

Regular rhythmic primes boost P600 in grammatical error processing in dyslexic adults and matched controls

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ABSTRACT

Regular musical rhythms orient attention over time and facilitate processing. Previous research has shown that regular rhythmic stimulation benefits subsequent syntax processing in children with dyslexia and specific language impairment. The present EEG study examined the influence of a rhythmic musical prime on the P600 late evoked-potential, associated with grammatical error detection for dyslexic adults and matched controls. Participants listened to regular or irregular rhythmic prime sequences followed by grammatically correct and incorrect sentences. They were required to perform grammaticality judgments for each auditorily presented sentence while EEG was recorded. In addition, tasks on syntax violation detection as well as rhythm perception and production were administered. For both participant groups, ungrammatical sentences evoked a P600 in comparison to grammatical sentences and its mean amplitude was larger after regular than irregular primes. Peak analyses of the P600 difference wave confirmed larger peak amplitudes after regular primes for both groups. They also revealed overall a later peak for dyslexic participants, particularly at posterior sites, compared to controls. Results extend rhythmic priming effects on language processing to underlying electrophysiological correlates of morpho-syntactic violation detection in dyslexic adults and matched controls. These findings are interpreted in the theoretical framework of the Dynamic Attending Theory (Jones, 1976, 2019) and the Temporal Sampling Framework for developmental disorders (Goswami, 2011).

1. Introduction

The role of rhythm in speech and language processing and the potential application to rehabilitation have attracted increasing interest (e.g., Kotz and Schwartz, 2010; Schön and Tillmann, 2015). Investigating the potential influence of auditory rhythmic stimulation on language processing has been motivated by previously observed links between musical rhythm processing and speech processing. Given that these domains share neural resources and require similar rhythm perception and production capacities, rhythm-based training has been suggested to benefit language processing (e.g., Fiveash et al., submitted, for reviews;

Fuji and Wan, 2014).

Numerous studies have demonstrated relations between rhythmic and linguistic skills. In typically-developing children, the ability to synchronize with the beat is associated with competences underlying reading acquisition, such as phonological awareness, verbal short-term memory, and rapid naming (Woodruff Carr et al., 2014). Rhythm perception abilities have also been reported to be associated with morpho-syntactic abilities in speech production (Gordon et al., 2015b). In children with developmental dyslexia and specific language impairment (SLI), rhythm competence has been associated with phonological awareness and reading skills (e.g. Corvieux and Goswami, 2009;

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Flaugnacco et al., 2014; Huss et al., 2011; Thomson and Goswami, 2008). These links between rhythmic and linguistic skills have been further supported by studies demonstrating that musical training can benefit phonological and reading skills in dyslexic children (e.g., Overy, 2000; Flaugnacco et al., 2015).

The benefit of rhythm for speech processing has been shown not only with long-term musical training (e.g., Flaugnacco et al., 2015), but also with short-term exposure to musical material within an experimental session. Implemented as a priming paradigm, participants listened to a rhythmic music-like sequence before performing a linguistic task (see Schön and Tillmann, 2015 for a review). The temporal structure of the music-like sequences was either exactly matched to the accent structure of the following sentence (and compared to a mismatched structure, e.g., Cason et al., 2015; Cason et al., 2014) or contained a strongly metrical structure that primed a set of subsequently presented sentences (e.g., Chern et al., 2018; Kotz et al., 2005; Przybylski et al., 2013). This latter approach is not based on a one-by-one matching of a given prime with its associated sentence, but taps into more general processes by stimulating temporal attention by the regular structures of the rhythmic prime (e.g., Jones, 1976). A beneficial effect of a regular metrical prime on subsequent sentence processing was first shown for patients with basal ganglia lesions. While the typically observed electrophysiological marker of grammatical error detection (the P600) has been reported to be missing in this population (Kotz et al., 2003), listening to regular march music for 3 min before listening to blocks of grammatical and ungrammatical sentences re-elicited this marker (Kotz et al., 2005). This approach was further developed by studying beneficial effects of rhythmic priming on language processing in children with developmental language disorders. Przybylski et al. (2013) showed that the regularity of a musical prime influenced subsequent grammatical processing (i.e., morpho-syntactic processing) in dyslexic children, SLI children and typically developing children. For all participant groups, grammaticality judgments were better after a metrically regular prime compared to a temporally irregular prime without a clear underlying meter (see also Chern et al., 2018). This effect of relative facilitation (i.e., comparing regular to irregular primes) was extended to the observation of a benefit of regular primes over baseline primes, implemented in environmental sound scenes or musical excerpts based on spectro-temporal patterns without rhythmic features (Bedoin et al., 2016; Canette et al., 2020). These findings support the hypothesis that the observed rhythmic priming effect relies on a benefit of the regular structure of the musical primes rather than a cost of the irregular primes. It is interesting to highlight that SLI and dyslexic children can benefit from the temporally regular structure of the primes despite their previously reported rhythm processing difficulties (e.g., Corriveau and Goswami, 2009; Muneaux et al., 2004). A recent study combined the rhythmic priming paradigm with a linguistic training program focusing on syntax processing and extended the beneficial effect of musically rhythmic primes to hearing-impaired children with cochlear implants (Bedoin et al., 2017).

The reported beneficial priming effects of regular musical structures on language processing can be interpreted within the framework of the Dynamic Attending Theory (Jones, 1976, 2019; Jones and Boltz, 1989; Large and Jones, 1999). According to this framework, attention is not distributed equally across time, but aligns with external regularities (for example, to beat onsets in musical structures). This allows listeners to develop expectations about when future events will occur (i.e., predictive timing), leading to facilitated event and structure processing at expected time points thanks to enhanced attentional resources. In the rhythmic priming paradigm, the hypothesis is that the entrainment to the regular musical prime benefits subsequent language processing, aiding sequencing and structural integration. More specifically, the regular events in the musical prime provide predictable cues that may allow for boosting and entraining of internal oscillators. These oscillators then persist after the musical prime has stopped and facilitate entrainment to the less regular speech signal. Consequently, this

entrainment then benefits sentence processing by facilitating segmentation and sequencing of the speech signal and thus favoring the processing of its syntactic structure.

The present study investigated the beneficial effect of regular rhythmic musical primes on syntax processing in dyslexic adults and their matched controls by measuring event-related potentials (ERPs). Based on Kotz et al. (2005), in which a regular musical prime evoked a P600 to grammatical errors in subsequently presented sentences in patients with basal ganglia lesions (who are missing this component without the prime, see Kotz et al., 2003), we predicted an enhanced P600 after regular musical primes in comparison to irregular primes. The P600 component is of particular interest as a biomarker because several studies have shown P600 abnormalities in dyslexic adults in response to morpho-syntactic violations (e.g., subject-verb agreement), as used here (Cantiani et al., 2013; Rispens et al., 2006). In particular, the P600 peaked later for dyslexic participants in comparison to control participants.

Our study recorded EEG during the rhythmic priming paradigm in dyslexic adults and their matched control participants. The effect of regular primes was compared to that of irregular primes within the same participants, thus avoiding a comparison across studies and patient groups (as in Kotz et al., 2005). The rhythmic priming paradigm was implemented as in Przybylski et al. (2013), but with four main changes. First, we measured not only behavioral performance of grammaticality processing, but also recorded EEG, aiming to observe an enhanced P600 in response to grammatical errors after the regular primes. Second, we elaborated a set of new musical primes (instead of using only one prime pair), which were also musically more attractive and complex. Third, we constructed new sentence material that controlled error positions to be optimal for the ERP measurements and that was complemented with filler sentences. Fourth, in addition to the grammaticality judgments performed on the sentences presented after the primes, participants performed behavioral tests to (1) assess complex morpho-syntactic skills and (2) measure rhythm perception and production skills. Rhythm skills were assessed with tapping tasks (i.e., free spontaneous tapping, synchronization) and an adaptation of the complex Beat Alignment Test (Einarsen and Trainor, 2016; based on Iversen and Patel, 2008).

