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The rhythmic priming effect in second language perception appears reliant on individuals' musical background

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ABSTRACT

Exposure to musical rhythms has been shown to influence the perception of subsequently presented speech. Until now, this effect has only been studied in native language (L1) processing. The present study investigated whether rhythmic priming could also benefit second language (L2) processing. A musical rhythmic priming experiment was designed based on previous studies in L1 children. Over two experiments, L2 adult speakers of French were asked to detect grammatical errors in naturally spoken French sentences. Sentences were either preceded by a regular or an irregular musical rhythmic prime. We also assessed participants' French language level, rhythmic perception abilities, and musical training. In Experiment 1, 34 participants from various L1 backgrounds were recruited. In Experiment 2, 33 participants with a Romance-family L1 were recruited. For both experiments, grammaticality judgments did not significantly differ after regular versus irregular rhythmic primes. However, in collapsing both experiments, grammaticality judgments correlated significantly with rhythmic abilities, suggesting that participants with better rhythm perception were better at grammaticality judgment tasks. Moreover, with the same French level, musicians were better at detecting grammatical errors than those who had not received music training. We also found that the rhythmic priming effect (better grammatical judgments after regular than after irregular rhythms) increased with the number of years of musical training, suggesting that regular rhythmic primes may improve L2 perception in particular for musically trained participants. These results suggest some interesting connections between music training, second language learning, and rhythmic priming, that can be explored in future research.

1. Introduction

Music and language processing have been reported to share cognitive and neural correlates (Ladányi et al., 2020; Schön & Tillmann, 2015). Such findings have been supported by links between skills and deficits across domains, such as numerous correlations between music and language skills (Fiveash et al., 2023; Ladányi et al., 2021; Przybylski et al., 2013). For example, rhythmic skills correlate with phonological awareness (Ozernov-Palchik et al., 2018; Woodruff Carr et al., 2014), reading (Bekius et al., 2016; González-Trujillo et al., 2014; Strait et al., 2011; Tierney & Kraus, 2013) and grammatical skills (Gordon, Jacobs, et al., 2015; Gordon, Shivers, et al., 2015; see Heard & Lee, 2020 for a meta-analysis). Conversely, individuals with language disorders have associated rhythm processing deficits (Fiveash et al., 2021; Lense et al., 2021) and atypical rhythm skills are linked to developmental speech and language disorders (Ladányi et al., 2020).

To test a potential beneficial transfer from music to speech processing, studies have shown that rhythm-based training programs appear to improve speech processing in both pathological and typically developing brains. Long-term musical training has been shown to causally improve several aspects of language processing in different populations and age groups (compared with a control group), including phonological awareness (Degé & Schwarzer, 2011; Patscheke et al., 2016), reading (Bonacina et al., 2015; Flaugnacco et al., 2015), prosody processing (Moreno et al., 2009) and speech signal tracking (Chobert et al., 2014). Long-term musical training effects were observed not only for native language (L1) skills, but also for foreign language skills. For example, musicians are better at detecting tonal violations and prosody

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variations in spoken sentences than non-musicians, whether in their L1 (Schön et al., 2004) or in an unfamiliar language (Marie et al., 2011; Marques et al., 2007). In a non-native language, strong musical skills are linked to better performance in pronunciation (Turker et al., 2017), phonemic perception and production (Christiner & Reiterer, 2018), phonological awareness (Slevc & Miyake, 2006) and syntax skills (Brod & Opitz, 2012). Further, musical skills better predicted fluency in silent reading in a foreign language than other skills related to reading or auditory working memory (Foncubierta et al., 2020), and Italian students' grades in music classes correlated with their grades in English and French classes (Picciotti et al., 2018).

In addition to long-term music training, short-term stimulation with musical rhythm has been reported as a potential tool for improving the processing of language, in particular by enhancing the temporal expectations generated by the musical stimulus. The music rhythmic priming paradigm involves presenting a short (~30s), regular musical rhythmic stimulus (compared to a silent or irregular control condition), followed by several naturally spoken sentences, during which participants perform a language-related task, typically focused on grammar. Using this paradigm, several studies have shown that children with and without developmental language disorders (such as dyslexia or developmental language disorder, DLD), perform better on grammaticality judgments after having listened to regular rhythmic primes compared to irregular rhythmic primes as a control condition, from which it is not possible to extract an underlying pulse (e.g., Bedoin et al., 2016; Fiveash et al., 2020; Przybylski et al., 2013). In adults, one study showed that French speakers performed better on a grammaticality judgment task after regular compared to irregular primes (Canette et al., 2019). Listening to regular as opposed to irregular rhythmic primes also increased brain responses to syntactic violations (measured by the P600 response in EEG) in dyslexic adults as well as control adults performing a grammaticality judgment task (Canette, Fiveash, et al., 2020). These results suggest that highly rhythmic musical structures enhance neural responses involved in speech processing, an effect that appears robust in both children and adults.

To date, rhythmic priming has only been tested in the context of L1 processing; no studies on rhythmic priming have explored the benefit of regularity on second language processing. Yet language rhythm processing appears to play an important role in the acquisition of a new language. Several studies have shown that the inherent rhythmicity of the L1 influences general rhythmic perception (Bhatara et al., 2016; Iversen et al., 2008; Soley & Hannon, 2010; Yoshida et al., 2010), suggesting that native language rhythm could also impact L2 rhythmic perception, as well as the ability to segment a foreig language with a different rhythm from that of the native language (e.g. French and English) as early as 8 months of age (Polka & Sundara, 2012). The L1 rhythm influence also seems to extend to L2 production, since speakers tend to articulate the second language using the rhythmic patterns of their L1, which can lead to difficulties related to stress and intelligibility (Ordin & Polyanskaya, 2015). However, this view is debated, as Ordin et al. (2019) have proposed that discrimination of rhythmic patterns may be governed by general properties of the auditory system and cognitive mechanisms shared by all humans, regardless of their L1. Ordin et al.' (2019) findings thus suggest that rhythmic priming could have an effect independently of the individual's L1.

The aim of this study was to investigate the influence of musical rhythmic primes on foreign language speech processing. We conducted two experiments that focused on the link between rhythm and grammar and examined whether rhythmic priming affected grammaticality judgment performance for auditorily presented French sentences in adults' L2. Experiment 1 examined the priming effect in a sample of participants whose L1 was not predefined. From this group of participants, we also tested whether the priming effect was L1-dependent. Furthermore, to explore whether the priming effect could arise in a more L1-homogeneous sample whose L1 is grammatically close to French, Experiment 2 tested participants whose native language was exclusively of Romance origin. For both experiments, we predicted that adult L2 speakers would show improved grammaticality judgments after regular primes compared to irregular primes. Then, we tested, across both samples, whether other factors could influence the effect of rhythmic priming. We hypothesized that music training (as indexed by the number of years of musical instrument lessons with a one-to-one teacher) would have an impact on rhythm processing and its effect on syntactic processing in L2.

2. Experiment 1: Participants with diverse L1 backgrounds

2.1. Method

2.1.1. Participants

Thirty-four adults (21 women, 13 men, *M*age = 27.53 years, *SD* = 5.53 years, range 18–40) participated in the study. Participants reported normal hearing, a minimum intermediate level (B2) in French, and no neurological or language disorders. Before starting the experiment, all participants took an audiometry test that confirmed their normal hearing. Participants were from 21 different nationalities and with 16 different native languages. All participants lived in France at the time of the study. Their average time spent in France was 2.81 years (*SD* = 2.75 years). All participants took French lessons, and the average number of years of French lessons was 6.36 years (*SD* = 4.67 years). They reported a level of French between intermediate and advanced, i.e., B2 and C2 according to the Common European Framework of Reference for Languages (CEFR). This was largely validated with the French test administered during the study (described below in the 'Additional tests and questionnaires' part of the materials section). One participant obtained level A1/A2 and was still included in the study (excluding this participant did not change the patterns of results). Written informed consent based on the French ethics procedure approval Committee (CPP Sud Méditerranée II, 2020-A01231-38) was obtained from all participants prior to the experiment, which was conducted in accordance with the guidelines of the Declaration of Helsinki.

