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## TITLE

Rhythmic and textural musical sequences influence differently syntax and semantic processing in children

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## INTRODUCTION

Cross-domain influences between music and language processing have been demonstrated separately for syntax processing and conceptual (or semantic) processing and mostly in adults for the latter. Our study used rhythmic and textural features of music to investigate their respective influences on syntax and semantic processing in children.

Rhythm is a key aspect in music and speech. Sensitivity to temporal regularities has been shown early in infancy for both linguistic and musical materials (for reviews see Gordon, Jacobs, Schuele & McAuley, 2015a; Hannon, Nave-Blodgett & Nave, 2018; Hannon & Trainor, 2007). Rhythm is part of speech prosody, which is characterized by melody, stress, rhythm, speed and breaks. Rhythmic variations in speech contain important cues for syntax events (e.g., Gordon et al., 2015a). In language development, the prosodic bootstrapping hypothesis suggests that prosodic cues (including rhythm) in speech represent useful information for grammar acquisition (Morgan & Demuth, 2014). For example, 20-month-old children are able to exploit phrasal prosody to access the syntactic structure of sentences (de Carvalho, Dautriche, Lin & Christophe, 2017). Furthermore, syntactic abilities seem to be closely related to rhythmic and musical abilities even in young children. For example, abilities in rhythm perception have been reported to be associated with morpho-syntactic abilities in speech production (Gordon et al., 2015b), and musically trained children show better morpho-syntactic abilities than non-musically trained children (Jentschke & Koelsch, 2009; Marin, 2009). In adults, electrophysiological data have shown the impact of temporal regularities in speech on syntax processing (Schmidt-Kassow & Kotz, 2008).

The link between rhythm and syntax processing has been further shown by the effects of musical rhythmic primes on subsequent speech processing: A short exposure to a musical sequence with a strongly established regular underlying beat can improve subsequent syntax processing in typically-developing children and in children with developmental language disorders (in French: Bedoin, Brisseau, Molinier, Roch & Tillmann, 2016; Przybylski et al., 2013; and in English: Chern, Tillmann, Vaughan & Gordon, 2018). Rhythmic priming also increases the benefit of a syntax training program in children with cochlear implants (Bedoin et al., 2018). The beneficial effect of listening to regular rhythms has been reported in comparison to irregular temporal sequences (Chern et al., 2018; Przybylski et al., 2013) and to neutral baseline sequences (i.e., environmental sounds) (Bedoin et al., 2016 and 2018). Furthermore, Chern et al. (2018) reported that the influence of rhythmic priming does not extend to two non-linguistic control tasks (i.e., requiring mathematical and visuo-spatial processing). These findings suggest that the rhythmic priming effect on grammatical processing is not due to general cognitive benefits thanks to enhanced arousal from listening to music, but rather based on cognitive mechanisms shared between rhythm and syntax processing (e.g., cognitive sequencing).

Potentially shared mechanisms between music and language processing have also been shown for semantics. For example, the duration of music training predicts children's performance on a vocabulary test (i.e., the ability to explain the meaning of words) (Forgeard, Winner, Norton & Schlaug, 2008), and children who followed musical training in a longitudinal study have enhanced vocabulary skills compared to control children (Linnavalli, Putkinen, Lipsanen, Huotilainen & Tervaniemi, 2018; Moreno et al., 2011). In adults, priming studies have shown that listening to music can activate semantic concepts. A musical piece (the prime) can influence semantic processing of a subsequently presented word, which has been experimentally manipulated to be related or unrelated to the prime. This relatedness manipulation is based on the hypothesis that music can convey meaning. Two main classes of meaning have been described to emerge from music: (1) extra-musical meaning (i.e. related to things outside the music: concepts, ideas, events, psychological states), and (2) intra-musical meaning (e.g., relationships between musical elements) (e.g., Koelsch, 2011; Patel, 2008).

Koelsch et al. (2004) have demonstrated that listening to real musical excerpts as primes evokes

semantic priming effects (as reflected in the electrophysiological evoked-related component N400, referred to as a marker for semantic integration) similarly to listening to sentences as primes (as has been classically done in psycholinguistic research; e.g., Kutas & Hillyard, 1980): musical excerpts and sentences as primes evoke a larger N400 for subsequently presented unrelated target words than related target words. In a behavioural follow-up study, Poulin-Charronnat, Grieser, Meyer and Koelsch (2006) showed that reaction times in a lexical decision task were also influenced by the relatedness between musical primes and target words. In these first studies, the musical primes had rather long durations (e.g., 10.5 seconds on average in Koelsch et al., 2004), but the N400 priming effect has also been observed for target words following very short musical excerpts (i.e., 1 second) (Daltrozzo & Schön, 2009a, 2009b). The N400 priming effect has also been observed when the order of presentation was reversed, leading to musical excerpts as targets, which were related or unrelated to the prime words. These effects were observed with direct (Daltrozzo & Schön, 2009a) and indirect tasks (Daltrozzo & Schön, 2009b), that is, with participants' attention drawn on the potential relation (relatedness judgment task) or not (lexical decision task). These findings thus demonstrate that one second of music is sufficient to communicate conceptual information.

Other studies did not use musical excerpts as primes, but focused on specific musical parameters to investigate whether they convey meaning. Sollberger, Reber and Eckstein (2003) manipulated the consonance/dissonance of prime chords, aiming to induce positive/negative emotions and investigated their effect on affectively (un)related target words. Response times to target words in a word-evaluation task (i.e., to judge whether each word was positive or negative) were longer after an affectively incongruent chord prime (e.g., a consonant prime chord followed by a negative word) than after an affectively congruent chord prime (e.g. a consonant prime chord followed by a positive word). Steinbeis and Koelsch (2011) manipulated three musical parameters: consonance/dissonance, mode (major/minor) and timbre. For each of these parameters, response times were increased and the N400 emerged for affectively incongruent pairs compared to affectively congruent pairs. Manipulating the timbre of the musical primes independently of the affective dimension, Grieser Painter and Koelsch (2011) showed an N400 priming effect with short musical sounds. They concluded that a basic feature of music, such as timbre, can activate meaningful representations and independently of the emotional valence of the sounds. A similar conclusion has been reached by Schön, Ystad, Kronland-Martinet and Besson (2009) who used sounds without recognizable sound sources as primes, chosen on the basis of the classification of sound objects proposed by Schaeffer (1966). Their EEG measurements revealed an enhanced negativity to target words that were unrelated to the sound primes (in comparison to related primes), further supporting the role of timbral, spectro-temporal characteristics of sound in concept activation.

Previous priming research thus suggests shared resources in music and language processing in the domains of rhythm and syntax, as well as semantics (e.g., Przybylski et al., 2013; Schön et al., 2009). For each aspect of language processing, some specific features of music have been highlighted in relation: syntax processing has been related to rhythmic processing and cognitive sequencing, whereas semantic and concept activation has been related mostly to musical timbres and spectro-timbral features in the sounds. On this basis, the present study tested the influence of different types of musical sequences, which focussed on either rhythm or texture, on subsequent language processing, notably syntax processing and semantic processing. We thus contrasted regular rhythmic sequences – with a strong underlying beat and metrical structure – and textural sound sequences – focusing on timbre and its spectro-temporal changes and progressions. The effect of these two musical conditions on subsequent language processing was measured with two linguistic tasks, investigating either syntax processing (i.e., grammaticality judgments) or semantics (i.e., verbalize concepts evoked by the musical sequence; referred to as semantic evocation task). If the influence of music on syntax and semantic processing is related to different musical features, we expect differential effects of each musical sequence type on these two linguistic processes. Regular

rhythmic sequences should boost processing that requires sequencing and structure processing (i.e., the grammaticality judgment task), while textural sound sequences should promote and enhance semantic concept activations, leading to enhanced and more various productions in the semantic evocation task. In addition, regular rhythmic and textural sound sequences should evoke different semantic contents in line with the musical parameters of the sequences. If, however, the potential effects of different types of musical sequences on subsequent language processing are solely the result of non-specific mechanisms (such as related to mood or arousal, e.g., Thompson, Schellenberg & Husain, 2001), the same effects should be observed for both types of task and we should not observe the described cross-over pattern. Our study thus aims to further our understanding of cognitive mechanisms influenced by prior listening to music with different parameters and opens perspectives for the use of music in language training and rehabilitation (e.g., syntax and semantic disorders).