2. Methods

2.1. Participants

Twenty-six adults participated in the study: 13 dyslexic adults (7 women, 10 right-handed, mean age = 23.2 years, SD = 2.95) and 13 matched control adults (7 women, 10 right-handed, mean age = 22.5 years, SD = 2.07). All participants reported French as their native language, with one dyslexic participant reporting bilingualism with English. None reported auditory deficits. Education levels did not differ between the dyslexic group ($M = 14.92$ years; $SD = 1.55$) and the control group ($M = 15.31$ years, $SD = 0.95$), $p = .45$. Musical background, as measured by years of instrumental instruction, did not differ between the dyslexic group ($M = 2.00$ years; $SD = 2.16$) and the control group ($M = 1.69$ years, $SD = 2.13$), $p = .72$.

As part of a larger research project investigating dyslexia at the university (Abadie and Bedoin, 2016), dyslexic participants completed a set of language and neuropsychological tests. All dyslexic participants had developmental dyslexia and reported having seen a speech therapist for the diagnosis and for training sessions designed to reduce reading difficulties for at least two years during childhood, while none of the controls reported this.² None of the controls reported history of spoken or written language disorders. All dyslexics had scores in the normal range for Raven's matrices (mean standard score = 10.31, $SD = 3.25$)

² One control participant reported to have consulted a speech therapist for tongue position correction.

and for reading comprehension (average z-score placed them above the mean = 1.91, SD = 0.60). None had any current or past psychiatric or neurological diagnosis nor attention disorder with or without hyperactivity (ADHD). Eleven dyslexics had a pathological score in reading and/or orthographic skills for pseudo-words and/or irregular words according to the *ECLA-16* + battery (Gola-Asmussen et al., 2010), a set of standardized tests adapted for adult assessment and broadly based on the *Batterie Analytique du Langage Ecrit* (BALE, Jacquier-Roux et al., 2010), which is widely used in France to assess dyslexia in children. It is difficult to precisely categorize the form of dyslexia in adults because of successful compensation mechanisms – especially in the case of students. Among these eleven dyslexics, four had a pathological score in phonological awareness, two had a pathological score in a visual attention skill, which is frequently disturbed in surface dyslexia (measured with *EVADYS* test, Valdois et al., 2014, see Bosse et al., 2007), and four had a pathological score in both phonological awareness and visual attention skill.³ The remaining two dyslexics did not have scores currently reaching the pathological threshold in reading or orthographic skills, despite having been diagnosed as dyslexic children when they were at school, and while still experiencing reading difficulties. However, they had pathological scores in phonological awareness (a persistent deficit underlying phonological and mixed forms of dyslexia) and/or a visual-attentional deficit (frequently observed in surface dyslexia). Therefore, our dyslexic participants were mainly experiencing phonological difficulties (i.e., phonological or mixed forms of dyslexia, which are the most frequently observed forms of this neurodevelopmental pathology) (see Table 1).

Each participant performed the EEG experiment in one testing session and the behavioral tests on syntax processing and rhythm perception and production in a second testing session (except for one dyslexic participant who did not come back to the second session). Written informed consent based on French ethics procedure approval Committee

Table 1

Means and standard deviations (SD) of the dyslexic participants' results reported in z-scores for language abilities and visual-attentional span, and in standard scores for one measure of nonverbal intelligence (Raven's Matrices). Pathological z-scores are defined as scores that place the participant at least 1.65 SD below the mean of the normative group in linguistic tests (i.e., the usual criterion for speech therapists) and at least 2.00 SD below the mean of the normative group in the test of visual attention span (global report of five-letter strings). For the Matrix test, a standard score at or below 4 is considered as pathological. Reading, orthographic and phonological skills were assessed with the test *ECLA 16+* (Gola-Asmussen et al., 2010); reading comprehension was assessed with the test *Le Vol du PC* (Boutard et al., 2004); and visual attention span was assessed with the test *EVADYS* (Valdois et al., 2014). A star (*) indicates pathological scores.

		Mean z-score	SD
Reading times	Pseudo-words	-2.23*	2.20
	Irregular words	-1.72*	1.93
Reading comprehension	Text	1.91	0.60
	Pseudo-words	-1.59	1.19
Spelling	Irregular words	-1.40	1.25
	Suppression of initial phoneme	-2.47*	1.28
Phonology (time)	Global report	-1.55	2.15
	(correct letters)		
		Mean standard score	SD
Non-verbal fluid intelligence and abstract reasoning	Raven's matrices	10.31	3.25

³ Information about phonology and visual attention skills is missing for one dyslexic participant.

(CPP Sud-Est II, 2007-009-3: *Processing of Music and Language*) was obtained from all participants prior to the experiment, which was conducted in accordance with the guidelines of the Declaration of Helsinki.

2.2. Materials

2.2.1. Rhythmic material

Twenty-two rhythmic sequences were used. In addition to the regular and irregular sequences of Przybylski et al. (2013), 20 new sequences were constructed (10 regular, 10 irregular) with the same features related to meter as in Przybylski et al. (2013), but with more temporal and timbral variety with the aim of creating more musical and diverse material. The regular sequences were constructed on the basis of a 4/4 meter and a 120 BPM tempo (i.e., inter-beat-interval of 500 ms or 2 Hz). The new sequences were formed by four overlaid rhythmic patterns. To vary and characterize the sequences in timbre, each layer was played by one (and sometimes two) percussion instrument(s) (i.e. bass drum, snare drum, tom-tom, and cymbal). All sequences were played with MIDI VST instrument timbres. Four of the sequences also contained some samples of electronic percussions. Each sequence was composed of one cycle of 16 beats that was repeated four times, thus leading to a duration of 32 s. At the end of a cycle, a short rhythmic pattern or a percussion sound was added to reinforce the sensation of formal periodicity. To create a feeling of completion at the end of the sequence, the first beat of the cycle was added at the end, thus adding about 2 s with a short reverberation effect, leading to the total duration of 34 s.

The irregular sequences were derived from the regular sequences. The percussion sounds, the total duration and the durations of each event were identical. For each of the four rhythm patterns, the number of percussive events was the same as for the regular sequences, but reordered across the sequence to obtain a maximum of rhythmic irregularity. In this way, it was not possible to perceptually extract an underlying pulse or a regular metric. Each rhythmically regular sequence led to the construction of one rhythmically irregular sequence. All sequences were recorded with Cubase 4 and Kontakt 3 VST instruments. A short reverb effect was added (reverb time 1.75 s, mixed at 25%). They were exported in 16 bits/48 000 Hz mono wav files and normalized in loudness.

2.2.2. Linguistic material

The experimental material was composed of 768 French sentences that were grammatically correct (384) or incorrect (384). Grammatical and ungrammatical sentences were composed of an average of 9.15 syllables (range = 7–12; SD = 1.12). All sentences were composed of five words (average duration of the sentences = 1996 ms ± 199 ms) and had the same syntactic construction (i.e., pronoun, verb, determiner, adjective and noun or noun and adjective). Incorrect sentences contained a subject-verb (i.e., number) agreement error (e.g., *Je finirai/*finirons les derniers exercices – I will finish_[singular, plural] the last exercises* or *Nous finirons/*finirai les derniers exercices – We will finish_[plural, singular] the last exercises*). Verbs were in future tense, allowing for time-locking the ERPs to the critical morpheme (i.e., just after the phoneme [ʒ]) always at the same location regardless of the verb. For the construction of the sentence set, 192 different sentences were used as the basis and for each sentence, four versions were constructed: two correct versions (with either *Je* (I) or *Nous* (we) as the subject) and the two derived grammatically incorrect versions. The resulting 768 sentences were split into four lists of 192 sentences, with one of the four versions per list. In each list, there were 48 correct sentences with *Je* (I) as the subject, 48 correct sentences with *Nous* (we) as the subject, 48 incorrect sentences with *Je* (I) as the subject, and 48 incorrect sentences with *Nous* (we) as the subject. Each participant heard one of the lists with 48 sentences in each experimental condition (i.e., four experimental conditions, crossing Rhythmic Prime and Grammaticality as factors), thus hearing only one of the four versions of each sentence, and never the same sentence in its grammatically correct and incorrect versions.