2.1.2. Materials

Musical prime stimuli. The 32-s rhythmic musical primes (regular and irregular) from Fiveash et al. (2020) were used. Four regular rhythmic primes (R1, R2, R3, R4) consisted of a 4/4 m with an inter-beat interval (IBI) of 500 ms (corresponding to 2 Hz and a tempo of 120 beats per minute). This tempo was previously used in other rhythmic priming studies (Bedoin et al., 2016; Canette, Fiveash, et al., 2020; Canette, Lalitte, et al., 2020; Chern et al., 2018; Fiveash et al., 2020; Ladányi et al., 2021; Przybylski et al., 2013) as it seems appropriate with the hypothesis as it is in the common tempo range of western tonal music (Patel, 2008) and fits roughly with packages of two syllable durations (Arvaniti, 2009; Ding et al., 2017). The four primes differed in the electronic percussion instrument timbres used to create them, to increase acoustic complexity and musicality (see Fiveash et al., 2020 for more details). They contained four cycles of 16 beats (i.e., two beats per second). The first beat of the cycle was played back at the end of each rhythm and a subtle reverb of 1 s was added at the end of the rhythmic sequence, resulting in a total duration of approximately 33 s. Four irregular primes (I1, I2, I3, I4) were created from the regular rhythmic primes. The regular primes and the irregular primes contained the same acoustic information (i.e., percussion instruments, duration of acoustic events, total duration), but the acoustic events of the irregular primes were temporally distributed in such a way that it was difficult to find a hierarchical metrical organization of the beats, creating highly temporally irregular sequences with no recognizable pulse or meter. Musical stimuli were created with Musical Instrument Digital Interface (MIDI) VST (Virtual Studio Technology) (Fiveash et al., 2020, 2023).

Speech stimuli. We used the 192 French spoken sentences of the grammaticality judgment task from Fiveash et al. (2020). The stimulus set contained 96 grammatically correct sentences and 96 grammatically incorrect sentences (directly derived from the correct sentences). Each ungrammatical sentence had one grammatical error among the eight types of violation used: number (No), person (Pe), gender (Ge), tense (Te), auxiliary "être" (to be) (Au), morphology (MS), position error (Po) and past participle (PP) agreements (Table 1 for examples). Speech stimuli were spoken by a native French female speaker with a natural speech speed and recorded with a Røde NT1 microphone in a sound-attenuated booth. Sentences were normalized in intensity using a custom-made program in MATLAB, and with a sample rate of 44,100 Hz.

Two lists of 96 sentences were constructed, each comprising 48 grammatically correct sentences and 48 ungrammatical sentences. Each grammatically correct sentence placed in list 1 was matched to another grammatically correct sentence in list 2 in terms of number of letters, number of syllables, number of words, and lexical word frequency (from the standard frequency index in MANULEX; Lété et al., 2004). The sentence lists provided to each participant were constructed so as not to contain matched grammatical-ungrammatical pairs (i.e., one participant would not hear the grammatical and ungrammatical version of the same sentence). The ungrammatical sentence types No, Pe, Te and Ge were referred to as 'primary error types' as there were eight sentences of each in a list. The ungrammatical sentence types Au, MS, Po and PP were referred to as 'secondary error types' because there were four sentences of each in a list (see Fiveash et al., 2020 for more details).

Additional tests and questionnaires. We assessed participants' level of French with a 5-min sheet-based French test, in which the instructions were translated into French, from a single-choice questionnaire called "Lingaguest" from the Escola de Línguas para Comunicação Empresarial (https://linguagest.com/) (see in Supplementary materials).

Participants also completed a self-reported music and dance questionnaire as well as a language background questionnaire (adapted from the LEAP-Questionnaire - Marian et al., 2007; translated by Bhatara et al., 2011).

In addition, we assessed rhythmic perception abilities using an adaptation of the Beat Alignment Test (BAT) (adapted from Dalla Bella, Farrugia, et al., 2017, see also Dalla Bella et al., 2024; based on Fiveash et al., 2022). The BAT is a rhythm processing test that assesses the participants' ability to detect aligned or misaligned pulses in musical excerpts. The participant was presented with a short piano sequence (with a total duration of around 15 s). After a few seconds, a triangle sound was added to the music, and the participant had to determine whether the triangle sound was "aligned" with the music (i.e., whether it was on the beat/pulse of the music), or whether it was "non-aligned" (i.e., the triangle sound was offset from the pulse of the music).

Table 1
Examples of grammatical and ungrammatical sentences.

Error type	Grammatical sentences	Ungrammatical sentences
Number (No)	L'air est. pur dans la montagne *The air is pure in the mountains*	L'air sont* pur dans la montagne *The air are* pure in the mountains*
Person (Pe)	L'enfant va aller se changer *The child is going to change*	L'enfant vais* aller se changer *The child am* going to change*
Gender (Ge)	Le vent souffle sur la colline ce soir *The wind is blowing on the hill tonight*	Le vent souffle sur le* colline ce soir *The wind is blowing on the[M]* hill [F] tonight* M = masculine, F = feminine
Tense (Te)	J'aimerais qu'ils aillent au cinéma *I wish they'd go to the cinema*	J'aimerais qu'ils vient* au cinéma *I wish they'd* come to the cinema*
Auxiliary (Au)	Hier, je me suis cassé le bras *Yesterday I broke my arm*	Hier, je m'ai* cassé le bras *Yesterday I'm* broke my arm*
Morphology (MS)	Ce parc paraît grand comparé à l'autre *This park looks big compared to the other one*	Ce parc paraît grand comparé que* l'autre *This park looks big compared of* the other one*
Position (Po)	Tu as un nouveau chat, montre-le-moi tout de suite *You've got a new cat, show it to me now*	Tu as un nouveau chat, montre-moi-le* tout de suite *You've got a new cat, show to me it* now*
Past participle (PP)	Elle a lu une histoire aux élèves *She has read a story to the students*	Elle a lire* une histoire aux élèves *She have read* a story to the students*

2.1.3. *Experimental design and procedure*

The participants were tested in a soundproof experimental booth at the Lyon Neuroscience Research Centre. All participants received the same instructions and performed the tests on a computer with headphones. The auditory stimuli were presented at a comfortable loudness level. The experimenter remained in a side room throughout the session to initiate each task, and to ensure understanding and compliance. The participant was seated at a comfortable distance from the experimental table and the computer. The experiment was created using OpenSesame (version 3.3.9) software.

The rhythmic priming paradigm was adapted from Fiveash et al. (2020) (Fig. 1), which was also used in previous research (e.g., Bedoin et al., 2016; Canette, Fiveash, et al., 2020; Canette, Lalitte, et al., 2020; Przybylski et al., 2013). It consisted of 16 blocks. Each block began with a 33 s musical prime (either regular or irregular) followed by six spoken French sentences, on which participants performed the grammaticality judgment task. The sentences were randomized so that each block included three ungrammatical sentences (including two different types of primary errors and one type of secondary error) and three unmatched grammatical sentences. Each block began with either a regular or an irregular rhythm. The same rhythmic prime type was presented for two consecutive blocks, and the rhythmic prime type alternated every two blocks (i.e., R, R, I, I, etc.). The order of the four individual regular and irregular sequences was pseudo-randomized, so that one prime (i.e., R1, R2, etc.) appeared only once in the first eight blocks and only once in the last eight blocks.

The experimenter asked the participant to listen carefully to the rhythmic sequences and sentences and to indicate whether each sentence was grammatically correct or incorrect by pressing one of two keys on the computer keyboard. Participants could only respond at the end of the sentence. A break was offered every four blocks, and the participant could choose to rest or continue by pressing a button. The rhythmic priming experiment lasted approximately 20 min, depending on the participants' pace. The session started with the grammaticality judgment task (i.e., the rhythmic priming experiment), then participants performed the BAT and the French level test, and then filled out the musical/language background questionnaires.

2.1.4. *Data analyses*

We calculated an index of sensitivity (d prime, *d'*) (Stanislaw & Todorov, 1999), that can be used to assess sensitivity to grammatical error detection in the grammaticality judgment task. To define *d',* we used the proportion of correct responses (p[hits]) and the proportion of false alarms (p[FAs]), i.e., when the participant detected an error when there was none. Their respective z-scores were subtracted (z(p[hits]) − z(p[FAs]) to obtain d'. We also calculated the response bias C (Macmillan & Creelman, 1991), which corresponds to the preference of participants to favor one response option over the other, as −0.5[z(p[hits]) + z(p[FAs])]. Negative and positive scores indicate a bias towards "ungrammatical" and "grammatical", respectively; whereas a score close to zero indicates the absence of response bias. Moreover, we calculated Cohen's *d* (Cohen, 1988) to assess effect size. Significant effects of rhythmic priming on the grammatical judgment task were investigated with two-sided paired samples *t*-tests comparing *d'* after regular primes and after irregular primes, as well as response bias *c* after regular primes and after irregular primes. We also ran a Bayesian statistical analysis on d' with the ttestBF function from the R package BayesFactor (version 0.9.12–4.7), which performs the "JZS" *t*-test described by Rouder et al. (2009). This approach models the standardized difference $\delta = (\mu - \mu_{mean})/\sigma$ and implements competing hypotheses as distinct prior