## **MATERIAL AND METHODS**

### **1. GENERAL METHODS**

**1.1. Participants.** Thirty native French-speaking children participated in the syntax task or the semantic task. They were split into two groups to prevent the children from listening to the same musical material twice. Sixteen children performed the syntax task (8 boys, average chronological age: 8 years 0 month, SD = 6 months, range: 7 years 2 months – 8 years 11 months). Fourteen children performed the semantic task (7 boys, average chronological age: 7 years 11 months, SD = 4 months, range: 7 years 6 months – 8 years 5 months). In addition, sixteen other children participated in a follow-up of the syntax task (7 boys, average chronological age: 7 years 3 months, SD = 5 months, range: 6 years 10 months – 8 years 7 months). Parents gave informed consent, and schools were part of an agreement between the LEAD (The Laboratory of Research on Learning and Development) and the regional representative of the French Ministry of education (labelled as “Inspection Académique de la Côte d’Or”).

### **1.2. Material**

Musical stimuli. Two types of musical sequences of 17 seconds were used: regular rhythmic sequences and textural sound sequences. Six regular rhythmic sequences were constructed on the basis of a 4/4 meter and a 120 BPM tempo, that is with an underlying inter-beat-interval of 500 ms (i.e., 2 Hz). These sequences were formed by 4 layers of rhythmic patterns, leading to a four-level rhythmic hierarchy. To create variety across the sequences beyond the temporal pattern, each layer was played by one (and sometime two) percussion instrument(s) (i.e., bass drum, snare drum, tom-tom, or cymbal). All sequences were based on MIDI VST musical instruments. Four of the sequences also contained some samples of electronic sounds. Each sequence was composed of one cycle of 16 beats that was repeated identically two times. To create a feeling of completion at the end of the sequence, the first beat of the cycle was added at the end with a short reverberation effect. Note that at the end of a cycle, a short rhythmic pattern or a percussion sound was added to reinforce the sensation of formal periodicity. All sequences were recorded with Cubase 4 and VST sampler. A short reverb effect was added (reverb time 1.75 s, mixed at 25 %). Finally, they were exported in 16 bits/48 000 Hz mono wav files.

Textural sound sequences were extracted from contemporary art music (see Appendix A for more details). They were characterized by the blending of continuous melodic or harmonic strata evolving across time, without regular rhythmic patterns or underlying pulse or meter. All musical sequences were taken from real recordings and normalized in loudness (dBA). See supplemental material for examples.

**1.3. Procedure.** Children were asked to listen to the musical sequences and to perform a linguistic task immediately afterwards. They heard the 12 sequences during the task (i.e., 6 regular rhythmic sequences and 6 textural sound sequences). Details of musical materials and each language task are described here below. At the end of the language task, the musical sequences were presented again (in pseudo-random order, with the constraint to avoid listening to the same musical sequence type more than twice successively), and children were asked to judge each musical sequence on three different subjective scales. Each scale was composed of five drawings representing a schematic face of a child (a girl or a boy, chosen depending of the gender of the participant), and the corresponding description below each drawing. The first scale assessed perceived emotion, requiring children to provide a judgement from 1 to 5: from “very sad” (i.e., depicted by a crying face) to “very happy” (i.e. depicted by a face with a big smile). The second scale assessed interest, from “very boring” (i.e. depicted by a yawning face) to “very interesting” (i.e. depicted by a smiling face with wide open eyes). The third scale assessed pleasure, from “I don’t like at all” (i.e. depicted by a face representing disgust) to “I like very much” (i.e. depicted by a smiling face). We designed these judgment scales to measure whether and to what extent the children distinguished the two music conditions (i.e., regular rhythmic vs. textural sound materials) on the three aspects, notably emotion, interest and pleasure. Children were tested individually in a quiet room at their school. The duration of the experiment was about 25 min.

## 2. TASK SPECIFIC METHODS

### 2.1. Syntax task

To investigate the effect of musical sequence types on subsequent syntax processing, the syntax task required grammaticality judgements on auditorily presented sentences. In addition, a follow-up of the syntax task measured the performance in this task without musical sequences, aiming to obtain a baseline performance for children of that age.

#### 2.1.1. Material

*Linguistic stimuli.* The linguistic material was composed of 96 French sentences that were grammatically either correct (48) or incorrect (48). The incorrect sentences were created on the basis of the correct sentences. Four sentence types composed the material, corresponding to four types of violations: (1) gender agreement violation between the specifier and the noun (e. g. La fille a joué à la/\*le poupée [The girl plays with \*the doll]), (2) number agreement violation on the verb (e. g. Les policiers ont/\*a arrêté le voleur [The policemen \*apprehended the robber]), (3) auxiliary violation between “be” and “have” (e.g. Vous êtes/\*avez partis avec des gâteaux [You \*left with cakes]), (4) past participle violation (e.g. Le gardien a éteint/\*éteindre les lumières [The watchman \*switched off the lights]). All sentences had the same syntactic construction: (1) subject (specifier and noun or personal pronoun), (2) verb (conjugated in past tense), (3) complement (direct or indirect object complement, or circumstantial complement). Word frequencies were controlled with two databases: Lexique 3 (New, Pallier & Matos, 2011) and Manulex (Lété, Sprenger-Charolles & Colé, 2004). Sentences contained on average 6.21 words (SD = 0.77, range = 5 to 8) and 8.82 syllables (SD = 1.06, range = 7 to 11). To avoid children listening to the same sentence in its correct and incorrect versions, sentences were split into two lists (A and B) of 48 sentences. Each correct sentence of list A was matched in word frequency, number of words and number of syllables with another correct sentence in list B. Two experimental sets were thus constructed: (1) correct sentences of list A and incorrect sentences of list B, (2) correct sentences of list B and incorrect sentences of list A. Each child heard one of the sets. Sentences were spoken by a female native speaker of French at a natural speed of production, and were normalized in loudness.

**2.1.2. Procedure.** The linguistic material was presented by blocks of four sentences. Each block was preceded by a musical sequence. Sentence distribution over blocks and sentence order in each block were randomized for each participant. The experiment consisted of 12 blocks; half of the blocks were preceded by a regular rhythmic sequence and the other half by a textural sound sequence. Three consecutive blocks were presented with the same type of musical sequence, then changed to the other sequence type for the following three blocks. Half of the children started with regular rhythmic sequences and half with textural sound sequences. Children were asked to listen to the music and to perform the grammaticality judgment task for each of the subsequently presented sentences. The instructions were presented as a little story. Two dragons were shown on the computer screen during the sentence, and the children were asked to determine which dragon told the sentence: the dragon who looked satisfied because he spoke well, or the dragon who looked puzzled because he made an error. Children answered by pressing one of two buttons under the dragon pictures. Musical sequences and sentences were triggered by the experimenter. Children performed four practice items (two grammatical sentences and two ungrammatical sentences, which were presented without music) during the instructions. Musical sequences and sentences were presented over loudspeakers at a comfortable loudness level. In the follow-up of the syntax task, the procedure was the same, except that there was a silence instead of musical sequences before listening to the sentences. The silence lasted the same duration as the musical sequences in the syntax task (i.e., 17 seconds), and was presented to the children as a short break.