Additionally, 192 filler sentences, grammatically correct (96) or incorrect (96), were constructed to avoid participants focusing only on the verb agreement manipulation in the experimental sentences. The incorrect filler sentences contained gender agreement errors on other words within the sentence, such as a determiner or adjective (e.g., Je garerai la/*le voiture grise – *I will park the_{f, m, J} grey car*). The filler sentences also contained on average 9.00 syllables (range = 7–11; SD = 1.04), were composed of five words with the same syntactic construction, and had an average duration of 2041 ms \pm 216 ms.

For experimental and filler sentences, word frequency was controlled using lemma frequency per million according to the movies corpus (Lexique 3; New et al., 2001). Mean frequency of verbs, adjectives and nouns used for experimental and filler sentences were 188.7 (SD = 460.4). Sentences were recorded by a native female speaker of French with a natural speed of production with the Rocme! Software (Ferragne et al., 2012).

The experiment was run using the software Presentation (Neurobehavioural Systems). Stimuli were presented via headphones (Pioneer, HDJ-500).

2.2.3. Material for additional behavioral tests

2.2.3.1. Syntax test. To evaluate morpho-syntactic processing in speech perception, a new test was created with subtle morpho-syntactic errors, covering errors regarding tense, prepositions and person agreement (in French). We first created 48 correct sentences and derived one incorrect sentence from each correct sentence. Sentences were spread into two lists of 48 sentences (24 correct sentences and 24 incorrect sentences) to avoid participants listening to the same sentence in its correct and incorrect versions. Each correct sentence of the first list was matched in number of words, number of syllables and word's lexical frequency (Lexique 3; New et al., 2001) to a correct sentence of the second list. Half of the participants heard the correct sentences of one list and the incorrect sentences of the other list, and the reverse for the other half of the participants. Sentences were recorded by a native female speaker of French with the same material and procedure as for the sentences used in the EEG recording. The experiment was run using the software Open Sesame (Mathôt et al., 2012) and stimuli were presented via headphones.

2.2.3.2. Temporal processing test. For the synchronization tasks, isochronous sequences of a duration of 20 s (played with a metronome sound, duration = 100 ms) were created at three tempi, notably with inter-sound-intervals of 400 ms, 550 ms and 700 ms. The cBAT (complex Beat Alignment Task) contained eleven musical excerpts that were used for perception and production tasks, and an additional one as an example (see Einarson and Trainor, 2015, for details). These musical excerpts had an average target inter-beat-interval of 500 ms (ranging from 366 ms to 692 ms across the excerpts).

For the perception task, an isochronous sequence with a woodblock sound was superimposed on the musical excerpts. This superimposition was either correctly aligned with the beat of the musical excerpt ("on the beat") or misaligned in either phase (shifting the isochronous woodblock sequence to be 25% too early or 25% too late relative to the beat of the music) or tempo (increasing or decreasing the tempo of the woodblock sequence by 10% compared to the tempo of the music). Thus, there were three versions of each of the 9 musical excerpts. Participants responded on a computer keyboard as to whether the woodblock was aligned with the excerpt on each trial.

For the production task, participants drummed with a stick on a drum pad (Roland, V-Drums) to the beat of each excerpt. Both the perception and production parts of the temporal processing task were implemented with the software Presentation (Neurobehavioural Systems) and stimuli were presented over headphones.

2.3. Procedure

2.3.1. EEG experiment

The experimental material was presented over 48 blocks, each block consisting of one rhythmic sequence followed by six sentences. In each block of six sentences, there were four experimental sentences (two correct and two incorrect) and two filler sentences (one correct and one incorrect). Sentence distribution in the blocks, sentence order in each block and block order were randomized for each participant. Similarly, the presentation order of the rhythmic sequences was pseudo-randomly determined with the constraint that within the 48 blocks, four consecutive blocks presented the same type of musical sequences (regular or irregular), followed by the other type for the following four blocks (e.g., RRRRIIIIRRRR...). Half of the participants started with regular sequences and half with irregular sequences.

Participants were comfortably seated in a sound-attenuated booth in front of a monitor with a computer mouse. Participants wore headphones and were asked to listen to the music while looking at a fixation cross on the computer screen. At the end of the musical sequence, they judged each of the six following sentences for grammaticality by pressing one of two buttons on the computer mouse. Participants were able to respond 1 s after the end of the sentence when response choices were indicated on the screen by the words *grammatical* and *ungrammatical*. After the participant had responded, the next sentence was triggered after an average delay of 750 ms (randomly determined from a distribution between 500 and 1000 ms). This type of jittered delay was also inserted before each musical sequence and the first sentence of the set. Participants were told to look at the fixation cross and to blink as little as possible during the experiment, and were instructed to avoid blinking during the sentences in particular. There was a short break after every 12 blocks. The experiment lasted 50 min.

2.3.2. Behavioral post-tests

For the rhythm perception and production tests, participants first performed the production tasks: (1) spontaneous regular tapping at their preferred rate for a duration of 30 s, (2) tapping along to the isochronous sequences with the three different tempi (see above), and (3) tapping along to the beat of nine musical excerpts from the cBAT production test. Then, participants performed the perception test of the cBAT and judged whether the sound of a metronome was aligned or not with the beat of 24 musical excerpts (8 correctly aligned, 8 phase-shifted, 8 tempo-shifted). Participants could respond during the musical excerpt. After responding, participants indicated their confidence level in their response (on a scale from 1 to 3). These tests lasted about 30 min.

For the syntax test, participants were asked to judge the grammaticality of each sentence by pressing one of two keys on the computer keyboard. Participants were alerted about the difficulty of the test and to be careful and rigorous in their judgments. A fixation point was displayed on the screen during the presentation of the sentence, and it disappeared when participants gave their response. A new sentence was triggered after each response. Presentation order of the sentences was randomized for each participant. This test lasted about 5 min.

2.4. Data acquisition and analyses

2.4.1. EEG recording and analyses

The EEG signal was recorded with 95 Ag/AgCl active electrodes (ActiCAP, Brain Products GmbH) configured according to the international 10–20 system. The signal was recorded with a BrainAmp amplifier at a resolution of 16 bits, a sampling rate of 500 Hz, and with an analog low pass of 1000 Hz and high pass of 0.016 Hz. The ground electrode was placed at position AFz, the reference electrode on the tip of the nose, and an eye-movement monitoring electrode under the right eye with the electrode Iz. Electrode impedances were kept below 20 k Ω .

The EEG signals were analyzed using EEGLAB/ERPLAB (Lopez-Calderon and Luck, 2014). Datasets were bandpass-filtered between 0.1 and

30 Hz. Data were segmented into 1200 ms epochs beginning 200 ms before the critical morpheme and ending 1000 ms after. A semi-automatic artifact rejection was done: artifact rejection was performed automatically using a ± 100 μ V rejection threshold throughout all electrodes except IZ, and manually by removing any trials contaminated with eye movements or muscle activity on any of the electrodes. The mean percentage of rejected trials was 24.56 (SD = 16.02) for the dyslexic group and 25.84 (SD = 16.06) for the control group, leading to on average 36.22 trials per condition (SD = 0.76) for the dyslexic group and on average 35.58 trials per condition (SD = 0.40) for the control group. Epochs were averaged for each condition and each participant and then averaged across participants for visual display.

ERP data were analyzed based on Regions of interest (ROIs) as well as for the midline electrodes (Fz, Cz, Pz) to cover most of the recorded scalp area. ROIs were defined on the basis of Mathias et al. (2014): (1) left frontal region (F1, F3, F5, F7, AF3, AF7, AFF1h), (2) right frontal region (F2, F4, F6, F8, AF4, AF8, AFF2h), (3) left central region (C1, C3, C5, T7, FCC3h, FTT7h, CCP1h, CCP5h), (4) right central region (C2, C4, C6, T8, FCC4h, FTT8h, CCP2h, CCP6h), (5) left posterior region (P1, P3, P5, P7, PO3, PO7, PPO1h), (6) right posterior region (P2, P4, P6, P8, PO4, PO8, PPO2h).