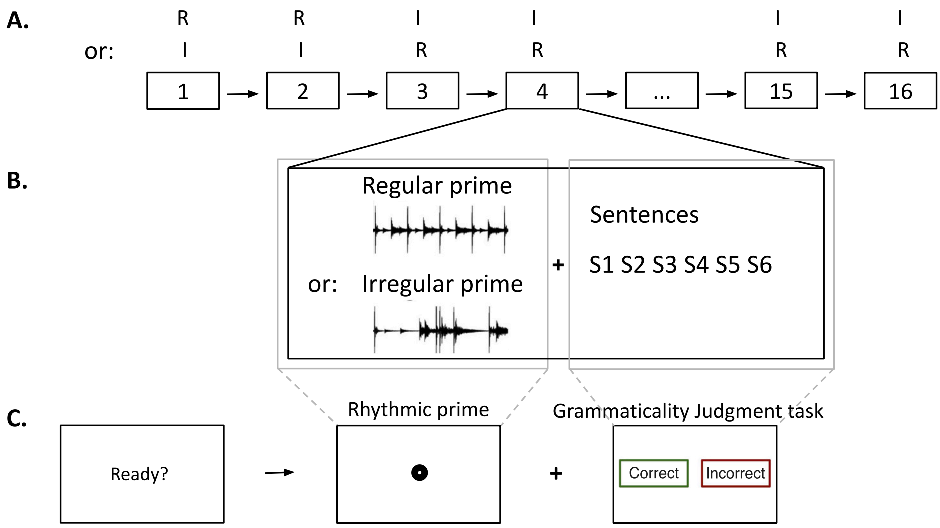

Fig. 1. The rhythmic priming paradigm with a grammaticality judgment task. A. The experiment consisted of sixteen blocks. Each block began with an irregular (I) or regular (R) rhythmic prime, depending on the counterbalancing, conditioning the order of the following primes which alternated between two regular and two irregular primes. B. Each block consisted of a regular or irregular prime followed by six sentences, either grammatically correct or incorrect. C. During the experiment, instructions were displayed on the computer screen. A central black point appeared on the screen when the prime was played. When the sentences were played, the choices "correct" and "incorrect" were displayed on the screen and the participant pressed a button on the keyboard to give their response.

distributions over δ: δ is assumed to be 0 under the null hypothesis, and Cauchy(scale = r) under the alternative. The default r scale in BayesFactor for *t*-tests is $\sqrt{2}/2$ (ROPE = [−0.10; 0.10]). We reported the Bayes Factor in favor of the null hypothesis (BF01): a BF01 superior to 3 presents evidence in favor of the null hypothesis compared to the alternative.

In addition, a generalized linear mixed effects model (GLMM) (Bates et al., 2014) was run to investigate the effect of rhythmic priming and grammaticality on response accuracy (binomial data, 0 for incorrect response and 1 for correct response), using the *lme4* package (version 1.1–35.3) in RStudio software (version 2022.12.0 + 353). Prime type (regular, irregular) and Grammaticality (grammatical, ungrammatical) were included as fixed effects, Participants and Sentences as random effects. Random intercepts were nested within the participant number and within the unique name of each sentence (modeling differences between participants and sentences, respectively, that cannot be explained by the independent variables). See the model Model1:

$$\begin{aligned}\mathrm{Model1} <- \mathrm{glmer}(&\mathrm{Response} \sim \mathrm{Prime}*\mathrm{Grammaticality}\\ &+ (1 \mid \mathrm{Participants}) + (1 \mid \mathrm{Sentences}), \mathrm{data} = \mathrm{data}, \mathrm{family}\\ &= \mathrm{binomial}(\mathrm{link} = \text{"logit"})).\end{aligned}$$

Predicted probabilities, odd ratios and their confidence intervals were calculated using *emmeans* (version 1.10.2) at a 95 % confidence level. A power analysis was performed for a paired *t*-test to determine the sample size required to detect a difference with an effect size of 0.5 (Cohen's $d = 0.5$), a power of 80 %, and a significance level of 0.05 (two-tailed). The calculation was performed using the *pwr* function (version 1.3–0) in R, and suggested that a total of 34 participants were required to achieve the required power.

2.1.5. Supplementary analysis

We also assessed the influence of native language linguistic roots on the priming effect, running an additional model including L1 (romance, germanic, semitic, other) as an additional fixed factor. See Model2:

$$\begin{aligned}\mathrm{Model2} <- \mathrm{glmer}(&\mathrm{Response} \sim \mathrm{Prime}*\mathrm{Grammaticality}*\mathrm{L1}\\ &+ (1 \mid \mathrm{Participants}) + (1 \mid \mathrm{Sentences}), \mathrm{data} = \mathrm{data}, \mathrm{family}\\ &= \mathrm{binomial}(\mathrm{link} = \text{"logit"})).\end{aligned}$$

2.2. Results

2.2.1. Rhythmic primes did not significantly impact grammatical judgments

Discrimination sensitivity *d'* and response bias *c* did not significantly differ between regular and irregular prime conditions (*d'*: $t(33) = 0.73$, $p = 0.47$, Cohen's $d = 0.12$, Fig. 2A; response bias *c*: $t(33) = -0.04$, $p = 0.97$, Cohen's $d = 0.007$, Fig. 2B). Bayesian statistical analysis showed moderate evidence towards the null hypothesis or at best a small effect size of rhythmic priming on d' in our grammaticality judgment task for Experiment 1. The estimated effect was M = 0.08, 95 % CI [−0.15; 0.29], $BF_{01} = 4.26$, BF_ROPE = 6.0, with 55.16 % of the posterior distribution falling within the ROPE. The GLMM model of grammaticality judgment accuracy with fixed effects of Prime * Grammaticality, did not reveal a significant main effect of Prime ($\chi^2(1) = 0.04$, $p = 0.85$, $\mathrm{emmean}_{\mathrm{Reg}} = 0.819$, $\mathrm{emmean}_{\mathrm{Irreg}} = 0.817$, odd ratio = 0.992, 95 % CI [0.821, 1.2]) or an interaction between Prime and Grammaticality ($\chi^2(1) = 0.191$, $p = 0.66$). However, it showed a significant main effect of Grammaticality ($\chi^2(1) = 74.8$, $p < 0.001$), with higher performance for grammatical sentences than for ungrammatical sentences ($\mathrm{emmean}_{\mathrm{Gram}} = 0.901$, $\mathrm{emmean}_{\mathrm{Ungram}} = 0.689$, odd ratio = 4.13, 95 % CI [3, 5.7]) (Fig. 2C).

2.2.2. Supplementary analysis

Our model including L1 as a fixed factor showed no significant main effect of L1 ($\chi^2(3) = 7.20$, $p = 0.066$) and a no significant interaction Prime * L1 ($\chi^2(3) = 7.46$, $p = 0.059$, Table S1).

2.3. Discussion

In Experiment 1, the grammatical judgment performance of adult participants with French as their L2 was not significantly affected by the type of musical prime. This contrasts with our hypothesis and the results of previous research on rhythmic priming and syntactic processing of L1 languages and suggests that the rhythmic priming effect does not extend to L2 processing. Although we did not show any influence of L1 on the rhythmic priming effect, the large diversity in terms of native languages in our sample may have partially obscured the rhythmic priming effect. Moreover, most studies showing a beneficial effect of rhythmic priming were conducted with participants whose native language was French (Bedoin et al., 2016; Canette, Fiveash, et al., 2020; Canette, Lalitte, et al.,

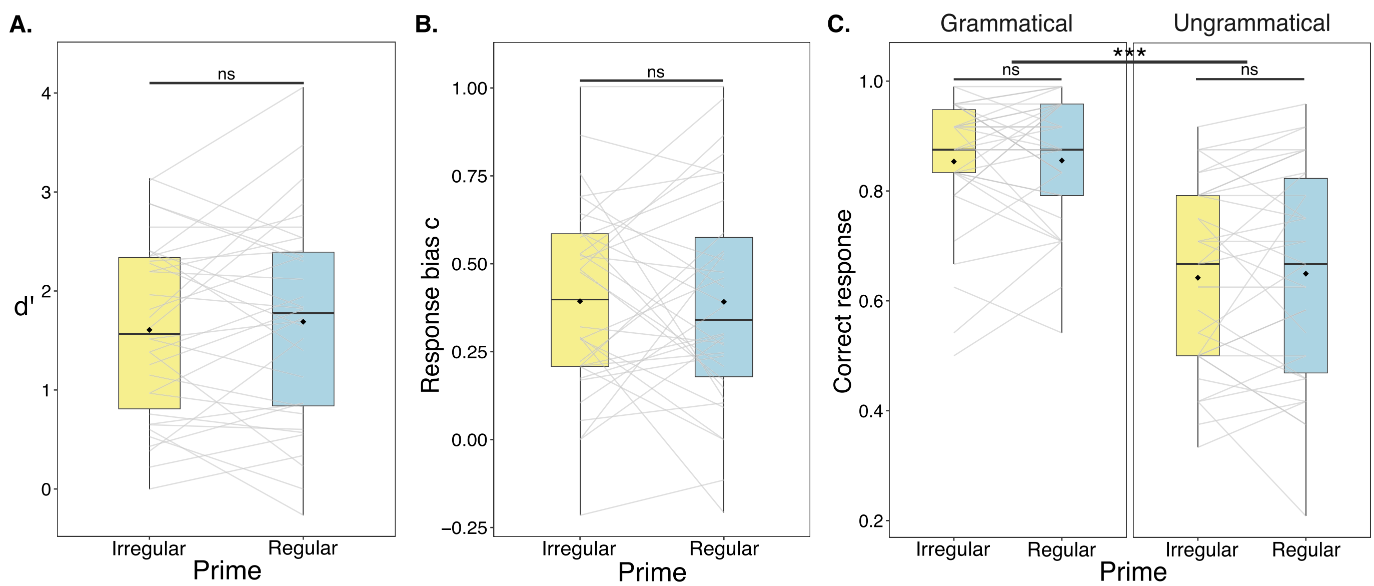

Fig. 2. Grammaticality judgment performances in Experiment 1. (A) d', (B) response bias c and (C) correct response (in proportion), after regular and irregular primes. The boxplots represent the dispersion of the data and the median. The diamond represents the mean in each condition. Individual lines represent individual data. Asterisks denote the significance of the estimated marginal means derived from the GLMM applied to response accuracy (***) p' ≤ 0.001.