## **2.2. Semantic evocation task**

To investigate the effect of musical sequence types on semantic processing, we designed a semantic fluency or production task, and we analysed children's verbal productions for quantity and content. Based on previous studies investigating the link between music processing and conceptual processing (e.g., Koelsch et al., 2004), we expected the semantic content of the productions to be influenced by the previously heard musical sequences.

**Procedure.** Children were told to listen to a musical sequence and then to tell the experimenter what the music made them think about and what they had imagined during listening to the music. Children's productions were recorded. There was no time limit, and the experimenter asked the children whether they had finished before presenting the next musical sequence. The order of the musical sequences was pseudo-randomly determined for each child with the constraint to avoid listening to the same sequence type more than twice consecutively. Half of the children started with a regular rhythmic sequence and half with a textural sound sequence.

## **3. DATA ANALYSIS**

For the grammaticality judgment task, a signal detection analysis was performed on responses, leading to a measure of discrimination sensitivity with  $d'$ , and a response bias with  $c$  for each musical sequence type condition. To compare performance between conditions, two-sided paired t-tests were performed. Two-sided independent t-tests were performed to compare performance between the baseline condition (follow-up of the syntax task) and each of the sequence types (rhythmic vs. textural). Effect sizes were reported with partial  $\eta^2$  (Cohen, 1988).

For the semantic evocation task, children's productions were first transcribed. Sentences or clauses that indicated the end of the response (e.g., "that's all") were removed. Transcriptions were encoded in xml (extensible markup language). The resulting corpus was analysed with the software TXM, version 0.7.8 (Heiden, 2010), an open-source textual analysis software for textometry, and the software RStudio (RStudio



Team, 2016). Part-of-speech tagging was realized in TXM with TreeTagger (Schmid, 1994), which is commonly used in most of textometric tools. For a first analysis, we extracted the number of words and the number of lemmas (i.e., number of unique words) for each sequence for each child. This analysis focused on grammatical types of content words (nouns, verbs, adverbs, adjectives) to investigate the lexical structure of the corpus. For the second analysis, the aim was to identify the semantic content of each sequence type condition. Two statistical analyses were run on lemmas: an analysis of specificities and a factorial correspondence analysis. The analysis of specificities was performed on productions after each of the two sequence types. It assessed the probability of appearance of each lemma after each sequence type (i.e., the regular rhythmic sequences and the textural sound sequences) considering the representativeness of the productions after the other sequence type. A score superior to 2 (i.e. the banality threshold) indicates an “over-use”, and a score lower than -2 indicates a “deficit” (Poudat & Landragin, 2017). The factorial correspondence analysis was conducted by separating the productions after each of the 12 musical sequences, leading to 12 sets. It allowed us to investigate the lexical structure of the textual corpus, on the basis of a frequency table (i.e. number of words for each lemma in each set). Two sets will be represented with small distance (i.e., close in the space) when they have similar lexical profiles, and two units (e.g. lemmas) will be close if they have comparable textual distribution profiles across the sets (Poudat & Landragin, 2017).

For each scale, children’s judgements for the two sequence type were compared with two-sided paired t-tests.

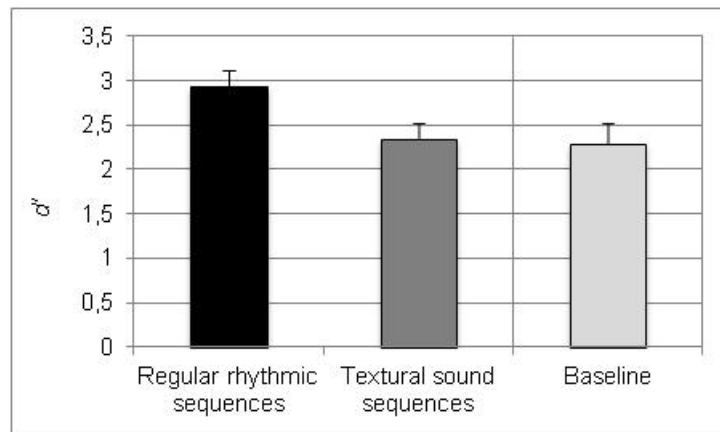
Finally, we ran supplementary analyses investigating children’s performance in the two tasks. Z-scores were calculated on the basis of the  $d'$  data in the syntax task and the mean number of words and the mean number of lemmas for content words in the semantic task, respectively. They were analysed with a 2x2 ANOVA with Task (syntax, semantic) as between-participants factor and Musical sequence type (rhythmic, textural) as within-participant factor. Although the two tasks required different processes and were thus not fully comparable, this supplementary analysis aimed to directly account for the overall data pattern and notably to confirm the cross-over pattern suggested by the first analyses. We also ran 2x2 ANOVAs to compare children’s judgements on each of the scales.

## RESULTS

### 1. Syntax task

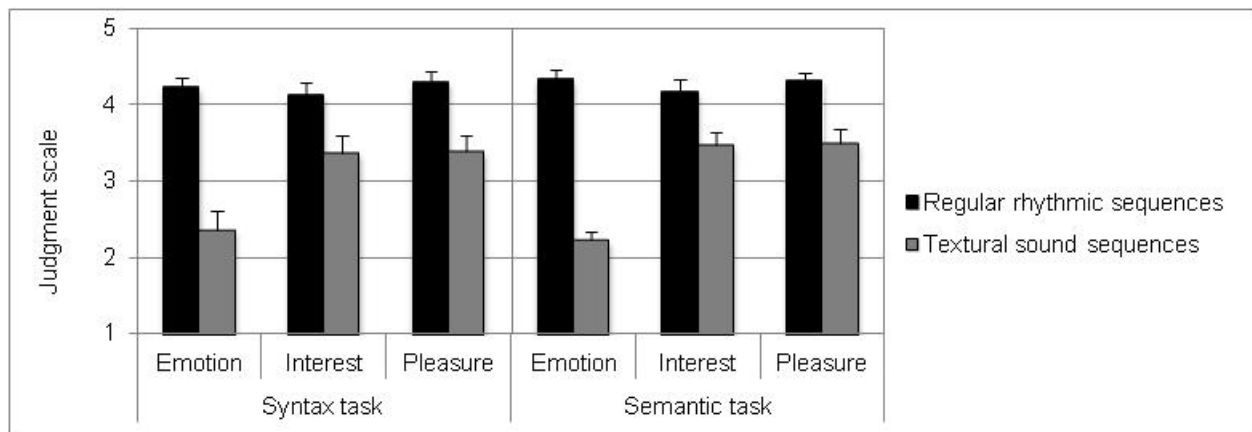
Performance in the grammaticality judgement task, as measured by  $d'$ , was significantly better after regular rhythmic sequences (mean  $d' = 2.93$ , SD = 0.71) than after textural sound sequences (mean  $d' = 2.35$ , SD = 0.75),  $t(15) = -2.53$ ,  $p = .023$ ,  $\eta_p^2 = .30$ . There was no significant difference in response bias  $c$  between the two musical sequence type conditions,  $p = .990$  (regular rhythmic sequences:  $0.17 \pm 0.52$ ; textural sound sequences:  $0.17 \pm 0.34$ ). Response bias  $c$  did not differ significantly from zero for regular rhythmic sequences,  $p = .210$ , and it just fell short of significance for textural sound sequences,  $t(30) = 2.00$ ,  $p = .054$ .