The time windows for the analysis of the P600 component were chosen based on previous studies (e.g., Rispens et al., 2006), and visual inspection of grand averages for Cz, Fz and Pz (Fig. 1) and shifted earlier in time as our trigger was not located at the onset of the critical verb, but shifted to the occurrence of the phoneme [ʌ] (i.e., the first acoustic cue for the number agreement) inside the critical verb. We calculated the mean amplitude within the post-stimulus time window [300–900 ms]. ANOVAs were computed in an analysis based on the ROIs as well as in an analysis based on the midline electrodes. For the ROI analysis, we ran a 2x2x3x2x2 ANOVA with Rhythmic Prime (regular, irregular), Grammaticality (correct, incorrect), Region (frontal, central, posterior) and Hemisphere (left, right) as within-participant factors, and Group (dyslexic, control) as a between-participants factor. For the midline analysis, we ran the same ANOVA, except that the factor Region was defined as (Fz, Cz, Pz) and the factor Hemisphere was removed.

In addition, we calculated the difference wave between grammatical and ungrammatical sentences and extracted peak amplitude and latency in the P600 time window for midline electrodes. We used a custom-made MATLAB script from Fiveash et al. (2018): <https://github.com/nicalbee/erpPeak>. Amplitude and latency were separately analyzed with a $2 \times 3 \times 2$ ANOVA with Rhythmic Prime (regular, irregular), Region (Fz, Cz, Pz) as within-participant factors and Group (dyslexic, control) as a between-participants factor.

For all analyses, we calculated partial η^2 (Cohen, 1988) to estimate effect sizes, and Greenhouse-Geisser correction was applied when necessary.

2.4.2. Behavioral data analyses

Grammaticality judgments were analyzed with signal detection theory, calculating discrimination sensitivity d' and response bias c for each participant (based on hits; i.e., correct responses for ungrammatical sentences) and false alarms (FAs; i.e., errors for grammatical sentences) (Macmillan and Creelman, 1991).⁴ For grammaticality judgments acquired during the EEG recording, 2x2 ANOVAs with Rhythmic Prime (regular, irregular) as a within-participant factor and Group (dyslexics, controls) as a between-participants factor were performed for d' and c , separately. For the syntax post-test, participant group differences for d' and c were assessed with two-sided independent t -tests. In addition, performance was also analyzed with proportion of correct responses, with a $2 \times 2 \times 2$ ANOVA, with Group, Grammaticality and Rhythmic Prime as factors for data acquired during the EEG recording, and a 2x2

ANOVA with Group and Grammaticality as factors for the syntax post-test. To estimate effect sizes, we calculated partial η^2 (Cohen, 1988).

For the rhythm perception and production tests, group differences were investigated with two-sided independent t -tests on the following measures: (1) Free tapping data were analyzed with average Inter-Tap-Interval (ITIs), within-trial variability (standard deviation of ITIs), and coefficient of variation (CV), defined as the standard deviation divided by the mean ITI; (2) The production performance of the synchronization tasks for isochronous sequences and musical excerpts were analyzed with circular statistics (see Berens, 2009; Dalla Bella and Sowinski, 2015), leading to two measures related to the resulting vector R : its *angle*⁵ (with degrees being transformed back into ms), representing synchronization accuracy (negative values indicate that, on average, participants' taps precede the beat (leading), whereas positive values indicate average taps followed the stimuli (lagging)), and its *length* (ranging from 0 to 1), representing synchronization consistency (with 1 representing perfect consistency); (3) For the cBAT perception task, data were analyzed with d' and c , as well as with response times (for correct responses) and subjective confidence judgments (scale from 1 to 3).

3. Results

3.1. Electrophysiological data

3.1.1. Mean amplitude

The main effect of *Grammaticality* was significant for the ROI analysis, $F(1, 24) = 60.21, p < .001, \eta_p^2 = 0.72$, and the midline analysis, $F(1, 24) = 61.13, p < .001, \eta_p^2 = 0.72$, with a larger P600 for ungrammatical than grammatical sentences. The main effect of *Region* was significant for the ROI analysis and the midline analysis [$F(1.23, 29.60) = 15.59, p < .001, \eta_p^2 = 0.39$, and $F(1.33, 31.96) = 7.47, p = .006, \eta_p^2 = 0.24$, respectively]: The P600 was larger in posterior regions than central regions, and larger in central regions than in frontal regions. The *Grammaticality* \times *Region* interaction was significant for the ROI analysis, $F(1.21, 29.02) = 13.85, p < .001, \eta_p^2 = 0.37$, and the midline analysis, $F(1.36, 32.76) = 16.80, p < .001, \eta_p^2 = 0.41$. Even though significant for all regions, the difference between grammatical and ungrammatical sentences was strongest for the posterior region (ROI: $F(1, 24) = 70.32, p < .001, \eta_p^2 = 0.75$; midline: $F(1, 24) = 77.77, p < .001, \eta_p^2 = 0.76$), followed by the central region (ROI: $F(1, 24) = 52.63, p < .001, \eta_p^2 = 0.69$; midline: $F(1, 24) = 57.91, p < .001, \eta_p^2 = 0.71$), and then the frontal region (ROI: $F(1, 24) = 36.20, p < .001, \eta_p^2 = 0.60$; midline: $F(1, 24) = 34.41, p < .001, \eta_p^2 = 0.59$) (Fig. 2).

Most importantly, the factor *Rhythmic Prime* interacted with the factor *Grammaticality*: the difference between grammatical and ungrammatical sentences was stronger after the regular prime than after the irregular prime (see Fig. 3). For the midline analysis, this interaction was significant, $F(1, 24) = 4.78, p = .039, \eta_p^2 = 0.17$. For the ROI analysis, the same pattern was observed, but less strongly, as reflected in the marginally significant interaction, $F(1, 24) = 3.41, p = .077, \eta_p^2 = 0.12$.

In addition, for the ROI analysis, there was a main effect of *Hemisphere* (i.e., overall larger amplitude in the left than right hemisphere), $F(1, 24) = 9.03, p = .006, \eta_p^2 = 0.27$, and it interacted with *Grammaticality* and *Region*: $F(1.74, 41.71) = 5.67, p = .009, \eta_p^2 = 0.19$. Ungrammatical sentences led to increased amplitude in comparison to grammatical sentences, but differences in laterality (with increased amplitude for the left hemisphere) were observed only for the grammatical sentences, not the ungrammatical ones. Additionally, amplitude increased for the parietal regions for ungrammatical sentences for both hemispheres, but for grammatical sentences only in the right hemisphere. Finally, the ROI

⁴ The correction of the d' and c measures used 0.01 for cases without false alarms and 0.99 for the maximum number of hits.

⁵ Note that further analyses (including vector length analyses) were based only on trials where the Rayleigh test yielded significant results.