2020; Fiveash et al., 2020; Przybylski et al., 2013). Consequently, to take the present investigation further, we wanted to replicate this experiment with a group of participants more homogeneous in terms of grammatical and phonetic proximity to French, i.e., native speakers of a Romance language.

3. Experiment 2: L2 speakers of French with a native Romance language background

3.1. Method

3.1.1. Participants

Thirty-three adults (17 women, 16 men, *M*age = 31.80 years, *SD* = 4.47 years, range 18–40) participated in the study. None reported auditory deficits or language disorders, and all participants had normal or corrected to normal vision. All participants took an audiometry test that confirmed their normal hearing before starting the experiment. One participant was excluded from data analyses because they obtained 100 % correct responses in the grammaticality judgment task. Therefore, thirty-two participants were included for the analyses. Participants were from 10 different nationalities and had a Romance language as their native language (Spanish, Italian, and Brazilian Portuguese). All participants lived in France at the time of the study. The average number of years of French lessons was 2.38 years (*SD* = 2.02). Their average time spent in France was 6.21 years (*SD* = 4.60). They reported an intermediate to advanced French language level (between B2 and C2 according to the CEFR), which was validated by the French test. As in Experiment 1, written informed consent was obtained based on the French ethics procedure approval Committee (CPP Sud Méditerranée II, 2020-A01231-38) from all participants prior to the experiment.

3.1.2. Materials

Musical prime stimuli. The musical stimuli of Experiment 1 were used.

Speech stimuli. The speech stimuli from Experiment 1 were used. However, the randomization of sentences in the grammaticality judgment task was modified to better balance the task difficulty of the blocks and to evenly distribute error types across the two priming conditions. The six-sentence unpaired structure was maintained (i.e., three grammatical and three ungrammatical sentences; two sentences of the "primary" error types and one of the "secondary" error types). In Experiment 2, we controlled for each error type to be presented the same number of times after the regular primes and after the irregular primes, in the first half (i.e., the first 8 blocks) as well as in the second half (i.e., the last 8 blocks).

Questionnaires, experimental design and procedure. All tasks and questionnaires were the same as in Experiment 1.

3.1.3. Data analyses on Experiment 2

The same analyses as in Experiment 1 were conducted.

3.2. Results for Experiment 2

3.2.1. Rhythmic priming did not significantly impact grammatical judgments

The paired sample *t*-tests on *d'* and on response bias c showed no significant effect of prime (Fig. 3A–B, *d'*: $t(31) = -0.55$, $p = 0.59$, $d = -0.10$, response bias *c*: $t(31) = 0.425$, $p = 0.67$, $d = 0.08$). Bayesian statistical analysis showed moderate evidence towards the null hypothesis or at best a small effect size of rhythmic priming on d' in our grammaticality judgment task for Experiment 2. The estimated effect was M = −0.06, 95 % CI [−0.30; 0.19], $BF_{01} = 4.61$, a = 6.7, with 55.05 % of the posterior within the ROPE. Our GLMM model with fixed effects of Prime * Grammaticality, did not reveal a main effect of Prime ($\chi^2(1) = 1.38$, $p = 0.240$, $emmean_{Reg} = 0.915$, $emmean_{Irreg} = 0.922$, odd ratio = 1.1, 95 % CI [0.844, 1.42]) or an interaction between Prime and Grammaticality ($\chi^2(1) = 0.64$, $p = 0.42$). However, it showed a main effect of Grammaticality ($\chi^2(1) = 84.38$, $p < 0.0001$), with higher performance for grammatical sentences than for ungrammatical sentences ($emmean_{Gram} = 0.973$, $emmean_{Ungram} = 0.778$, odd ratio = 10.2, 95 % CI [6.24, 16.8]) (Fig. 3C).

3.3. Discussion

In Experiment 2, we found no significant differences in grammaticality judgment performance as a function of priming type in L2 French adults whose first language was a Romance language. One possible explanation for the absence of significant findings in both Experiments 1 and 2 is that the size of the effect of rhythmic priming on L2 grammaticality judgments is smaller than $d = 0.5$. Another possibility is that

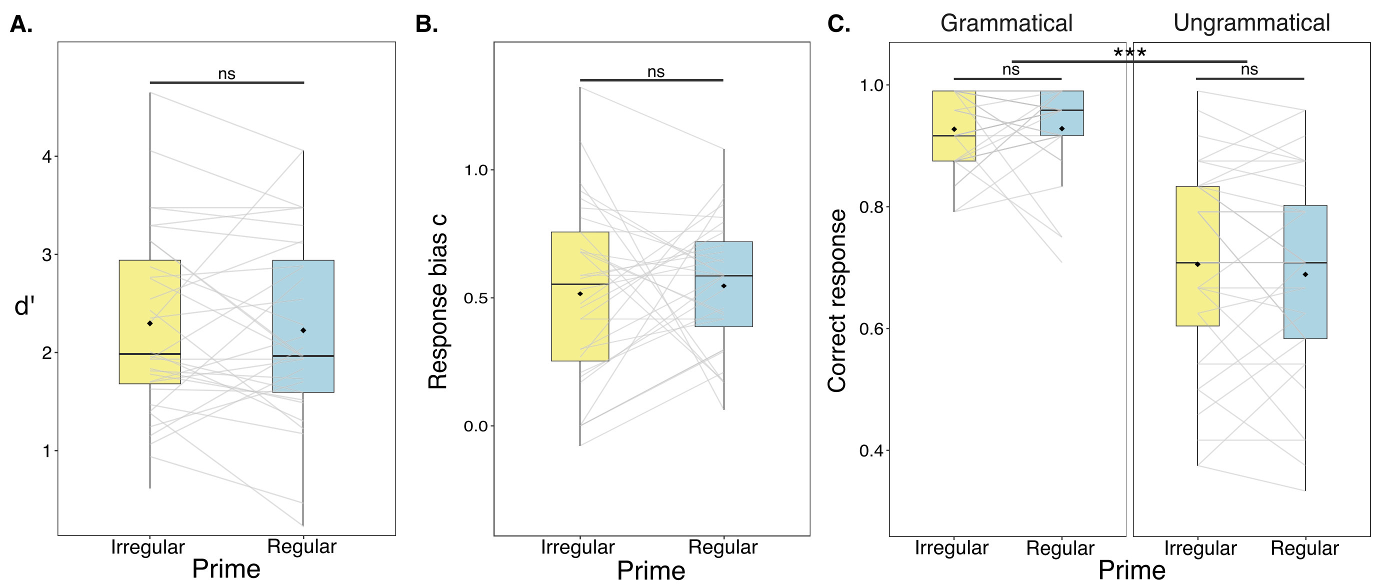

Fig. 3. Grammaticality judgments performance in Experiment 2. (A) d', (B) response bias c and (C) correct response (in proportion), after regular and irregular primes. The boxplots represent the dispersion of the data and the median. The diamond represents the mean in each condition. Individual lines represent individual data. Asterisks denote the significance of the estimated marginal means derived from the GLMM applied to response accuracy (***) p' ≤ 0.001.

the effect is moderated by speakers' rhythmic capabilities, musical training or French level. In the next section, we test these hypotheses by carrying out exploratory analyses on the combined data from both experiments (n = 66), which affords 80 % statistical power to capture small-to-medium effects (d = 0.35).