Performance after regular rhythmic sequences was better than baseline performance (mean = 2.29, SD = 0.98),  $t(30) = -2.14$ ,  $p = .040$ ,  $\eta_p^2 = .09$ . Performance after textural sound sequences and baseline performance did not differ significantly,  $p = .848$  (Figure 1).



**Figure 1.**  $d'$  data pattern of the syntax task and the follow-up group averaged over participants, presented as a function of musical sequence type (regular rhythmic and textural sound) and for baseline (follow-up of the syntax task). Error bars represent standard error.

Results of the subjective scale judgments (Figure 2) revealed that children judged the regular rhythmic sequences as emotionally more positive than the textural sound sequences,  $t(15) = -5.69, p < .001$ , and also as more interesting than the textural sound sequences,  $t(15) = -3.12, p = .007$ . The third scale (i.e., on pleasure) showed that children appreciated the regular rhythmic sequences more strongly than the textural sound sequences,  $t(15) = -4.03, p = .001$ .

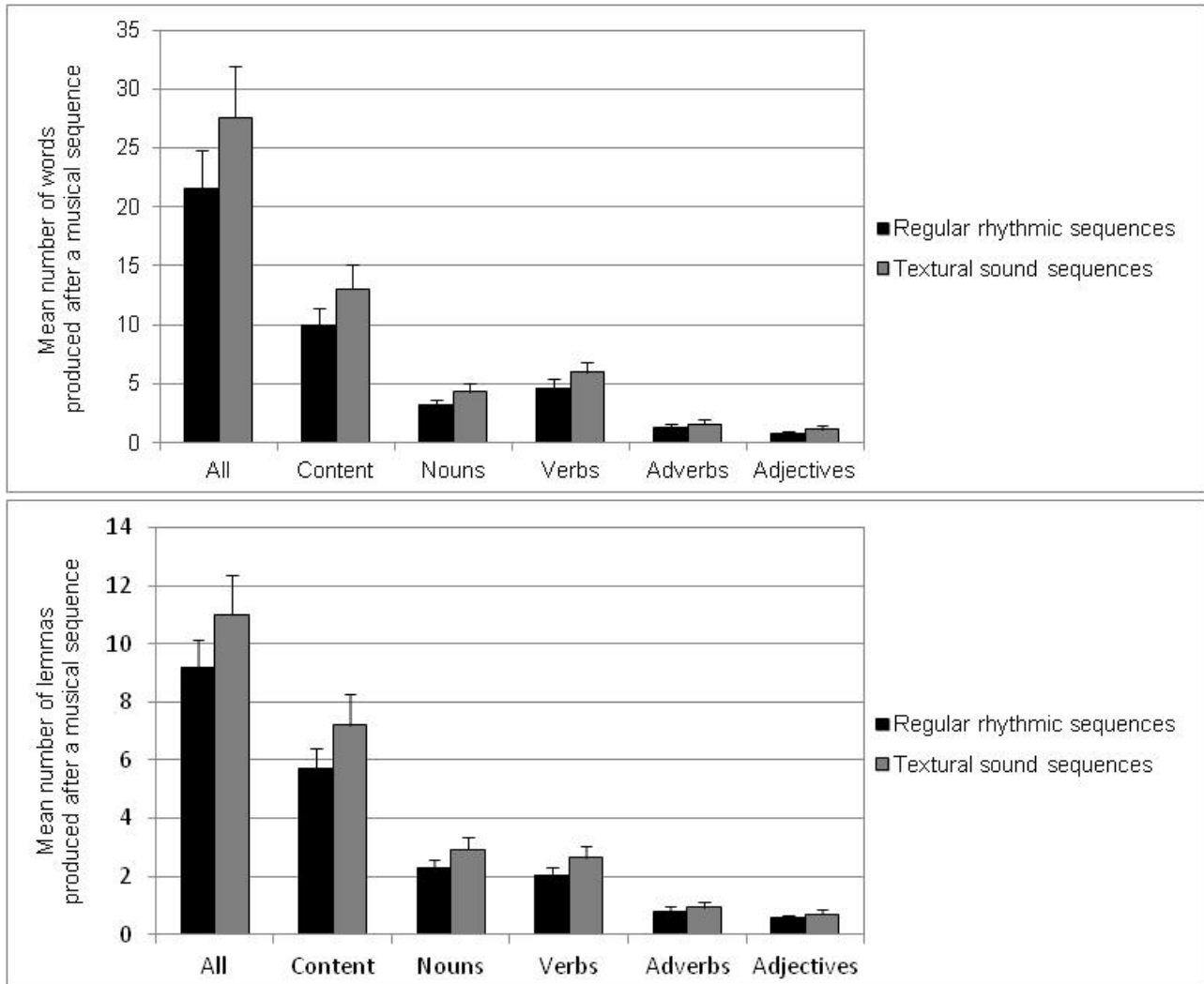


**Figure 2.** Mean results (judgements from 1 to 5) for regular rhythmic and textural sound sequences on the three scales (the first scale assessed emotion, from “very sad” (1) to “very happy” (5); the second scale assessed interest, from “very boring” to “very interesting”; the third scale assessed pleasure, from “I don’t like at all” to “I like very much”). Error bars represent standard error.

## 2. Semantic evocation task

Children produced significantly more words after the textural sound sequences (mean = 27.55, SD = 16.68) than after the regular rhythmic sequences (mean = 21.52, SD = 12.13),  $t(13) = -2.54, p = .025, \eta_p^2 = .33$ . More specifically, they produced significantly more content words after textural sound sequences (mean = 13.04, SD = 7.86) than after regular rhythmic sequences (mean = 9.92, SD = 5.69),  $t(13) = -2.88, p = .013, \eta_p^2 = .39$ . When detailed for each of the content word categories, this advantage for textural sound sequence production was observed for nouns,  $t(13) = -2.43, p = .030, \eta_p^2 = .31$ , and verbs,  $t(13) = -3.01, p = .010, \eta_p^2 = .41$ , but not for adverbs,  $p = .336$ , and adjectives,  $p = .222$ , which were produced less frequently (Figure 3). The analyses on lemmas confirmed the advantage of textural sound sequences over regular rhythmic sequences in children productions: Lemmas of all grammatical categories as well as content lemmas were

more numerous after textural sound sequences than after regular rhythmic sequences,  $t(13) = -2.66$ ,  $p = .020$ ,  $\eta_p^2 = .35$ , and,  $t(13) = -2.70$ ,  $p = .018$ ,  $\eta_p^2 = .36$ , respectively. When separated for lemmas of each grammatical type, this difference was significant for verbs,  $t(13) = -3.26$ ,  $p = .006$ ,  $\eta_p^2 = .45$ , marginally significant for nouns,  $t(13) = -1.84$ ,  $p = .09$ ,  $\eta_p^2 = .21$ , but not significant for adverbs,  $p = .437$ , and adjectives,  $p = .276$ , probably related to their low production level (Figure 3).