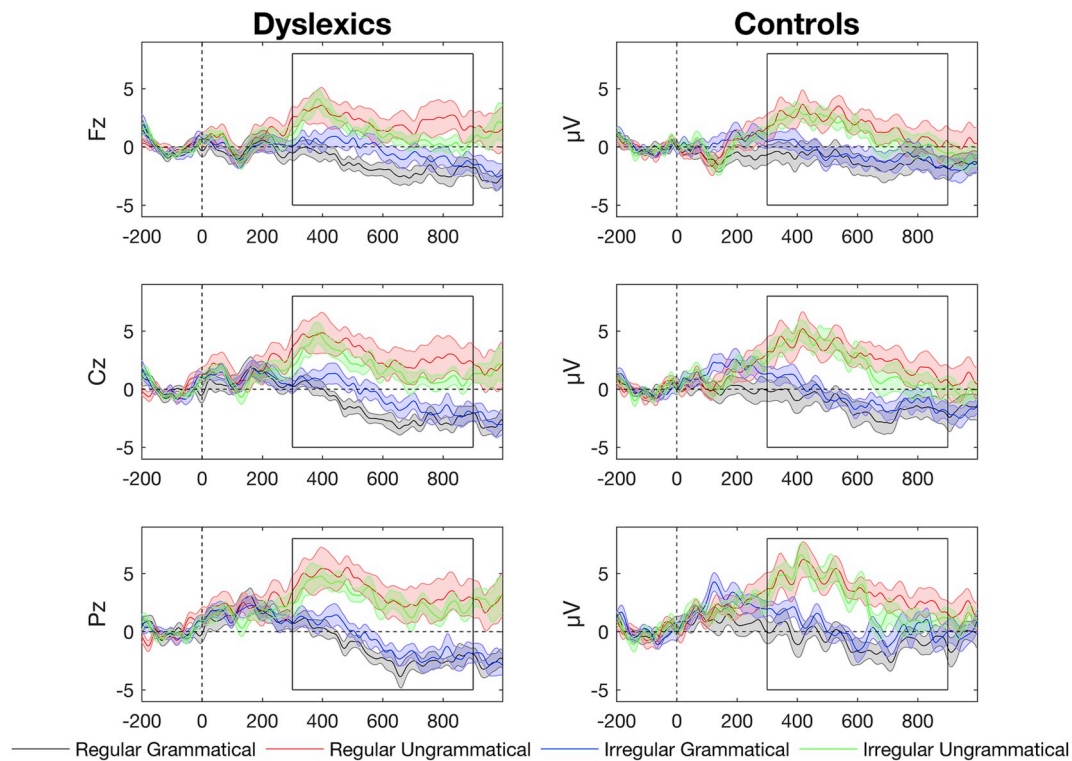


Fig. 1. Grand-averages of ERPs mean amplitude for grammatical and ungrammatical sentences depending on the Rhythmic Prime (regular, irregular), for Fz, Cz and Pz electrodes, in each participant Group (control and dyslexic). The square represents the time window defined for the analyses. Shaded error bars represent one standard error on either side of the mean.

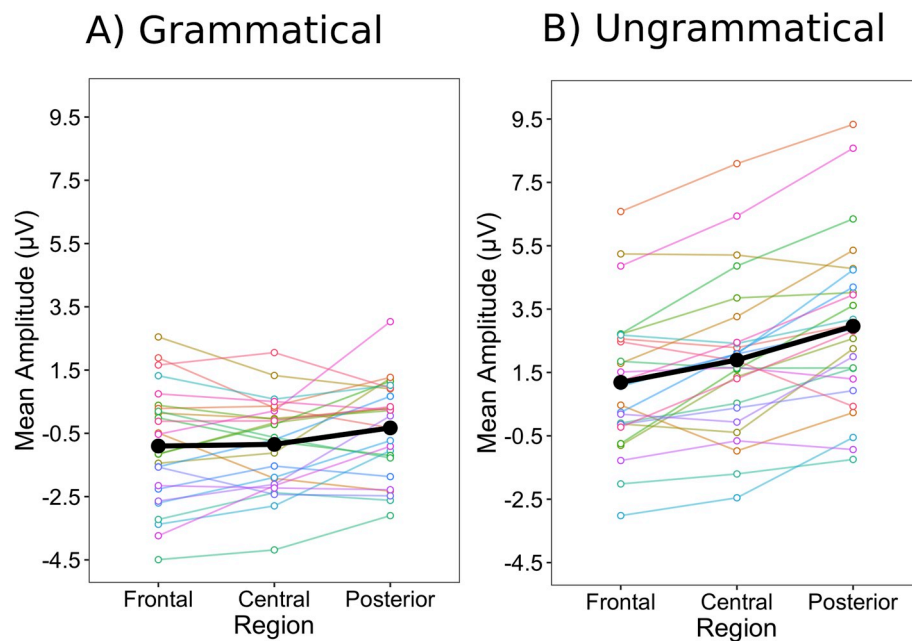


Fig. 2. Representation of the Region \times Grammaticality interaction for the analyses of the ROIs in the defined time window. Mean amplitudes (μV) were presented as a function of Grammaticality (grammatical vs. ungrammatical) and Region (frontal, central, posterior). Individual colored lines represent individual participant data. The black line represents the mean.

analysis also showed a marginally significant interaction between *Rhythmic Prime, Region, Hemisphere and Group*, $F(1.73, 41.43) = 3.28$, $p = .054$, $\eta_p^2 = 0.12$. For the control group, the amplitude was stronger in the left hemisphere than in the right hemisphere in the frontal region after the regular prime, $F(1, 24) = 4.70$, $p = .040$, $\eta_p^2 = 0.16$, and in the central region after regular and irregular primes, $F(1, 24) = 4.98$, $p =$

$.035$, $\eta_p^2 = 0.16$ and $F(1, 24) = 6.50$, $p = .018$, $\eta_p^2 = 0.21$, respectively. In the dyslexic group, the amplitude was also stronger numerically in the left hemisphere, but not significantly in each region.

3.1.2. Peak amplitude and latency

The peak *amplitude* midline analysis showed a main effect of

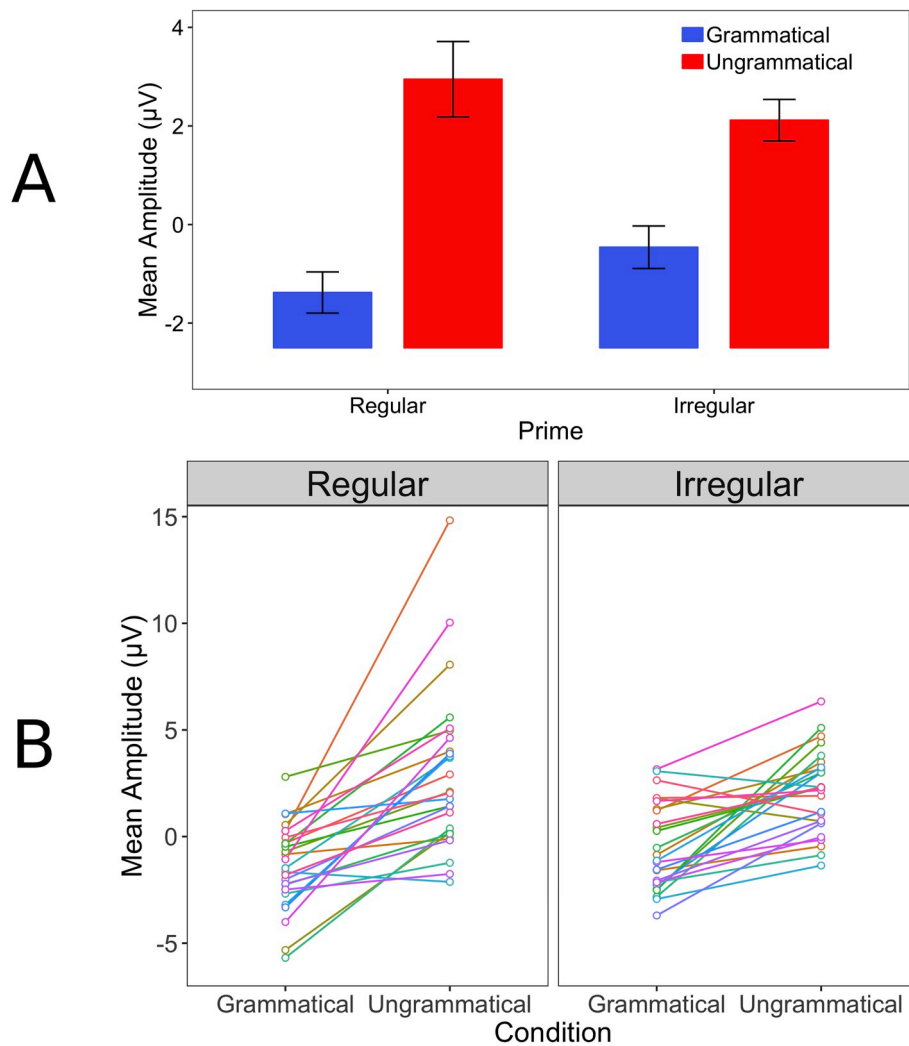


Fig. 3. A) Mean amplitude (µV) for grammatical and ungrammatical sentences depending on Rhythmic Prime (regular, irregular), in the time window for midline electrodes. B) individual participant data.

Rhythmic Prime, $F(1, 24) = 5.96$, $p = .02$, $\eta_p^2 = 0.20$, and a main effect of *Region*, $F(2, 48) = 33.09$, $p < .001$, $\eta_p^2 = 0.58$, revealing that peak amplitudes were larger after regular primes ($M = 10.07$, $SD = 4.36$) compared to irregular primes ($M = 7.90$, $SD = 3.48$), and that amplitude increased from the frontal Fz electrode ($M = 7.46$, $SD = 3.15$) to the central Cz electrode ($M = 9.19$, $SD = 3.40$) to the posterior Pz electrode ($M = 10.30$, $SD = 3.62$). There were no other significant effects, all p -values $> .30$.