4. Combined Experiments 1 and 2

4.1. Method

4.1.1. Information from the questionnaires and additional tests

From the French test, we obtained a general score (up to 100) which was used for correlation analyses. A score under 20 corresponds to CEFR level A1/A2; a score between 20 and 70 corresponds to CEFR level B1/B2; and a score above 70 corresponds to CEFR level C1/C2. Participants obtained an average French level score of 67.8 (± 19.2 *SD*, range = [19.5, 100]). For the BAT score, we calculated the d' based on the number of hits (when a misaligned metronome was correctly detected) and false alarms (when a misalignment was erroneously reported). Participants obtained an average BAT score of 3.08 (± 1.52 *SD*, *range* = [− 0.75, 4.65]). We also defined the response times for correct responses as the time between the onset of the triangle sound and the response (average BAT RT = 4.55 s ± 1.87 s SD, range = [1.54 s, 9.50s]). We considered participants with musical training to be those who had received at least one year's formal musical training from a music teacher. The other participants were considered as having no musical training.

4.1.2. Data analyses

The same analyses as in Experiment 1 were conducted.

In addition, we ran Spearman's interindividual correlations in a correlation matrix between different measures of interest in the study, using *Hmisc* (version 5.1–3) and *corrplot* (version 0.92) packages in RStudio. From the BAT, we used the d' and the response times. From the French test, we used the general scores. From the grammaticality judgment test, we used the average *d'* and the rhythmic priming effect per participant, which corresponds to the difference between *d'* after regular primes and *d'* after irregular primes (i.e., a positive difference refers to a beneficial effect from regularity). We also included the "Music training" variable (i.e., the number of years of individual music instrument lessons with a private teacher) in the correlation analyses. We applied the Holm correction for multiple comparisons (p') (Holm, 1979). A power analysis showed that correlational analyses on the combined sample of 66 could detect coefficients as low as 0.34 with 80 % statistical power and a significance level of 0.05 (two-tailed).

Furthermore, to investigate whether other factors could influence the rhythmic priming effect, a GLMM on binomial data (as applied in Experiment 1 and 2) was run to investigate the four-way interaction between prime (regular, irregular), grammaticality (grammatical, ungrammatical), music training (yes, no), and the French test score. See Model3:

$$\text{Model3} < -\text{glmer}(\text{Response} \sim \text{Prime*Grammaticality*MusicTraining*FrenchTest} + (1 \mid \text{Participants}) + (1 \mid \text{Sentences}), \text{data} = \text{data}, \text{family} = \text{binomial}(\text{link} = \text{"logit"})).$$

4.2. Results for Experiments 1 and 2 combined

4.2.1. No rhythmic priming effect in a larger sample of L2 adults

Pooling Experiments 1 and 2, paired sample t-tests on d' and on response bias c showed no significant effect of prime (d': $t(65) = 0.10$, $p = 0.92$, Cohen's $d = 0.01$, Fig. S1A; or response bias c: $t(65) = 0.33$, $p = 0.74$, Cohen's $d = 0.01$, Fig. S1B). Bayesian statistical analysis showed evidence towards the null hypothesis or at best a small effect size for rhythmic priming on d' in our grammaticality judgment task (M = 0.0082, 95 % CI [−0.16; 0.17], BF01 = 7.4, BF_ROPE = 14.9, 80.63 % in ROPE). The model with fixed effects of Prime * Grammaticality, did not reveal a main effect of Prime, ($\chi^2(1) = 0.03$, $p = 0.85$, emmean$_{Reg}$ = 0.862, emmean$_{Irreg}$ = 0.863, odd ratio = 1.01, 95 % CI [0.871, 1.17]) or an interaction between Prime and Grammaticality ($\chi^2(1) = 0.03$, p = 0.87). However, it showed a main effect of Grammaticality ($\chi^2(1)$ = 104.08, $p < 0.001$), with higher performance for grammatical sentences than for ungrammatical sentences (emmean$_{Gram}$ = 0.936, emmean$_{Ungram}$ = 0.727, odd ratio = 5.51, 95 % CI [3.97, 7.65]) (Fig. S1C).

4.2.2. Music training has an impact on the rhythmic priming effect

Across both experiments, as expected, we found positive links between the grammaticality judgment d' and the French test score (r = 0.536, 95 % CI [0.334, 0.685], $p < 0.001$, $p' < 0.01$), showing that participants with higher French proficiency were more accurate in the grammatical judgment task. Interestingly, we also found a significant correlation between the d' and the BAT response time ($r = -0.404$, 95 % CI [−0.608, −0.160], $p < 0.001$, $p' < 0.02$) (Fig. 4A), suggesting that the faster participants responded correctly to the rhythmic perception test (BAT), the better they were at detecting grammatical errors. Furthermore, an interesting correlation was found between the rhythmic priming effect and music training ($r = 0.374$, 95 % CI [0.111, 0.593], p = 0.002, p' = 0.047) (Fig. 4B), showing that the more musical training, the more positive the difference between the performance after regular and irregular primes. We also found a positive correlation between the BAT score and music training (r = 0.529, 95 % CI [0.338, 0.691], $p <$ 0.001, $p' < 0.01$), showing that the higher the number of years of musical training, the better their rhythmic perception skills. Finally, we found a negative correlation between the BAT score and correct response times to the BAT ($r = -0.329$, 95 % CI [−0.554, −0.093], p = 0.007, p' = 0.08), suggesting that participants with a high BAT score were also those who responded most quickly; however, this did not survive correction for multiple comparisons.

4.2.3. The rhythmic priming effect differed between participants who had no musical training and those who had

Across both experiments, there was no main effect of Prime (χ^2 (1) = 0.04, $p = 0.84$), and no main effect of Music Training ($\chi^2(1) = 1.49$, p = 0.22, see Table S2). There was a main effect of Grammaticality ($\chi^2(1)$ = 100.91, $p < 0.001$), with higher performance for grammatical sentences than ungrammatical sentences (emmean$_{Gram}$ = 0.938, emmean$_{Ungram}$ = 0.722, odd-ratio = 5.87, 95 % CI [4.2, 8.21]) and a main effect of French test (χ^2 (1) = 25.44, $p < 0.0001$), showing that the higher the score on the French test, the greater the accuracy on the grammaticality judgment task. More interestingly, we found a significant interaction between Prime and Music Training (χ^2 (1) = 7.58, $p = 0.006$), suggesting that the rhythmic priming effect was influenced by the participants' musical background (Fig. 5). Concerning participants who had music training (n = 38), we observed a non-significant tendency in the expected direction: performance was better after regular than after irregular primes (emmean$_{Reg}$ = 0.880, emmean$_{Irreg}$ = 0.858, odd ratio = 0.82, 95 % CI [0.671, 1.00], $p = 0.051$). For participants who never had music training (n = 28), performance was significantly better after irregular primes than after regular primes (emmean$_{Reg}$ = 0.835, emmean$_{Irreg}$ = 0.875, odd ratio = 1.38, 95 % CI [1.084, 1.77], p = 0.009). We found no interaction between the French test and musical training ($\chi2$ (1) = 0.26, $p = 0.61$), which shows that the level of French did not differ between the two musical training groups. Finally, we found a significant interaction between Grammaticality and Music Training ($\chi^2(1)$ = 14.52, p = 0.001). Participants who had music training were better at detecting grammatical errors in ungrammatical sentences than participants who never had music training (emmean$_{MusicTraining}$ = 0.763, emmean$_{NoMusicTraining}$ = 0.677, odd-ratio = 0.653, 95 % CI [0.437, 0.976], $p = 0.038$). Performance of grammatical sentences did not differ between the two groups (emmean$_{MusicTraining}$ = 0.933, emmean$_{NoMusicTraining}$ = 0.944, odd-ratio = 1.215, 95 % CI [0.775,