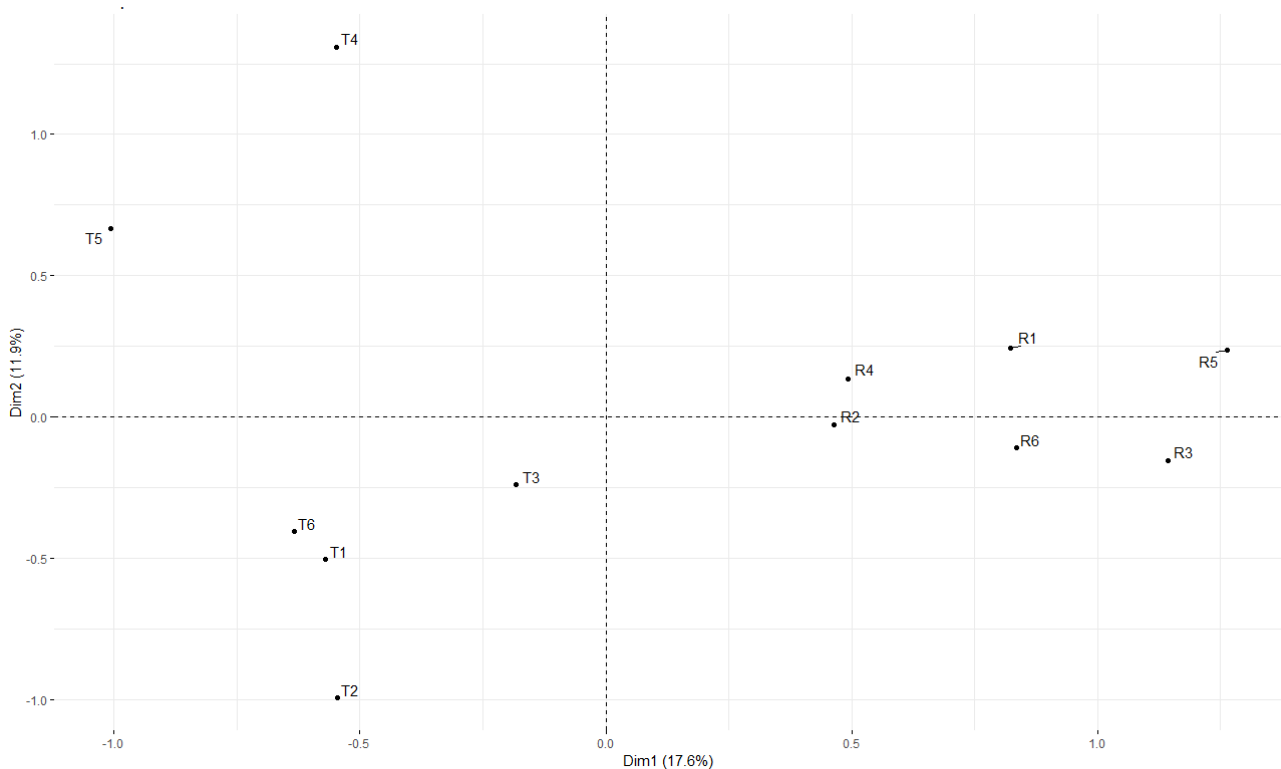
**Figure 3.** Mean number of words (Top) and lemmas (Bottom) produced after a musical sequence, presented as function of the musical sequence (regular rhythmic vs. textural sound) for all productions, content words only, and separated for each subgroup: nouns, verbs, adverbs and adjectives. Error bars represent standard error.

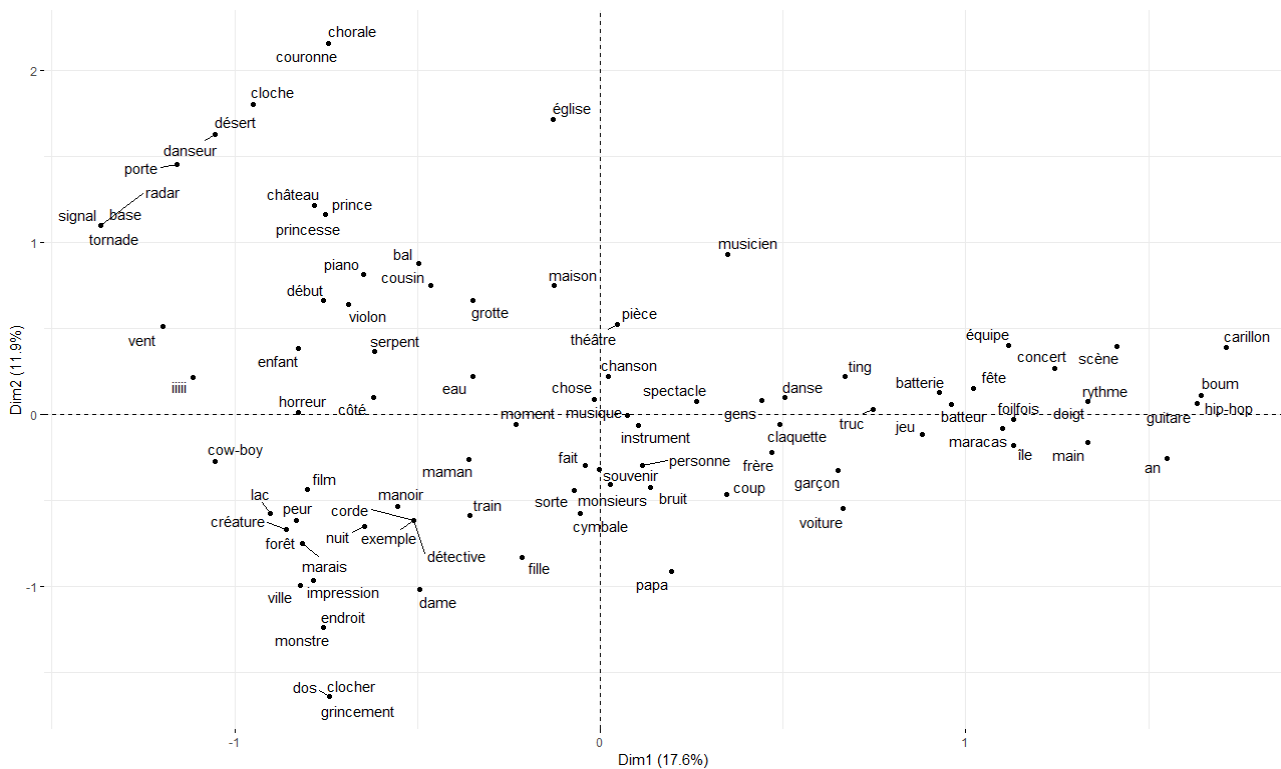
For content analysis on children’s productions we decided to focus on nouns because, among the content words, nouns were the most often produced. Moreover they appeared to be more representative of the semantic content than were other grammatical categories in the productions.

Analysis of specificities for nouns revealed several lemmas with a specificity score over banality threshold. For regular rhythmic sequences, five lemmas were over-used: “batterie” [drums] (5.91), “fête” [party] (2.96), “boum” [bang] (2.59), “concert” [concert] (2.22), “main” [hand] (2.22). For textural sound sequences, two lemmas were over-used: “peur” [fear] (5.23), “film” [movie] (3.21).

