed a limit of a 300- to 400-ms IBI, which widened with age, and the spontaneous tapping rate (suggesting an internal referent period) increased from approximately a 385-ms inter-tap interval (ITI) for 4- and 6-year-olds to a 456-ms ITI for 8-year-olds, a 478-ms ITI for 10-year-olds, and a 628-ms ITI for adults. Our rhythms had a 500-ms IBI. Therefore, it is possible that the older children in Experiment 2 had a preferred tempo that was closer to the beat level of the presented rhythms than the younger children. However, it is important to note that even the younger children can benefit from this slightly slower IBI when the prime duration is longer, as shown here with the 32-s primes and as seen in previous studies (e.g., Bedoin et al., 2016; Chern et al., 2018; Przybylski et al., 2013). Based on our current findings, it would be interesting to systematically manipulate CA and the relation of the prime's IBI with preferred tempo to investigate whether these factors have an effect on the strength of the rhythmic priming effect as well as the necessary prime duration.

Differences between CA and RA and implications

Data of Experiment 1 suggest an enhanced rhythmic priming effect for children with higher RAs, whereas data of Experiment 2 suggest an enhanced rhythmic priming effect for older children (increased CA). No significant differences in CA or RA were observed between experiments, suggesting that the children were comparable in CA and RA across experiments. The different effects may have emerged because of the duration of the primes being tested. To benefit from the rhythmicity of the short primes in Experiment 1, it was necessary to quickly and accurately entrain to the rhythm to create strong expectations that continued across the subsequent sentences. Children with higher RAs (perhaps also linked to greater beat processing abilities) may have been better able to quickly and successfully entrain to the rhythms compared with those with lower RAs. To benefit from the longer primes in Experiment 2, children needed to listen attentively for up to 32 s. Research has shown that the ability to sustain attention over time increases with CA (Greenberg & Waldman, 1993; Lin, Hsiao, & Chen, 1999), and Lin et al. (1999) showed a particular increase in sustained attention from 7 to 8 years of age. The current results, therefore, may reflect different skills necessary to benefit from rhythmic primes depending on their duration.

These findings have implications for future rhythmic priming and rhythmic training studies. Our results obtained with children in the age range of 7 to 9 years suggest that rhythmic priming (a) is more successful with longer prime durations and for older children and (b) may also be successful at shorter prime durations for children with higher RAs. For the longest prime length (32 s), a benefit for regular primes compared with irregular primes was found across all children, suggesting that this prime duration is appropriate for use with the current age group (as seen in previous research, e.g., Bedoin et al., 2016; Przybylski et al., 2013). A recent study by Canette et al. (2020) used 16-s regular rhythmic primes as in the current experiments and found a significant benefit for regular rhythmic primes compared with textural sound primes and a baseline silence condition (tested in a different sample of participants) on a grammaticality judgment task in children aged 7;2 to 8;11. It is possible that the children in this study had high RAs or that the comparison with textured primes changed the experimental context, resulting in a benefit from short rhythmic primes. Another difference from the current experiment is that Canette et al. (2020) presented only four sentences after each prime instead of six sentences. Therefore, it would be interesting to further investigate the potential interaction between prime duration and the persistence of the priming effect over time. Our current findings suggest that RA should be more systematically assessed and reported in studies of rhythmic processing abilities as well as studies investigating rhythmic stimulation in language processing.

One outstanding question relates to the observation that correlations with RA and performance after a regular prime were observed in all regular conditions except the 16-s condition in Experiment 2. It is possible that the priming effect is related to RA most strongly at short prime durations and that the experimental context played a role in the current result pattern. As discussed above, children with higher RAs may have been better able to immediately entrain to the beat of the 8-s primes, which then persisted over time to the second part of the experiment with 16-s primes. However, the difference between children with low and high RAs when starting with 16-s primes might not have been so large given that both may have been able to successfully entrain, but not benefit from, sustained oscillations. Again, in the second part of Experiment 2, and for the longer primes, the correlation with RA emerged again, suggesting a benefit of the longer prime over time for children with higher RAs. To further investigate these questions, it would be valuable to measure rhythmic entrainment in children and investigate whether there are connections between entrainment to the beat, RA, and prime duration.

The current experiments provide an initial attempt to investigate CA and RA effects within the rhythmic priming paradigm. Future research should manipulate CA and RA more directly by creating distinct groups to compare and with a larger age range. The benefit of the rhythmic prime may also be optimal at different ages depending on the language tested; for example, English-speaking children

(Chern et al., 2018) might be able to benefit from rhythmic primes at a younger age than French-speaking children (Bedoin et al., 2016; Przybylski et al., 2013) due to a clearer rhythmic structure in English (Lidji, Palmer, Peretz, & Morningstar, 2011).

Conclusion

The current experiments replicated previous findings showing that 32-s regular rhythmic primes enhance grammaticality judgments compared with irregular rhythmic primes in 7- to 9-year-old children. Our study revealed this duration as optimal compared with shorter prime durations (8 s and 16 s), likely because of stronger expectations and neural entrainment to the regular rhythms that persisted across the subsequent block of sentences. Our study provides new contributions by showing that RA was correlated with sensitivity to grammaticality judgments after short regular primes (8 s and 16 s) in Experiment 1 and after long rhythmic primes (32 s) in Experiment 2 and that accuracy after 32-s regular rhythmic primes was linked with age in Experiment 2. Based on our findings, future research should continue to investigate effects of CA and RA on the rhythmic priming effect, in line with the development of neural entrainment and synchronization to the beat in young children within the dynamic attending framework (Drake et al., 2000; Jones, 2019; McAuley et al., 2006).

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jecp.2020.104885.

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