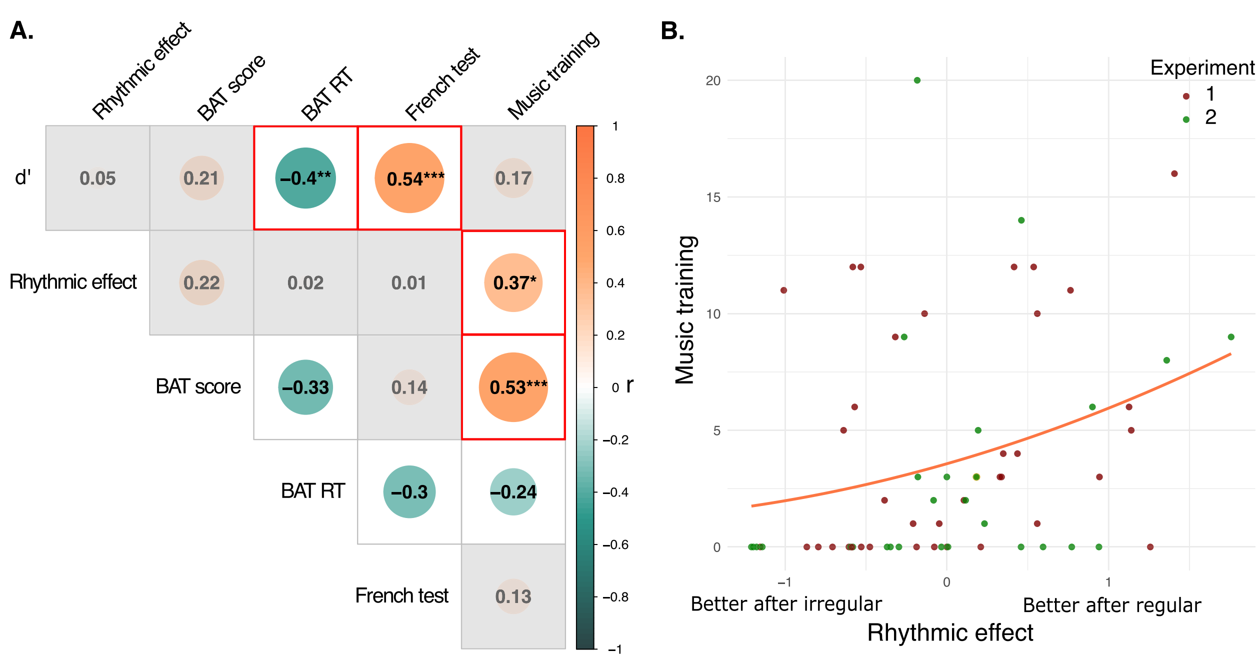

Fig. 4. Rhythmic skills correlate with grammatical judgments, and the rhythmic priming effect on grammatical judgments is dependent on musical training (A) Spearman Correlation matrix (data across Experiments 1 and 2, n = 66), including the grammaticality judgment d', the rhythmic priming effect (defined as the subtraction of d' after irregular primes from the d' after regular primes), the Beat Assessment Test score (BAT score), the correct BAT reaction times (BAT RT), the French test score (French test) and the number of years of supervised instrumental music training (Music Training). Positive correlations appear in orange and negative correlations in turquoise. Boxes shaded in grey are non-significant correlations. Ungreyed boxes are the significant correlations before correction and the boxes framed in red are the correlations surviving Holm's correction. (*) p' ≤ 0.05; (**) p' ≤ 0.01; (***) p' ≤ 0.001. (B) Correlation between Music Training and the Rhythmic Priming Effect. Each point on the scatter plot represents an individual participant. The orange line represents a second-degree polynomial fitted curve. Spearman's correlation coefficient (r) is 0.374, with a p-value of 0.002 and a Holm corrected p'-value of 0.047. This indicates a moderate correlation between the two variables. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

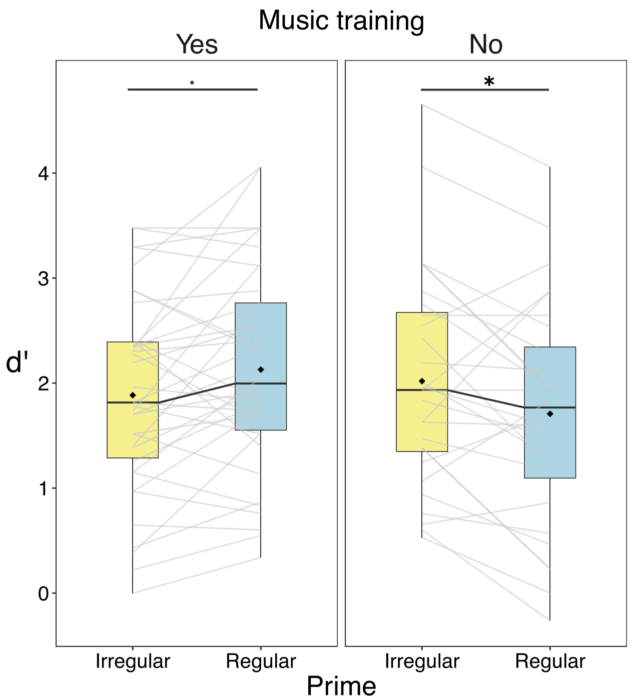

Fig. 5. Grammaticality judgments after regular and irregular rhythmic primes and according to the music training ("Yes" for participants who had individual lessons of musical instruments, and "No" for participants who never had individual musical instruments lessons), in adults for whom French is a second language through Experiments 1 and 2 (n = 66). The boxplots represent the dispersion of the data and the median d'. The diamond represents the mean in each condition. Individual lines represent individual participant data. Asterisks denote the significance of the estimated marginal means derived from the GLMM applied to the response accuracy (*) p' ≤ 0.05.

1.905], $p = 0.396$).

4.3. Discussion

We found no overall priming effect among our 66 participants across Experiments 1 and 2. However, we found correlations between grammaticality judgment performance and rhythmic perception performance, supporting the hypothesis of a link between grammatical and rhythmic skills previously established in the literature (e.g., Gordon, Jacobs, et al., 2015; Gordon, Shivers, et al., 2015; Heard & Lee, 2020). In addition, we also found that the rhythmic priming effect is related to musical training, as we observed a significant interaction between the priming effect on grammaticality judgment performance and musical training. Our results show that music training versus the absence of music training may influence how the musical rhythms were processed, which may in turn have influenced subsequent speech perception and performance on the grammaticality judgment task.

5. General discussion

The present study set out to examine the effect of rhythmic primes on grammaticality judgments, in two groups of adult learners of French as a second language (L2). We found no overall beneficial effect of regular rhythmic primes on L2 syntactic processing in adults, contrary to what was expected from the literature on native language (L1) processing in children (Bedoin et al., 2016; Canette, Lalitte, et al., 2020; Chern et al., 2018; Fiveash et al., 2020; Ladányi et al., 2021; Przybylski et al., 2013) and in adults (Canette, Fiveash, et al., 2020) with and without disorders. Nevertheless, our two experiments showed a positive correlation between performance on the grammaticality judgment task and performance on the Beat Alignment Test, providing converging evidence for the hypothesis that music and speech rhythm processing share common neural resources, and that syntactic and rhythmic skills are closely related (Fiveash et al., 2021; Gordon, Jacobs, et al., 2015; Heard & Lee, 2020; Ladányi et al., 2020). In addition, our data revealed a positive relationship between the number of years of musical training (measured by the number of years of supervised musical instrument lessons) and the effect of rhythmic priming: participants with musical training were more accurate in the grammatical judgment task when sentences were preceded by regular compared to irregular musical primes. These results suggest that rhythm processing, in both music and speech, may be influenced by long-term musical training.

5.1. The link between rhythm perception and speech processing

5.1.1. Potential common neural and cognitive mechanisms underlying rhythm and speech processing

The ability to predict ongoing sounds in time based on contextual rhythmic cues is of particular relevance in music and speech processing (Kösem & van Wassenhove, 2017; Zoefel & Kösem, 2024). It has been shown that auditory perception is modulated by the temporal predictability of its target (e.g., Bonnet et al., 2024), and that sounds are better discriminated when they are presented at timepoints that respect the beat of a preceding rhythm (Henry et al., 2015; Hickok et al., 2015; Jones et al., 2002; Lawrance et al., 2014; ten Oever et al., 2014). In speech processing, it has been shown that the speech rate defines expectations about the duration of words and syllables, which influences the perception of incoming words and word boundaries (Dilley & Pitt, 2010; Kösem et al., 2018; Reinisch et al., 2011). According to the Dynamic Attending Theory (DAT; Jones, 2018; Large & Jones, 1999; van Wassenhove & Herbst, 2020), exposure to a periodic rhythmic stimulus induces temporal attentional mechanisms that oscillate in synchrony with the rhythm, directing attention to predictable moments and providing more attentional resources at predicted temporal moments. Applied to musical rhythm and speech rhythms, the attentional cycles can synchronize with the beat in music and syllabic rate in speech, i.e., the moment in time when attention is at its highest, and which will enable the listener to make predictions about when the important element will appear in the next cycle. These oscillatory mechanisms would persist even after the external stimulus has ended, and can therefore influence subsequent perception, such as speech perception in our present study, by facilitating attention to temporally predictable elements (Kösem et al., 2018, 2020; van Bree et al., 2021). From a neural point of view, the inherent structure of a rhythmic stimulus facilitates the emergence of anticipatory behavior through the coupling of neuronal oscillations (see the Neural Resonance Theory; Large & Snyder, 2009). Neural phase entrainment enables the brain to enter a rhythmic mode, synchronizing periods of heightened neuronal excitability with key moments in the auditory signal (Schroeder & Lakatos, 2009). Therefore, rhythmic brain activity would underpin environmental sampling and would enable functional connections to be established between different brain regions, including motor and sensory regions (Fiebelkorn & Kastner, 2019). Even after rhythmic stimulation has ended, brain oscillations would continue to support temporal processing. This phase alignment would aid in predicting salient events in the speech signal, thereby enhancing the perception of complex rhythms and linguistic structures. Thus, by stimulating participants with an external musical stimulus that shares rhythmic characteristics with the natural flow of speech, temporal attention would improve the processing of temporal regularities in speech, which then allows for better perception and segmentation of linguistic units (Cutler, 1994; Giraud & Poeppel, 2012; Spinelli et al., 2010).