For the peak *latency* midline analysis, the main effect of *Region* was significant, $F(2, 48) = 4.71$, $p = .01$, $\eta_p^2 = 0.16$, and it interacted significantly with *Group*, $F(2, 48) = 3.67$, $p = .03$, $\eta_p^2 = 0.13$, as well as with *Rhythmic Prime*, $F(1.48, 35.46) = 4.98$, $p = .02$, $\eta_p^2 = 0.17$. The *Region* \times *Group* interaction (see Fig. 4) revealed that dyslexic participants reached the peak of the P600 later than did the control participants, in particular for the posterior Pz electrode, while they did not differ for the frontal Fz electrode. The *Region* \times *Rhythmic Prime* interaction revealed that the latency after regular primes was longer ($644 \text{ ms} \pm 189.53$) than after irregular primes ($535 \text{ ms} \pm 191.35$), $t(25) = 2.55$, $p = .017$, $d = 0.50$, for the frontal Fz electrode, in particular, but less so for Cz ($586 \text{ ms} \pm 182$ for regular; $521 \text{ ms} \pm 178$ for irregular, $p = .13$) and not for Pz ($610 \text{ ms} \pm 193$ for regular; $641 \text{ ms} \pm 177$ for irregular, $p = .46$). Together with the peak amplitude analyses, these results suggest that while the peak was higher in amplitude after the regular prime, it was reached later after regular primes, in particular for the frontal site.

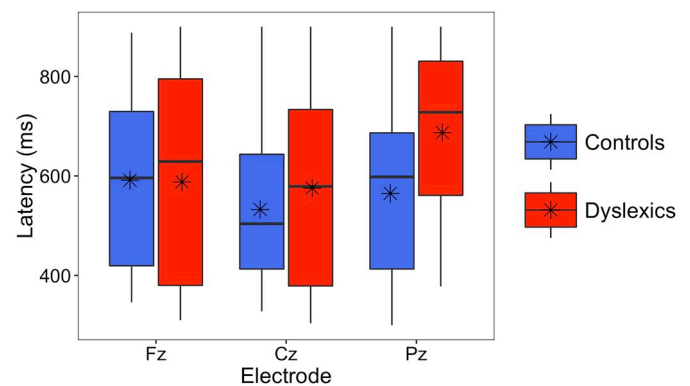


Fig. 4. Latency values for the P600 difference wave across the three midline electrodes depending on Group, averaged across both Rhythmic Prime types. Boxplots represent the interquartile range of the data (the 25th percentile to the 75th percentile). The black line represents the median, and the asterisk represents the mean. The whiskers of the boxplot represent the largest value that lies within 1.5 times the 75th or 25th percentile respectively.

Note that the main effects of *Rhythmic Prime* ($p = .16$) and *Group* ($p = .31$) were not significant. No other effects were significant, all p -values $> .61$.

3.2. Behavioral data

3.2.1. Grammaticality judgments during EEG recording

Response accuracy was high overall (97%, see Table 2), but higher for grammatical than ungrammatical sentences, as reflected in the main effect of *Grammaticality*, $F(1, 24) = 7.84$, $p = .010$, $\eta_p^2 = 0.25$. Dyslexics performed worse than controls, in particular for ungrammatical sentences, but the main effect of *Group*, $F(1, 24) = 3.45$, $p = .075$, $\eta_p^2 = 0.13$, and its interaction with *Grammaticality*, $F(1, 24) = 3.86$, $p = .061$, $\eta_p^2 = 0.14$, showed only marginal significance. There were no other significant effects (all p -values $> .26$). These results were confirmed by d' analyses: d' was higher in the control group (4.02 ± 0.43) than the dyslexic group (3.76 ± 0.52), even though not significantly, $F(1, 24) = 2.63$, $p = .12$, $\eta_p^2 = 0.10$. The main effect of *Rhythmic Prime* and its interaction with *Group* were not significant (p -values $> .38$). Response bias c differed only marginally between the two groups, with dyslexics tending more strongly to respond “grammatical” (0.16) than controls (0.03), $F(1, 24) = 3.43$, $p = .076$, $\eta_p^2 = 0.13$. No other effects were significant (all p -values $> .45$).

3.2.2. Complex syntax processing post-test

Percentages of correct responses were higher for grammatical than ungrammatical sentences, as reflected in the main effect of *Grammaticality*, $F(1, 23) = 28.16$, $p < .001$, $\eta_p^2 = 0.55$ (see Table 3). The main effect of *Group* was significant, with lower performance for dyslexic participants than control participants, $F(1, 23) = 17.09$, $p < .001$, $\eta_p^2 = 0.43$. Dyslexics' performance was particularly low for ungrammatical sentences, but the interaction between *Grammaticality* and *Group* just fell short of significance, $F(1, 23) = 3.95$, $p = .059$, $\eta_p^2 = 0.15$.

d' was significantly lower in the dyslexic group ($M = 1.91$, $SD = 0.58$) than in the control group ($M = 2.80$, $SD = 0.62$), $F(1, 23) = 13.96$, $p = .001$, $\eta_p^2 = 0.38$. Response bias c did not differ between the two groups (-0.34 for dyslexics; -0.46 for controls, $p = .37$). Note that d' for this post-test correlated positively with d' for the grammaticality judgment task during the EEG recording, $r(25) = 0.50$, $p = .011$.

3.2.3. Rhythm perception and production

In the production tasks (Table 4), the two participant groups did not differ in the free tapping task (p -values $> .56$) on any of ITI, within-trial variability and CV, or in the synchronization task to the isochronous sequences at an IOI of 400 and 700 ms in either synchronization accuracy (vector angle) or synchronization consistency (vector length). Only for the synchronization task to the isochronous sequence with an IOI of 550 ms was the synchronization accuracy (vector angle) of the dyslexics (+2 ms) significantly different from that of the controls (-72 ms); $t(23) = -2.16$, $p = .042$, $d = 0.80$. Notably, only the taps of controls anticipated the beat, suggesting entrainment. For the musical excerpts (cBAT), the dyslexics were less precise in their tapping, notably with weaker synchronization consistency (vector length) than the controls (0.72 versus 0.87; $t(23) = 2.43$, $p = .023$, $d = 0.89$). They also anticipated less than did the controls (vector angle), but not significantly, $t(23) = -1.68$, $p = .107$, $d = 0.65$.

For the perception part of the cBAT (Table 4), participant groups did

Table 2

Mean percentage of correct responses (and Standard Deviation) for each group (control, dyslexic) for grammatical and ungrammatical sentences, presented as a function of the Rhythmic Prime (regular, irregular).

	Regular prime		Irregular prime	
	Grammatical sentences	Ungrammatical sentences	Grammatical sentences	Ungrammatical sentences
Dyslexic group	97.92 (2.82)	95.51 (3.28)	97.76 (1.99)	93.75 (5.89)
Control group	97.76 (1.99)	97.60 (3.16)	98.08 (2.32)	97.12 (2.17)

Table 3

Mean percentage of correct responses (and Standard Deviation) for each group (control, dyslexic) for grammatical and ungrammatical sentences.

	Grammatical sentences	Ungrammatical sentences
Dyslexic group	90.63 (6.19)	65.97 (19.85)
Control group	95.51 (2.67)	84.89 (7.64)

not differ significantly for d' or c . Even though the mean d' of dyslexics was inferior to that of controls, this difference was not significant, $t(23) = 1.51$, $p = .144$, $d = 0.59$. However, the groups differed significantly in confidence judgments, with dyslexics being less confident in their responses, $t(23) = 2.85$, $p = .009$, $d = 1.00$, and there was a marginally significant difference for response times on correct trials, with dyslexics needing more time to respond, $t(23) = -1.96$, $p = .062$, $d = 0.74$.