The factorial correspondence analysis was performed on the lemmas of nouns with a minimum frequency of 2 across the corpus. The two first axes of the analysis explained respectively 17.64% and 11.93% of the total variability. The first axis discriminated between regular rhythmic sequences on the left

and textural sound sequences on the right (Figure 4, top). It showed an opposition between lemmas relative to music, movement and social behaviour on the right (e.g. “batterie” [drums], “concert” [concert], “hip-hop” [hip-hop], “fête” [party], “maracas” [maracas]) and lemmas relative to dark atmospheres and places on the left (e.g. “vent” [wind], “nuit” [night], “monstre” [monster], “château” [castle], “forêt” [forest]), (Figure 4, bottom). The second axis revealed an opposition between some textural sound sequences, whereas regular rhythmic sequences were represented around zero. The pattern observed for textural sound sequences can be interpreted as a consequence of homogeneity versus heterogeneity. In T4, and T5, the texture was rather homogeneous: there were few new timbres emerging from the background. These sequences were rather melodically and harmonically static. In T2 high-pitched sounds arose and broke away from the background. The other three sequences – T6, T1, and T3 – were even less homogeneous and less melodically and harmonically static than the sequences on the top of the axis.





**Figure 4.** Projection of the first two factors of the factorial correspondence analysis, representing the 12 musical sequences (up) or the lemmas (down). See Appendix B for a translation.

Results of the subjective scale judgments (Figure 2) revealed that children judged the regular rhythmic sequences as emotionally more positive than the textural sound sequences,  $t(13) = -12.96, p < .001$ , and also as more interesting than the textural sound sequences,  $t(13) = -3.23, p = .007$ . The third scale (i.e., on pleasure) showed that children appreciated the regular rhythmic sequences more strongly than the textural sound sequences,  $t(13) = -3.98, p = .002$ .

**3. Supplementary analyses on performance of the two tasks.** For z-scores of  $d'$  in the syntax task and mean number of words or mean number of lemmas in the semantic task, the combined analysis showed, as expected, a significant interaction between Musical Sequence Type and Task,  $F(1, 28) = 11.77, p = .002, \eta_p^2 = .30$ , and  $F(1, 28) = 11.46, p = .002, \eta_p^2 = .29$ , respectively (see Figure 5). The main effects of sequence type were not significant,  $p$ -values  $> .388$ .

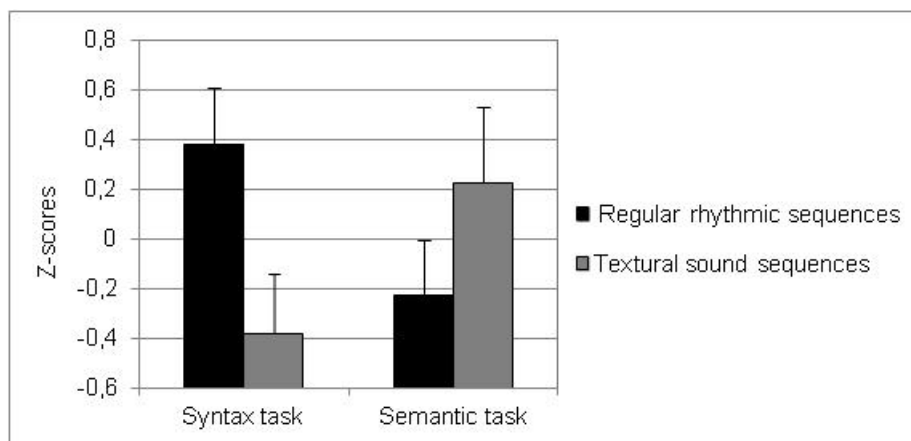


Figure 5. Z-scores data pattern of the syntax task and the semantic task (Z-scores for mean number of words) averaged over participants, for regular rhythmic and textural sound sequences. Errors bars represent standard error.

For each subjective scales, the combined analyses revealed a significant main effect of musical sequence type,  $F(1,28) = 107.77$ ,  $p < .001$ , for the *emotion* scale;  $F(1,28) = 19.64$ ,  $p < .001$ , for the *interest* scale about interest;  $F(1,28) = 31.16$ ,  $p < .001$ , for the *pleasure* scale about pleasure. For each scale, the main effect of Task and its interaction with sequence type were not significant, all  $p$ -values  $> .531$ .

## DISCUSSION

The potential effect of music on language processing has been a vivid object of investigation in cognitive psychology and neurosciences, with numerous researches reporting converging evidence for an overlap of cognitive and neural resources involved in both domains (e.g. Patel, 2008). Our present study was designed to contribute to this domain by investigating the specific effects of two musical components (i.e., rhythm and sound texture) on syntax and semantic processing in children. Influencing (and in particular stimulating) linguistic processing is of great interest for a pediatric population, in which rhythmic processing, syntax processing and semantic processing with lexical access are not fully developed yet. We here used a crossover design contrasting regular rhythmic sequences and textural sound sequences for both syntax and semantic tasks. Our findings shed new light on potential effects between music and language and the underlying representations and mechanisms.

### RHYTHM AND SYNTAX PROCESSING

Results of the syntax task showed a beneficial effect of listening to a regular rhythmic sequence on grammaticality judgments of auditorily presented sentences. This finding extends previous studies (Bedoin et al., 2016; Chern et al., 2018; Przybylski et al., 2013) to new comparison conditions and a shorter musical sequence duration.

We obtained a beneficial effect of the regular rhythmic sequences in comparison to a musical condition without rhythmic structures: the textural sound sequences. In previous studies, regular rhythmic sequences have been compared to either irregular sequences (Chern et al., 2018; Przybylski et al., 2013) or a more neutral, non-musical baseline condition (i.e., environmental sound scenes) (Bedoin et al., 2016). Our findings extend this investigation with comparisons to this new baseline condition, showing a beneficial effect of a regular rhythmic sequence. Moreover, with the follow-up group of the syntax task, we compared performance after the two musical sequences types (i.e., regular rhythmic, textural) with the performance of another baseline condition, notably without preceding musical sequences. These comparisons revealed that performance (a) was better after the regular rhythmic sequences than after silence, and (b) did not differ between textural sound sequences and silence. Although this comparison with the silent condition was not implemented with a planned between-participants design, the findings provide converging evidence that the rhythmic priming effect includes a benefit from the regular sequences rather than just a cost of processing due to the irregular sequences (see Bedoin et al., 2016 for converging evidence with a non-musical baseline). They further suggest that textural sound sequences did not affect syntax processing (at least not leading to a cost in processing) and provide an appropriate musical baseline for rhythmic priming experiments.

For rhythmic priming effects on subsequent language processing, it now becomes further relevant to investigate which prime duration is necessary to create the beneficial effect on syntax processing. While this question is more fully addressed with a gating paradigm (Fiveash et al., in preparation), our present study provides some first indication. In contrast to previous studies that have used primes of about 30

seconds, we here observed a rhythmic priming effect on syntax processing with primes of 17 seconds, suggesting that shorter primes are sufficient to create carry-over effects on subsequent linguistic processing.

### **SOUND TEXTURE AND SEMANTIC PROCESSING**

In the semantic evocation task, results revealed that even though both sequence types triggered verbalization and concept evocation in children, the textural sound sequences, as expected, promoted more productions, including more numerous (i.e., more words and more lemmas were produced) and more various (i.e., more extended lexical distribution and less specific words) concept activations than the regular rhythmic sequences. The observation of semantic and conceptual productions of the children after both sequence types is in agreement with conceptual priming studies between music and language (e.g. Koelsch et al., 2004), showing that music can activate concepts in adults. Unlike previous studies investigating semantic relations with selected musical material, our experiment used musical sequences without direct or evident links to a specific concept or semantic field. Our task required an active process of concept searching and an explicit elaboration of discourse. The sequence duration of 17 seconds, which was a rather long duration in comparison to previous studies (e.g., 10 seconds in Koelsch et al., 2004, 1 second in Daltrozzo & Schön, 2009a, 2009b), might have been helpful in the semantic evocation production (Grieser Painter & Koelsch, 2011).