5.1.2. No significant main effect of music rhythmic priming in our experiment

Unlike our initial hypothesis, we failed to report a main effect of rhythmic priming to grammatical judgment tasks in L2 adults. A potential limitation of the rhythmic priming paradigm was highlighted in the study by Hilton and Goldwater (2021), which showed that when the metric of a sentence conflicts with its syntactic structure, both sensorimotor synchronization with the metric and sentence comprehension are disrupted — a phenomenon they termed the “metrical Stroop effect”. This finding suggests that the ability to anticipate and align rhythms with syntax relies on fine coordination between sensory, motor, and linguistic systems. In other words, in the context of our study, if the rhythmic regularity of the prime does not match the syntactic structure of the target sentence, the prime may not only be unhelpful but could even hinder comprehension. Rassili and Ordin (2022) further indicated that, for rhythmic primes to effectively impact speech perception, the duration of the prime should be sufficient to establish a perception of temporal regularity. In the study conducted by Fiveash et al. (2020), a significant facilitatory effect was observed only with 32-s rhythmic primes, and not with shorter durations of 8 or 16 s. Accordingly, we employed 32-s primes from the aforementioned study, as previous research has demonstrated the efficacy of rhythmic priming on grammaticality judgments in both children (Bedoin et al., 2016; Canette, Lalitte, et al., 2020; Chern et al., 2018; Ladányi et al., 2021; Przybylski et al., 2013) and adults (Canette et al., 2019; Canette, Fiveash, et al., 2020; György et al., 2024). Collectively, these findings suggest that the duration of the rhythmic primes in the present study was sufficient to elicit a priming effect. While the rhythmic priming effect was not observable across participants, we observed distinct priming effects depending on their musical training (as discussed in Section 5.2.).

5.1.3. Better rhythm perception associated with improved grammatical perception

Our study found a relationship between rhythm perception and grammatical judgments: participants with better rhythm perception (as assessed with faster response times in the BAT) had overall better grammatical judgment performance. This is in line with other studies showing similar links between rhythm perception skills and syntax skills (for a review see Gordon, Jacobs, et al., 2015; Gordon, Shivers, et al., 2015; Heard & Lee, 2020; Kim et al., 2024) and, more generally, between speech and music rhythm (for a review see Fiveash et al., 2021; Slater & Kraus, 2016). Our results further reinforce the hypothesis that rhythmic abilities are instrumental in speech processing and, as a consequence, also influence grammar judgments in L2 speech perception.

5.2. The role of musical experience

5.2.1. Musicians demonstrate enhanced proficiency in detecting grammatical errors in spoken language

Several studies have shown that music training can influence the development of native (Schön et al., 2004) and foreign language skills (Chobert & Besson, 2013; Slevc & Miyake, 2006; Turker et al., 2017). Here, we found that the musically trained group detected syntactic violations in ungrammatical sentences better than the musically untrained group, with no difference in their French test score between the two groups. This result reinforces the idea of a close link between rhythmic and grammatical skills, even in L2.

5.2.2. The rhythmic priming effect is affected by individuals' musical background

Furthermore, our present study showed that musical training influences the rhythmic priming effect in L2 language perception. Musical training was correlated with the effect of rhythmic priming on grammatical judgments: participants with musical training had better grammatical judgments after regular primes, while participants without training performed better after the presentation of irregular musical primes. This result seems to be in line with the results of the Canette et al. (2019) study on L1 adults. Although they did not report an association between the number of years of formal music training and the rhythmic priming effect on syntactic processing (i.e. a non-significant regression model), they found that some self-reported rhythmic interest and abilities could predict the rhythmic priming effect: the desire to move and synchronize with music predicted it positively, while the inability to follow a musical rhythm tended to be a negative predictor.

5.2.3. Difference in rhythm processing between musicians and non-musicians

A potential explanation for the observed differences between musicians and non-musicians in the current study might be related to their difference in rhythmic processing abilities. Indeed, previous studies have shown that rhythmic abilities vary considerably among healthy individuals (Repp, 2010; Sowiński & Dalla Bella, 2013) and are influenced by musical training (Grahn & Schuit, 2012; Repp, 2010). Studies have shown that there are differences in time-tracking abilities between musicians and non-musicians (Gratton et al., 2016) and that neural responses to auditory rhythms vary, with musicians having more robust neural tracking of both rhythmic and metrical beats (Celma-Miralles & Toro, 2019; Doelling & Poeppel, 2015; Radchenko et al., 2023). Musicians also have a greater memory capacity for rhythms and can better recall the absolute tempo of musical excerpts than non-musicians (Schaal et al., 2015). For these reasons, musical training might help individuals extract onset regularity, entrain to the signal, and transpose it more easily to L2 speech, compared to non-musically trained individuals for whom this transfer might be possible in L1 processing, but more complex to achieve in L2 processing.

According to the DAT, subjectively preferred internal tempo may vary between individuals (DAT; Large & Jones, 1999). This reference period corresponds to the tempo at which individuals spontaneously clap their hands. Research conducted by Drake et al. (2000) revealed that individuals with formal musical training tend to tap along more slowly, create a wider variety of rhythms, and synchronize more effectively with isochronous and rhythmic sequences than non-musicians. It is plausible that adults who have received formal musical training are more adept at discerning regularity due to their greater flexibility in rhythm synchronization. In contrast, non-musicians may rely more heavily on an internal reference period, which could limit their flexibility to transfer the regularity of the prime to the analysis of the speech signal.

Music training has been shown to be associated with enhanced sensory-motor synchronization and this might foster the development of rhythmic skills (Dalla Bella, Farrugia, et al., 2017; Martins et al., 2023). Auditory-motor coupling in musicians is stronger than in non-musicians (Bangert et al., 2006; Bangert & Altenmüller, 2003; Baumann et al., 2007). According to the “active sensing framework,” the generation of neural oscillations by the motor system facilitates communication with auditory areas and promotes sensory predictions as well as the processing of temporal regularities in music and speech (Morillon et al., 2015; Schroeder et al., 2010). Musical practice may therefore strengthen connectivity in the auditory-motor pathway, which is considered crucial for processing temporal predictions during music and language listening (Bruderer et al., 2015; Chemin et al., 2014; Fiveash et al., 2021; Hickok et al., 2011; Zatorre et al., 2007). This might also lead to musicians increased ability to process and project rhythms more flexibly, processing complexity in rhythmic patterns (whether music or language), and this would then prevent them from rigidly synchronizing with the single tempo or metric structure of the prime, which might not always match with the rhythmic structure of the ongoing sentence (Hilton & Goldwater, 2021), thus leading to the observed suggestive regular prime benefit and absence of negative effect in contrast to the nonmusicians.

The enhanced performance after irregular compared to regular primes for the non-musicians in the current study was unexpected, and difficult to interpret. On the one hand, non-musicians might have been more surprised than musicians when they heard the irregular primes, leading to a heightened state of arousal compared to during the presentation of regular primes. On the other hand, non-musicians might also have synchronized less well with the regular rhythms and therefore benefitted less from the regularity, and/or the beat was costful to extract or transfer to the speech material. However, interpreting the benefit, or lack thereof, from irregular rhythms is complex, as we did not test an additional control/baseline condition (such as silence or environmental sound baselines), as in previous studies (Bedoin et al., 2016; Canette, Lalitte, et al., 2020; György et al., 2024; Ladányi et al., 2021). These studies have shown a beneficial effect of the regular prime in speech comprehension in children, compared to a silent baseline or environmental sounds. In future studies, it will be essential to include such control conditions in order to better determine whether and/or under which conditions the influence of the regular rhythmic primes might be beneficial, neutral, or potentially detrimental compared to a baseline condition. If some participants do not benefit from regular rhythmic priming - or perhaps even show a cost of extracting and/or transferring the regular pulse to speech or potentially benefit more from irregular rhythmic priming - such a result would have important implications, both theoretically and for rehabilitation approaches. Further, it would be interesting to include a larger set of temporal processing tests with music-like materials to cover the different aspects of temporal processing capacities (e.g., Fiveash et al., 2022) and thus deepen our understanding of their link to rhythmic priming and transfer effects.

In sum, our results reinforce the idea of not neglecting interindividual differences of participants (Fiveash et al., 2025) and highlight in particular the importance of not neglecting measures of rhythmic skills in general and of formal and prolonged musical training, even for a few years, in studies related to musical and linguistic rhythm processing.

