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Rhythmic Auditory Stimulation Influences Syntactic Processing in Children With Developmental Language Disorders

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Objective: Children with developmental language disorders have been shown to be impaired not only in language processing (including syntax), but also in rhythm and meter perception. Our study tested the influence of external rhythmic auditory stimulation (i.e., musical rhythm) on syntax processing in children with specific language impairment (SLI; Experiment 1A) and dyslexia (Experiment 1B). ***Method:*** Children listened to either regular or irregular musical prime sequences followed by blocks of grammatically correct and incorrect sentences. They were required to perform grammaticality judgments for each auditorily presented sentence. ***Results:*** Performance of all children (SLI, dyslexia, and controls) in the grammaticality judgments was better after regular prime sequences than after irregular prime sequences, as shown by d' data. The benefit of the regular prime was stronger for SLI children (partial $\eta^2 = .34$) than for dyslexic children (partial $\eta^2 = .14$), who reached higher performance levels. ***Conclusion:*** Together with previous findings on deficits in temporal processing and sequencing, as well as with the recent proposition of a temporal sampling (oscillatory) framework for developmental language disorders (U. A. Goswami, 2011, Temporal sampling framework for developmental dyslexia, *Trends in Cognitive Sciences,* Vol. 15, pp. 3–10), our results point to potential avenues in using rhythmic structures (even in nonverbal materials) to boost linguistic structure processing.

Keywords: specific language impairment, dyslexia, music, syntax processing, temporal processing

Recent research has dedicated increased attention to the investigation of neural resources potentially shared between language and music processing, notably for the processing of syntax (e.g., Patel, 2003), pitch (e.g., Besson, Schön, Moreno, Santos, & Magne, 2007; Magne, Schön, & Besson, 2006; Schön, Magne, & Besson, 2004), and timing (e.g., Kotz & Schwartze, 2010; Schmidt-Kassow, Rothermich, Schwartze, & Kotz, 2011). This research has also motivated the investigation of music processing in populations with impaired language processing. Impaired musical structure processing (regarding the pitch dimension; in par-

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ticular, harmonic structures) has been shown in aphasic patients (Patel, Iversen, Wassenaar, & Hagoort, 2008) and children with specific language impairment (SLI; Jentschke, Koelsch, Sallat, & Friederici, 2008). Impaired pitch processing has also been reported in SLI (McArthur & Bishop, 2004) and dyslexia (Baldeweg, Richardson, Watkins, Foale, & Gruzelier, 1999; Foxton et al., 2003; Santos, Joly-Pottuz, Moreno, Habib, & Besson, 2007). Impaired rhythm and meter processing has been reported in SLI (Corriveau & Goswami, 2009; Weinert, 1992) and dyslexia (Muneaux, Ziegler, Truc, Thomson, & Goswami, 2004; Overy, Nicolson, Fawcett, & Clarke, 2003; Thomson & Goswami, 2008).

Our study focused on temporal processing (i.e., rhythm, meter) and investigated its influence on language processing in both SLI children (Experiment 1A) and dyslexic children (Experiment 1B).[1] Recent research has increasingly investigated the two populations in parallel because of overlapping disorders in phonological skills and auditory processing (e.g., Fraser, Goswami, & Conti-Ramsden, 2010; Marshall, Harcout-Brown, Ramus, & van der Lely, 2009). Both populations have been shown to have deficits in rhythm and meter processing. SLI children's performance in a paced tapping task (i.e., tapping to a metronome) predicted their performance in word and nonword reading, rime awareness, nonword repetition, and reading comprehension (Corriveau & Goswami, 2009). Similarly, dyslexic children's performance in beat perception predicted word and nonword reading as well as phonological awareness (Muneaux et al., 2004). Congruent findings have been reported by Overy et al. (2003), who asked dyslexic children to tap to the rhythm of a song (i.e., "Happy Birthday"), which is a form of syllable segmentation and reflects a type of phonological awareness that is of major importance for (acquiring) skilled reading.