For the cBAT production task with musical excerpts, synchronization consistency (vector length) correlated positively with d' for grammaticality judgments during EEG recording, $r(23) = 0.41$, $p = .049$ and with d' for complex syntax processing in the post-test, $r(23) = 0.44$, $p = .033$. For the cBAT perception task, d' correlated positively with d' for grammaticality judgments during the EEG recording, $r(23) = 0.42$, $p = .037$, but not with d' for complex syntax processing in the post-test, $p = .23$.

4. Discussion

The current EEG study aimed to extend the previously observed rhythmic priming effects on behavioral grammaticality judgments (Chern et al., 2018; Przybylski et al., 2013) to the investigation of its underlying electrophysiological correlates for syntax processing in dyslexic adults and their matched controls. The results showed that the syntax violations in the ungrammatical sentences evoked a P600 component (in comparison to the grammatical sentences), which followed a centro-posterior distribution in both participant groups (Friederici, 2002; Osterhout and Holcomb, 1992). Most importantly, the P600 was enhanced in both groups when the sentences followed a rhythmic prime that had a regular rhythmic structure in comparison to an irregular structure. The priming effect was observed for the mean amplitude in the P600 over the time windows of interest, as well as for the peak amplitude analyses, with the peak of the difference wave being of larger amplitude after regular primes than irregular primes.

The enhanced P600 following the regular prime is in agreement with previous findings reported by Kotz et al. (2005) for basal ganglia patients. While these patients did not show the P600 component related to syntax violations (Kotz et al., 2003), listening to a regular rhythmic prime has been reported to restore the P600 for sentences presented thereafter (Kotz et al., 2005). The comparison between the two findings in basal ganglia patients (Kotz et al., 2003, 2005) suggests potential compensation of impaired syntax processing with rhythmic stimulation. Our findings extend the rhythmic stimulation effect (i.e., the beneficial effect of regular rhythmic primes) on the P600 from basal ganglia patients to dyslexic adults and their matched controls. Importantly, this benefit was shown within the same participants (comparison of irregular to regular prime conditions). These priming effects can be interpreted within the framework of Dynamic Attending Theory (e.g., Jones, 1976; Large and Jones, 1999), notably in terms of entrainment that modulates attentional resources and influences the P600 (e.g., Schmidt-Kassow and Kotz, 2008). The idea is that entrainment to a regular prime, with its influence on temporal attention and predictive timing, might persist subsequently via sustained oscillations (e.g., Jones, 1976; Large and Jones, 1999) and facilitate entrainment to the less regular speech signal. The sustained oscillations may then benefit sentence processing by facilitating segmentation and sequencing of the speech signal and the processing of its syntactic structures. Following the entrainment and the rhythmic allocation of attentional resources over time, the syntactic violation would be perceived as more salient, leading to the increased

Table 4

Mean results (and Standard Deviation) of the dyslexic group and the control group for free tapping and for the cBAT.

			Dyslexics		Controls	
			Mean	SD	Mean	SD
Production	Free tapping	Mean	490.73	187.87	514.85	173.72
		SD	17.07	4.33	18.69	8.67
		CV	0.04	0.01	0.04	0.01
	Tapping ISI 400 ms	R	0.87	0.07	0.85	0.05
		Angle	−34.08	8.37	−46.09	9.91
	Tapping ISI 550 ms	R	0.84	0.09	0.87	0.05
		Angle	2.02	24.21	−72.80	22.91
	Tapping ISI 700 ms	R	0.87	0.07	0.85	0.05
		Angle	−5.80	26.52	−51.70	19.44
	Music cBAT	R	0.72	0.05	0.87	0.04
Angle		−4.60	7.21	−22.59	7.87	
Perception	Music cBAT	d'	2.60	0.29	3.20	0.27
		c	0.37	0.16	0.37	0.16
		Confidence judgments	2.47	0.07	2.72	0.06
		Correct response times	7488.73	547.62	5838.20	631.39

P600 observed here (e.g., Jones, 2019; Schmidt-Kassow and Kotz, 2008, 2009). Future research now needs to further investigate the strengths and limits of the rhythmic priming effect, notably by testing how long the effect of the sustained oscillations might last over time (e.g., for how many sentences and/or for what duration), how long a musical prime needs to be to trigger the potential oscillator contribution (see Fiveash et al., submitted, for a first attempt) and also whether the effect might extend to other linguistic processing tasks that require sequencing and segmentation (see Bedoin et al., in preparation, for a reading task).

In the current study, sentences were presented as naturally spoken speech. The influence of the temporal structure of the musical prime on the naturally spoken speech signal, which was presented afterwards, extends previous findings that have manipulated the temporal structure of the speech signal itself. For example, Schmidt-Kassow and Kotz (2008) manipulated the metrical structure of sentences (regular, irregular) in conjunction with syntactically correct or incorrect sentences. They reported that metrical and syntactic structures interact in the processes underlying the P600. The regular metric structure of the incoming continuous speech stream, which allows for predictive timing and coding, influences syntactic processing, which requires some form of segmentation and sequencing as well as the prediction of future events. Considering that the P600 is thought to reflect controlled processes of structural reanalysis and repair (e.g., Hahne and Friederici, 2002), these and the current findings support the link to Dynamic Attending Theory, suggesting the involvement of attentional resources distributed over time. Here we show that grammatical processing is also sensitive to the presence of temporal regularity of a previously presented musical prime, and not restricted to regularities implemented in the speech signal itself, as shown previously, thus supporting the interpretation of prime entrainment providing a benefit to subsequent speech signal analyses.

The enhanced P600 (for average amplitude and peak amplitude) after the regular primes was observed for control participants and dyslexic participants. Both participant groups benefitted from the regular prime in comparison to the irregular one. The only amplitude difference that emerged between participant groups in interaction with the prime was observed in the second half of the time window and related to topography (see Supplementary materials). For the control participants, the effect of regular compared to irregular primes on P600 was mainly observed in centro-posterior regions, whereas for dyslexic participants, it also extended to frontal areas. This activation might reflect extended recruitment of cerebral networks in pathology, notably to compensate for deficits in syntax processing and/or temporal processing.

The participant groups also differed regarding the latency of the peak of the P600, with a later peak for dyslexic than for control participants. This finding is in agreement with previously shown delayed P600 peaks for dyslexic adults in response to morpho-syntactic violations (i.e.,

subject-verb agreement; Cantiani et al., 2013; Rispens et al., 2006), as used here. Interestingly, the P600 latency was not influenced by rhythmic prime type for either group, in contrast to the amplitude-related measures as presented above for both groups.

Regarding the P600, Gouvea et al. (2010) proposed that latency versus amplitude and duration of the P600 reflect different aspects of processing. In particular, latency might reflect the time needed to retrieve information related to structural relations while amplitude and duration of the P600 might reflect the construction and repair of syntactic relations. While latency of the P600 was delayed in the dyslexic group, latency was not sensitive to regular versus irregular primes, suggesting that a regular prime does not appear to facilitate an impaired processing step, that is, reduce the time needed to retrieve syntactic information in dyslexia. However, the amplitude of the P600 peak as well as its mean amplitude over the time window (i.e., related to P600 duration) were influenced by the rhythmic prime for both dyslexic and control participants. This finding is in agreement with the hypothesized effect of rhythmic primes on cognitive sequencing involving segmentation and structural processing as well as temporal attention and prediction (e.g., Przybylski et al., 2013).

The enhanced P600 following regular primes was observed for both participant groups, suggesting that dyslexic individuals can also benefit from regular primes despite previously reported temporal processing deficits (e.g., Leong and Goswami, 2014; Wolff, 2002 in dyslexic adults; and Muneaux et al., 2004, in dyslexic children). This observation echoes the findings by Kotz et al. (2005) who reported beneficial effects of a regular musical stimulus (a marching rhythm) on syntax processing in patients with basal ganglia lesions, even though deficits in temporal processing have also been reported for this population (Schwartz et al., 2011). For both pathological populations, temporal processing thus seems to be impaired, but not fully abolished. The decreased functionality may particularly affect language processing as rhythmic structures and regularities are more subtle and variable than in music, for example. The impaired system might be activated by the musical prime with its clear metrical structure, providing predictable cues to boost and entrain internal oscillators, which then also benefit sequencing and temporal segmentation at the sentence level, enhancing syntax processing (Przybylski et al., 2013). The benefit of a clear metrical structure (also referred to as “high-groove music” together with other features) in comparison to low-groove music has been observed also for motor-cueing (Leow et al., 2014).