Our findings further demonstrate that semantic activation by music can also occur in young children. To our knowledge, conceptual priming by music had never been studied in young children up to now. Exploring how musical characteristics could promote semantic activation in children seems to be particularly interesting as their vocabulary and lexical access skills are still in development (e.g. D'Amico, Devescovi & Bates, 2001). Our experimental paradigm might thus provide a useful tool for future studies investigating conceptual development over different age ranges. Moreover, it will be promising to study the influence of musical sequences on semantic processing in children with language acquisition delay or semantic disorders (deafness, e.g., Percy-Smith et al., 2013; Specific Language impairment, e.g., McGregor, Newman, Reilly & Capone, 2002) in future studies.

Regarding the semantic content of the productions, we observed that different semantic fields were associated with each type of musical sequence. Previous musical priming studies using pictures as targets have shown that the expression of spatial concepts (Zhou, Jiang, Delogu & Yang, 2014) and the expression of movement concepts (Zhou, Jiang, Wu & Yang, 2015) rely on different musical features. More precisely, these studies have shown that temporal features (i.e. tempo and spectral flux) were significant predictors of musical expression of movement. In our study, we also showed a link between rhythm and movement, as regular rhythmic sequences were specifically associated with concepts relative to movement, which was not the case for textural sound sequences.

Textural sound sequences focused on timbre and spectro-temporal changes, with the blending of continuous lines evolving across time with tension and harmonic density. Previous research has pointed out the importance of timbre as a musical feature able to activate concepts (Grieser Painter & Koelsch, 2011) or as a good candidate to convey concepts in a very short time span (Daltrozzo & Schön, 2009a). Our results confirm this hypothesis and go further by suggesting that timbre and texture might stimulate more numerous and more various concept activation than do the rhythmic structures. In addition, textural sound sequences were built with blended timbres and sound sources that were more difficult to identify and to label than were the familiar timbres used in the regular rhythmic sequences (e.g., percussion instruments). Although the task instructions were oriented towards imagination and not towards labelling, children talked more about the sources of the sounds for the regular rhythmic sequences than for the textural

sound sequences. This aspect could probably contribute to explain our results: difficult-to-label music could trigger more imaginative processes and semantic elaboration than solely label processes and identification.

The verbal productions of the children also show that textural sound sequences activated concepts and words related rather to negative mood whereas regular rhythmic sequences activated concepts and words related rather to positive mood. The difference in semantic evocation related to negative versus positive valence was also observed in children's subjective judgements on the scales: the textural sound sequences were judged as being sadder than the regular rhythmic sequences. Previous findings suggest that this difference in emotional valence might have at least led in part to the difference in verbal productions between the two types of musical material. Indeed, it has been shown that the expression of an emotion by music can activate associated concepts (i.e. positive vs. negative), depending on the valence of the music (Sollberger et al., 2003; Steinbeis & Koelsch, 2011). The emotional valence of music has been shown to influence differently cognitive processing in general, for example, listening to sad music compared to happy music is associated with stronger mind-wandering (Taruffi, Pehrs, Skouras & Koelsch, 2017). When listening to sad music, attention might focus more on self-directed thoughts, whereas when listening to happy music, attention might focus more on the music itself. In our study, textural sound sequences might have promoted mind-wandering as well as processes that increased verbalization and concept activation. Future studies could now further explore this hypothesis by systematically manipulating the emotional nature of the textural sound sequences as well as potential instructions related to mind-wandering.

#### **THEORETICAL FRAMEWORKS FOR THE INFLUENCE OF MUSICAL SEQUENCES ON LANGUAGE PROCESSING**

The combined analysis of the syntax task and the semantic task confirmed that regular rhythmic sequences had a beneficial effect on grammatical processing and that textural sound sequences promoted concept activation. The strength of our paradigm was to use the same musical materials for two types of linguistic tasks. Our findings suggest that different aspects of musical material might influence differently two aspects of language processing. The novelty of our approach was further to investigate these processes in children rather than in adults. We will now discuss the mechanisms and frameworks that could account for our results.

Previous music cognition research has led to the proposition of the mood- and arousal- hypothesis. According to this hypothesis, music can influence the perceiver's mood as well as arousal level, which can then affect performance on a variety of cognitive tasks in both adults and children (Schellenberg, 2005; Thompson, et al., 2001). In adults, listening to a particular Mozart Sonata has been reported to improve performance in tests of spatial ability or processing speed. This beneficial effect (referred to as the famous "Mozart effect"; Rauscher, Shaw & Key, 1993) has been shown to rely on increased arousal and positive mood as it was also evoked by other types of music (e.g., pop music by the band "Blur"; see Husain, Thompson & Schellenberg, 2002; Schellenberg, Nakata, Hunter & Tamoto, 2007; Thompson et al., 2001). This stimulating effect has been also observed for children, notably performance in a test of spatial abilities or a free drawing task were enhanced after listening to music that was pleasant and arousing for children (Schellenberg & Hallam, 2005; Schellenberg et al., 2007). The mood-and-arousal hypothesis would thus explain the observed effects of musical sequences on subsequent language processing as the result of non-specific mechanisms. For example, the previously reported rhythmic priming effects on syntax processing (e.g., Bedoin et al., 2016) could be interpreted as having been triggered solely by mechanisms related to enhanced arousal and positive mood rather than being related to specificities of the regular rhythms (see below). However, our present study shows that this general interpretation of the musical effect does not seem to be correct, notably with the cross-over effect observed here. Indeed, this hypothesis would have predicted that the positive mood and higher arousal should boost performance in both tasks. While the



prediction related to mood and arousal might be correct for the syntax task, it is incorrect for the semantic evocation task. The findings reveal that a low arousing and emotionally negative stimulus (i.e., the textural sound sequences) stimulates more strongly verbalization and concept activation than does an arousing and positive stimulus (i.e., the regular rhythmic sequences). Indeed, textural sound sequences are judged as sad, weakly interesting (or weakly arousing) and weakly pleasant by all children. The effect of music on language seems thus not only an effect of positive mood, arousal and pleasure, otherwise performance would be boosted more after the regular rhythmic sequences regardless of the linguistic task. These results argue for the contribution of other mechanisms to explain carry-over effects between music and language processing. We support that musical effects on language processing can be explained by specific cognitive mechanisms recruited in both music and language processing.

The rhythmic priming effect for syntax processing – or other processing requiring temporal attention and cognitive sequencing – can be interpreted in the framework of Dynamic Attending Theory (Jones, 1976; Jones & Boltz, 1989; Jones, Moynihan, MacKenzie & Puente, 2002). According to this framework, attention is not equally distributed over time, but synchronizes to environmental regularities (e.g. speech, music, walking). Thanks to this synchronization, perceivers develop temporal expectations about when the next event is supposed to occur. Consequently, event and structure processing is facilitated in regular sequences, and at expected time points. The Dynamic Attending Theory has originally been proposed for music processing, but was then also applied to speech processing (e.g., Kotz & Schwartz, 2010; Port, 2003; Quené & Port, 2005). At a neural level, cerebral rhythms have been shown to entrain with the temporal regularities of external stimuli and influence event processing (in music: Large, Herrera & Velasco, 2015; Large & Snyder, 2009; in speech: Giraud & Poeppel, 2012; Poeppel, 2003). The temporal regularities and the evoked neural oscillations have been reported to influence word segmentation and syntax processing (e.g., Gordon et al., 2015a; Schmidt-Kassow & Kotz, 2008). In the context of rhythmic priming, listening to a regular rhythmic sequence, with a strong regular beat at 2 Hz (i.e., related to the temporal intervals between stressed syllables), would adjust internal oscillators and temporal attention. As speech processing requires neural synchronization and temporal attention, it directly benefits from this pre-synchronization by music. Thanks to shared temporal processes, a transfer effect occurs between music and language processing. Chern et al. (2018) have provided first evidence in favour of specific mechanisms shared between music and language in a rhythmic priming study investigating its influence on syntax processing. Adding additional control tasks, they showed that rhythmic priming effect is restricted to the grammaticality processing of subsequently presented sentences, but does not extend to math and visuospatial tasks. This observation together with our finding here thus suggests that the beneficial effect of rhythm observed in the syntax task cannot be attributed to general cognitive benefits due to enhanced arousal. It rather suggests that the regularities and the related dynamic attending processes provide beneficial effects which are specific to processing that requires also temporal sequencing, segmentation, expectations and structure processing, as in speech processing and its syntax analyses, as tested here. However, the framework of dynamic attending cannot explain the effect of textural sound on semantic processing, thus requiring the need to consider other involved mechanisms.