5.3. Rhythm processing during childhood and adulthood

5.3.1. Development of rhythmic skills throughout the lifespan

The link between rhythmic priming and musical expertise may initially seem paradoxical compared to studies that have shown a beneficial effect of rhythmic priming on L1 in children with limited musical training (Bedoin et al., 2016; Przybylski et al., 2013). According to previous results on L1 in adults (Canette et al., 2019) and ours on L2, rhythmic abilities or even a short period of musical instrument lessons (at least one year of formal lessons) might impact rhythm perception and the effect of rhythmic priming.

During development, rhythmic skills follow an inverted U-shaped curve with age: rhythmic perception and synchronization improve during childhood and adolescence, then maintain stable from adolescence into adulthood (Drewing et al., 2006; Thompson et al., 2015), and decline after the age of 40 (Thompson et al., 2015). In a beat synchronization task involving tapping, Thompson et al. (2015) showed that the ages with the poorest precision and the greatest variability are children and older adults. Additionally, they compared the performance of participants with musical experience (defined as a minimum of 3 years of practicing music) to those without such experience (no more than 6 months of consistent practice). They found no difference in tapping asynchrony between musical training groups for children (aged 8–14) and young adults (aged 18–22), but a difference did appear among adolescents (aged 14–18) and middle-aged adults (aged 22–43). These results suggest that differences in rhythmic skills between individuals with and without musical training may be more pronounced at specific ages, and that with limited musical training in childhood, differences in rhythmic skills may be subtle to capture. Furthermore, such research is consistent with our findings, as the mean age of our sample ($n = 66$) was approximately 30 years (i.e., within the middle-age adult range for which interindividual variability is high), which show a difference in rhythm processing between participants with no musical training and those with some training (even if they had only a few years of music lessons).

5.3.2. Difference in rhythmic priming effects in adults and in children

Though temporal processing and sensitivity to these rhythms are already present from birth, the developing human brain might initially prefer regular, simple and familiar rhythmic patterns, in order to be able to efficiently process sound information from their environment and build their prediction system (e.g., Schellenberg & Trehub, 1996). As adult participants usually surpass young children in rhythmic abilities, they may easily process the complex temporal structure of speech, even in their L2, and therefore may benefit less from rhythmic priming. Rhythmic priming effects were not observed behaviorally in our study (as previously shown in Canette, Fiveash, et al., 2020). In the experiments by Kotz and Gunter (2015) and Canette, Fiveash, et al. (2020), rhythmic priming influenced the P600 response to the next utterance, but no difference in grammatical judgment was observed after regular and irregular primes due to a ceiling effect, i.e., the task being too easy for L1 adult subjects. In our experiment, the task was more difficult for participants, as we recruited L2 French speakers, yet we observed no significant difference of rhythmic priming on behavior. It would be interesting to investigate whether rhythmic regularity also boosts P600 in this population.

5.4. Does native language play a role in rhythm perception?

5.4.1. No influence of native language on rhythmic priming effect in L2 perception

According to the linguistic bias hypothesis (Smit & Rathcke, 2024), listeners transfer their perceptual bias to rhythm perception in a foreign language. This suggests that cultural and linguistic experience, both in language and in music, crucially contribute to rhythm perception (Cameron et al., 2015; Smit & Rathcke, 2024; Zhang et al., 2020). Indeed, rhythmic features inherent in the native language could influence how musical rhythm is processed (Bhatara et al., 2016; Iversen et al., 2008; Yoshida et al., 2010) and its impact on speech processing (Smit & Rathcke, 2024). In our two groups of L2 learners, the high linguistic heterogeneity may have masked the effects of rhythmic priming, particularly among non-musicians (musicians, being rhythmically more flexible, may more easily adapt to a fixed tempo, making them less sensitive to this factor). Although acoustic analyses have shown that speech tempo is relatively stable across languages — around 4 to 5 Hz, corresponding to syllable rate, or approximately 4 to 5 syllables per second (Ding et al., 2017) — slight cross-linguistic variations in speech rate have nonetheless been reported (Pellegrino et al., 2011). Thus, L2 learners may be accustomed to different speech tempi in their native languages, which could influence their preferred linguistic tempo. It is therefore possible that the fixed tempo of rhythmic primes contributed to the absence of effects observed in our studies. It would be relevant to explore whether an individual's preferred rhythmic tempo is correlated with their own speech production rate. For instance, if a participant is used to a faster-speaking language, a regular rhythmic prime with a 500 ms inter-beat interval (IBI) might seem too slow and thus interfere with processing. In the second experiment, although we attempted to reduce linguistic variability by selecting only speakers of Romance languages, it remains possible that differences in speech rate still exist even within a single language family.

However, in our study, we did not find an effect of the first language (L1) on the rhythmic priming effect. Given the small size of our language subgroups, this finding merits further exploration and confirmation by re-applying this study to a much larger sample of participants from a wide variety of languages. While this aligns with Ordin et al.' (2019) findings, suggesting that the ability to discriminate rhythmic patterns may be governed by general auditory system properties and cognitive mechanisms shared by all humans, regardless of their native language, the literature shows diverse findings regarding L1-background influences and regularities in the to-be processed materials. For instance, Liu et al. (2023) who compared speakers of tonal and non-tonal languages and showed that speakers of tonal languages performed worse on beat alignment tasks compared to speakers of non-tonal languages, and Fernández-Merino et al. (2025) comparing Spanish and Basque speech rhythms in Spanish-Basque bilingual adults, who found stronger rhythmic priming effects when rhythmic cues directly aligned with the speech rhythm of the target language (Spanish and Basque) compared to regular or irregular primes. This calls not only for the need to study various phenomena beyond English speakers only (Blasi et al., 2022) but also for adapting rhythmic primes to the specific rhythm of the language being tested might be key to improving processing. Taking into account the rhythmic characteristics of the target language and aligning primes accordingly could lead to more effective generalization of the rhythmic priming effect (Kotz et al., 2005; Ladányi et al., 2020).

5.4.2. Rhythmic priming effect in L1 and L2 speech perception

Most studies that have shown a beneficial behavioral effect of regular rhythmic priming on syntax processing were on L1, mostly with L1 being French (Bedoin et al., 2016; Canette et al., 2019; Canette, Fiveash, et al., 2020; Canette, Lalitte, et al., 2020; Fiveash et al., 2020; Przybylski et al., 2013), but also Hungarian (Ladányi et al., 2021) and English (Chern et al., 2018). Furthermore, despite the difficulty of acquiring the grammar of a foreign language, studies have shown that adult learners' grammatical and neurocognitive processing can approach that of native speakers (Birdsong & Molis, 2001; Hahne et al., 2006), even after months of non-exposure (Morgan-Short et al., 2012). Despite our expectations and these arguments, we did not replicate this effect in adult L2 learners of French, at least not in those without musical training. To go further, it would be interesting to first study whether the same effects regarding musical training would be found for adults whose second language is English or Hungarian, for example. Indeed, although the notion of clear rhythmic distinctions between languages is still debated, differences in speech rhythm are likely to exist between languages (Arvaniti, 2009; Bertinetto, 2021; Varnet et al., 2017) and these differences could be important in the perception of rhythm and the impact of rhythmic priming.

6. Conclusion

In contrast to previous studies that demonstrated a beneficial effect of rhythmic priming on native language (L1) processing in both children and adults, we did not observe the expected rhythmic priming effect among all adult L2 speakers of French. However, our study revealed a positive correlation between the rhythmic priming effect and the number of years of musical training, as well as an interaction between the rhythmic primes and musical background (defined as two groups of participants, i.e., with vs without musical training). Participants with musical training performed better on syntactic processing after regular primes, while non-musicians performed better after irregular primes. Furthermore, we observed that participants with better rhythmic skills performed overall better on the grammatical judgment task, providing converging evidence that grammatical error detection capacities are linked to musical rhythm perception skills (see also Gordon, Jacobs, et al. (2015) and Gordon, Shivers, et al. (2015) for L1 processing). Future research should include an additional non-rhythmic baseline condition aiming to further investigate how regular and irregular rhythmic primes influence speech processing (beneficially or detrimentally) and additional temporal processing tests. These next steps open up interesting perspectives on the impact of musical experience on temporal predictions in musical rhythm and speech processing, and on the underlying mechanisms involved in potential priming or transfer effects.

CRediT authorship contribution statement

Julie Camici: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Anna Fiveash:** Writing – review & editing, Software, Methodology, Formal analysis, Conceptualization. **Oussama Abdoun:** Writing – review & editing, Software, Methodology, Formal analysis. **Barbara Tillmann:** Writing – review & editing, Validation, Supervision, Investigation, Formal analysis, Conceptualization. **Anne Kösem:** Writing – review & editing, Validation, Supervision, Project administration, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT (GPT4, Open AI) in the writing process in order to improve the readability and language of the manuscript. The authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.actpsy.2025.105845.

Data availability

Data, stimuli, and code related to experimental design and analyses are available at the following link: https://researchbox.org/3674

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