Our additional temporal processing battery testing for perception and production also revealed some deficits in temporal processing in the dyslexic adults in comparison to the matched controls. Even though dyslexic participants performed in some tasks as well as non-musician control participants, deficits were observed for rhythm production and perception. For the synchronization task with isochronous sequences,

dyslexic adults' production differed significantly from controls for the tempo of 550 ms IOI. While controls were anticipating (i.e., responding 72 s before the tone onset), dyslexics were not (i.e., responding 2 s after the tone onset) – an outcome suggesting less or no entrainment for the dyslexics. As weaker tapping accuracy was not observed for the two other tempi (400 and 700 ms IOI), this impairment might be linked to previous data reporting a processing deficit for dyslexics at a 2 Hz-rate in particular (Power et al., 2016; Thomson and Goswami, 2008). The 2 Hz rate is relevant for speech decoding, as discussed by Goswami et al. (2013, 2018), in particular for the processing of stressed syllables and speech prosody. Impaired processing of these slow-frequency modulations (i.e., delta rate) might thus be linked to dyslexics' language deficits, as postulated in the Temporal Sampling Framework (Goswami, 2011).

In the present study, the beat rate of the musical primes was at 2 Hz, which might thus have boosted oscillatory activity at the related delta rate, benefiting encoding of the low-frequency speech envelope of the subsequently presented sentences. Future studies need to further investigate the underlying neural correlates of our observed priming effect and its relation to the 2 Hz-processing deficit in dyslexia, notably by measuring more specifically oscillatory activity during the musical prime and subsequent speech processing (Fiveash et al., in progress). Promising data for a potential sustained entrainment effect has been reported for sentences with strong accent structure preceded by an auditory non-verbal rhythmic cue in healthy young adults (Falk et al., 2017): After a regular cue with matching accent structure, phase coupling during sentence processing was stronger than after a non-matching irregular cue.

For the production part of the cBAT based on musical excerpts, dyslexics were less precise in their tapping (i.e., showed weaker synchronization consistency) than controls, and average performance further suggested weaker anticipation than controls (even though not significantly). For the perception part of the cBAT, dyslexics' performance was not significantly below controls, even though d' differences were in the direction of weaker performance for dyslexics. However, dyslexics were significantly less confident in their responses than controls, and tended to respond more slowly. Further, cBAT production and perception performance correlated positively with participants' performance on the grammaticality judgment task. This relation between syntax processing and beat perception and production is in agreement with previously reported findings for children and adults (e.g., Gordon et al., 2015a, b; Woodruff Carr et al., 2014). For example, performance in rhythm discrimination tasks predicts grammar skills in children (Gordon et al., 2015b).

The correlation between rhythmic perception/production performance and grammaticality judgments emerged even though performance of both controls and dyslexics was close to ceiling for the syntax task during the EEG recording session. The dyslexic adults processed the morpho-syntactic violations used in the experiment as successfully as the control participants. This finding is in agreement with Rispens et al. (2006) who also used subject-verb agreement violations and reported no deficit for dyslexics in the grammaticality judgments. However, our data as well as that of Rispens et al. (2006) revealed an increased latency for the P600 peak in the dyslexic participants for the processing of these syntax violations. When more subtle syntax violations were tested (as in our post-test), grammaticality judgments of the dyslexic participants were impaired in comparison to the control group. This performance correlated with the performance in the easier syntax task during the EEG recording. These data thus confirm some syntactic processing deficits in this population.

The syntax task during the EEG recording session might have been relatively easy because, as we aimed for reliable EEG recordings, we only used one type of morpho-syntactic error for the target sentences (time-locking the ERP to the same phoneme), even though these experimental sentences were combined with gender agreement errors of the filler sentences. With the ceiling performance for the syntax task

during the EEG recording, we did not observe the beneficial effect of the regular rhythmic prime (over the irregular prime) for the grammaticality judgments, as previously reported in children (e.g., Przybylski et al., 2013; Chern et al., 2018; Canette et al., 2020). As the task was somewhat easy for all adults, the rhythmic prime effect was observed at the electrophysiological level, reflected in the P600 component, but was not observed behaviorally. In a recent study, we have used the more subtle syntax violations of our post-test in a priming paradigm with healthy adults and have observed enhanced grammaticality judgments after regular musical primes compared to irregular primes (Canette et al., in revision). Future research could now apply this refined syntax material with electrophysiological recordings to dyslexic adults.

One caveat to be considered here is that in the present study, we compared regular musical primes to irregular primes, thus leading to the observation of “relative facilitation”, as previously shown in Przybylski et al. (2013) for children and behavioral measurements. For behavioral data, subsequent studies have shown better performance after regular primes in comparison to various baseline conditions, notably environmental sound scenes (Bedoin et al., 2016) and musical textures without rhythm or silence (Canette et al., 2020). These findings confirmed that the “relative facilitation” was not solely due to a cost of the irregular prime, but included also a benefit of the regular prime. Up to now, for the electrophysiological correlates, we can only refer to “relative facilitation” comparing regular to irregular primes, and future research is needed to measure neural correlates by including additional baseline conditions.

5. Conclusion

The present study examined the influence of a rhythmic musical prime on the late P600 evoked-potential associated with grammatical error detection, for dyslexic adults and matched controls. Our findings revealed an enhanced P600 after regular primes in comparison to irregular primes for both participant groups. These findings are in agreement with previous data for basal ganglia patients within a priming-like paradigm (Kotz et al., 2005) and for healthy controls within metrically manipulated speech (Schmidt-Kassow and Kotz, 2008, 2009). The P600, in particular regarding amplitude and duration (see Gouvea et al., 2010), has been interpreted as a marker of syntactic integration difficulty (Cantiani et al., 2013), being involved in syntactic repair (Rispens et al., 2006) and requiring controlled, attentional processes of structural reanalysis and revision (Hahne and Friederici, 2002). Based on our observed musical priming effect on the P600, together with the Dynamic Attending Theory (Jones, 1976), our findings suggest that a regular rhythmic prime benefits temporal attention, sequencing and structural integration, not only for the processing of the musical prime itself, but also extending to subsequently presented speech material that requires segmentation and other sequencing steps to process its syntax structures. In line with Kotz et al. (2005) and Goswami (2011), our findings are promising for the potential benefits of therapeutic interventions or educational practices based on rhythm and music to boost impaired oscillatory processes (as in dyslexia, for example) and stimulate language-related processes. This is consistent with reports that rhythm-based musical training programs can lead to benefits in phonological processing or reading in dyslexic children (e.g., Overy, 2000; Flaughnacco et al., 2015) and – more closely related to the paradigm used here – that the addition of regular musical primes within speech-therapy sessions on syntax processing can lead to enhanced training benefits, as shown for children with cochlear implants (Bedoin et al., 2017).

Declaration of competing interest

None.

CRediT authorship contribution statement

Laure-Hélène Canette: Writing - review & editing, Writing - original draft, Formal analysis, Data curation, Methodology, Conceptualization, Investigation, Visualization. **Anna Fiveash:** Writing - review & editing, Writing - original draft, Formal analysis, Visualization. **Jennifer Krzonowski:** Software, Formal analysis. **Alexandra Corneillie:** Writing - original draft, Formal analysis, Methodology, Software. **Philippe Lalitte:** Writing - original draft, Methodology, Conceptualization. **Dave Thompson:** Formal analysis, Methodology, Conceptualization, Software. **Laurel Trainor:** Writing - original draft, Formal analysis, Methodology, Conceptualization. **Nathalie Bedoin:** Writing - review & editing, Writing - original draft, Formal analysis, Methodology, Conceptualization, Funding acquisition, Project administration, Supervision. **Barbara Tillmann:** Writing - review & editing, Writing - original draft, Formal analysis, Methodology, Conceptualization, Funding acquisition, Project administration, Resources, Supervision.

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Appendix A. Supplementary data

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