In previous research related to conceptual, semantic priming by music or music-like sounds, Schön et al. (2009) propose a model describing how sounds can evoke concepts. The authors further suggest its relevance for music and in particular for the potential music-related meaning and conceptual processing. This model has been constructed on the basis of models of semantic processing (McNamara, 2005) and distributed network models (Anderson, 1993; McClelland & Rumelhart, 1986). It postulates the existence of an amodal concept lexicon, accessible via words as well as sounds. The amodal concept lexicon could thus be the link between concepts activated by sounds and concepts activated by words. When reading a word, three different levels specific to language processing would be successively activated: the letter level, the

lexical level, and the semantic level. Finally, the amodal concept lexicon is activated. When listening to a sound, acoustic features are first extracted from the sound. Then, this activation can take two different routes, either it directly activates the amodal concept lexicon or it activates first the sound lexicon, which contain labels, or the emotional level before then reaching the amodal concept lexicon. A clearly identifiable environmental sound would activate directly a specific item in the sound lexicon. In contrast, a sound difficult to identify will possibly not find a precise label in the sound lexicon. It would thus either activate directly representations in the amodal concept lexicon, or go through the emotional level. Once a concept is activated in the amodal concept lexicon, this activation would spread to the semantic level of the verbal part of the model. It allows to explain the observed priming effects between music and language (Schön et al., 2009). In the context of our experiment, the musical sequences might activate the sound lexicon, the emotional level and the amodal concept lexicon. Then, activation of the semantic and lexical level might allow verbalization. As sound sources of the textural sound sequences are more difficult to label than regular rhythmic sequences, they probably did not find easily related entries in the sound lexicon and thus activate a larger set of concepts and feelings in the amodal concept lexicon than did the regular rhythmic sequences. Because timbre has been proposed as a good candidate to convey concepts (Daltrozzo & Schön, 2009a), textural sound sequences with their timbral richness and textural changes should be more effective than regular rhythmic sequences in activating concepts in the amodal concept lexicon. Our findings suggest that textural sound sequences stimulate more processes that tap into amodal concept lexicon (with content oriented towards imagination and emotion) whereas rhythmic regular sequence lead to more labelling processes (with content closer to the acoustic signal).

In sum, mood and arousal might contribute to explain stimulating effects of music on language processing, but cannot account for the data pattern observed here. Our findings rather suggest that specific cognitive mechanisms can be triggered or boosted by specific musical features that then influence specific processes in the language tasks. They are in agreement with other recent evidence, such as Chern et al. (2018) showing the specificity of the rhythmic priming effect on syntax processing, not extending to math and visuospatial processing. Relatedly, for semantic processing, Giannouli, Kolev & Yordanava (2018) showed that listening to musical excerpts from different musical styles influences differently subsequent word fluency performance in young adults (either facilitating, inhibiting or not influencing semantic retrieval).

## **CONCLUSIONS**

To our knowledge, our study is the first to reveal cross-domain effects of musical manipulations on subsequent linguistic processing, here syntax and semantic processing. We demonstrated here that different musical parameters can influence different linguistic processes: rhythm seems particularly relevant to enhance syntax processing whereas textural information seems important to promote semantic activation (with more numerous and various concepts). These effects would rely on different cognitive mechanisms shared by music and language: rhythm boosts temporal attention and segmentation, important for syntax processing, whereas textural sound sequences activate more concept representations, shared with verbal processing.

Our study investigated the possibility of taking advantage of specific musical parameters to influence specific linguistic processing, thanks to shared cognitive mechanisms. Our results further suggest to consider the specific contribution of each musical parameter for taking advantage of music in a more targeted way. Recently, it has been shown that listening to semantically congruent music during novel word learning promotes word acquisition in adults (Fritz et al., 2019). Together with studies in children showing a link between musical expertise and grammatical skills (e.g. Gordon et al., 2015) as well as vocabulary skills (e.g. Linnavalli et al., 2018), these results and our results suggest that music, and notably the manipulation

of different features, could be considered as a relevant tool to boost syntax abilities and semantic knowledge and for developing perspectives of the use of music in stimulation or rehabilitation settings.

## **SUPPLEMENTAL MATERIAL**

The supplemental material can be found online at [*to be completed later*].

## **APPENDICES**

### **A. Musical pieces used for textural sound sequences**

T1: György Ligeti – Chamber Concerto for 13 instruments (1970)

T2: Peter Eötvös – Chinese Opera for Ensemble (1986)

T3: György Ligeti – Lontano for Orchestra (1967)

T4: György Ligeti – Melodien for Orchestra (1971)

T5: Tristan Murail – Le lac for Ensemble (2001)

T6: Roger Reynolds – Symphony [Myths] for Orchestre (1990)

### **B. Words translation for the factorial correspondence analysis**

an : year

bal : dance

base : basis

batterie : drums

batteur : drummer

boum : bang

bruit : noise

carillon : chime

chanson : song

château : castle

chorale : choir

chose : thing

claquette : tap dance

cloche : bell

clocher : bell tower

concert : concert

corde : rope

côté : side

coup : thus

couronne : crown

cousin : cousin

cow-boy : cowboy

créature : creature

cymbale : cymbal

dame : lady

danse : dance

danseur : dancer

début : beginning  
désert : desert  
détective : detective  
doigt : finger  
dos : back  
eau : water  
église : church  
endroit : place  
enfant : child  
équipe : team  
exemple : example  
fait : fact  
fête : party  
fille : girl  
film : movie  
fois | fois : time  
forêt : forest  
frère : brother  
garçon : boy  
gens : people  
grincement : grinding  
grotte : cave  
guitare : guitar  
hip-hop : hip-hop dance  
horreur : horror  
iiii : iiii (onomatopoeia used as a noun)  
île : island  
impression : impression  
instrument : instrument  
jeu : game  
lac : lake  
main : hand  
maison : house  
maman : mother  
manoir : manor  
maracas : maracas  
marais : swamp  
moment : moment  
messieurs : gentlemen  
monstre : monster  
musicien : musician  
musique : music  
nuit : night  
papa : dad  
personne : personne  
peur : fear

piano : piano  
pièce : room  
porte : door  
prince : prince  
princesse : princess  
radar : radar  
rythme : rhythm  
scène : stage  
serpent : snake  
signal : cue  
sorte : kind  
souvenir : memory  
spectacle : show  
théâtre : theatre  
ting : ting (onomatopoeia used as a noun)  
tornado : tornado  
train : train  
truc : thing  
vent : wind  
ville : city  
violon : violin  
voiture : car

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