These rhythm-processing deficits have been suggested to lead to difficulties in accurately processing relevant auditory cues in speech. They can lead to deficits in language processing by disrupting suprasegmental processing required to extract words and syllables from the speech stream (Corriveau & Goswami, 2009; Thomson & Goswami, 2008), and by impairing the to-be-developed phonological representations (e.g., onset-rime awareness), which are also related to reading (Muneaux et al., 2004). Impaired encoding of suprasegmental information (e.g., word stress, intonation, rhythm) in SLI and dyslexia also has consequences on syntactic structure processing (Sabisch, Hahne, Glass, von Suchodoletz, & Friederici, 2009; Marshall et al., 2009; Weinert, 1992). Syntax deficits are particularly pronounced in SLI, in addition to deficits in phonology and semantic processing (Bishop & Snowling, 2004; Catts, Adlof, Hogan, & Weismer, 2005), but syntactic difficulties have also been documented in dyslexia. For example, dyslexic children showed a delayed early left anterior negativity (an early event-related potential [ERP] component for syntactic violations) and no right anterior negativity (associated with prosodic violations; Sabisch, Hahne, Glass, von Suchodoletz, & Friederici, 2006).

The relation between temporal regularity, phonological processing, and syntax processing is further supported by recent ERP studies in healthy adults. In second-language perception, the regularity of metric cues provides relevant cues not only for prosodic processing, but also for segmentation and syntax processing (Schmidt-Kassow et al., 2011). In native language perception, the manipulation of temporal intervals between word onsets further confirms that regular, predictable presentation boosts syntax processing, as reflected by an increase of an electrophysiological marker for syntactically incorrect events (i.e., the P600, a positivity starting about 600 ms after the onset of an incorrect event; Schmidt-Kassow & Kotz, 2008, 2009).

Rhythmic and temporal processing can be understood in Jones's framework of dynamic attending (e.g., Jones, 2008; Jones & Boltz, 1989). Originally inspired by the processing of musical structures, this framework has been more recently applied to speech (e.g., Kotz, Schwartze, & Schmidt-Kassow, 2009; Quené & Port, 2005). The framework postulates that attention is not equally distributed over time, but develops in cycles: Internal oscillators synchronize to the temporal regularities of an external stimulus. They orient attention over time and allow developing expectations about the temporal occurrence of a next event, which then facilitates processing of events at expected time points and facilitates segmentation and structural, temporal integration.

Converging evidence comes from a different line of research proposing to stimulate internal oscillators with an external stimulus in order to provide benefit for structure processing. As syntax processing is impaired in patients with basal ganglia lesions, who are notably not showing the P600 (Kotz, Frisch, von Cramon, & Friederici, 2003), Kotz, Gunter, and Wonneberger (2005) tested whether these patients might benefit from external regularity (oscillator), such as a rhythmically regular (metrical) musical prime. This prime should stimulate internal oscillator set-ups and thus help subsequent speech processing. Patients first listened to a rhythmic prime (i.e., a sequence of a march) for 3 min, followed by the language-testing blocks with syntactically correct and incorrect sentences. The external rhythmic stimulation showed a compensatory effect and restored the P600 to syntactic violations in patients with basal ganglia lesions (Kotz et al., 2005) and Parkinson's disease (Kotz & Gunter, 2012). Note that both populations have been shown to encounter difficulties in temporal processing (e.g., rhythm, intervals; Grahn & Brett, 2009; Schwartze, Keller, Patel, & Kotz, 2011).

Our aim was to test the potential influence of external rhythmic stimulation on syntax processing in children with developmental language deficits. This hypothesis was based on the work by Kotz et al. (2003; Kotz & Gunter, 2012; Kotz et al., 2009) and further supported by the view that developmental language disorders are linked to a more general procedural deficit (Nicolson & Fawcett, 2007; Ullman, 2001; Ullman & Pierpont, 2005). In Ullman's (2001, 2004) "declarative/procedural" model, the procedural component concerns learning and processing of context-dependent stimulus–response rule-like relations, particularly in temporal sequences (e.g., syntax, morphology, phonology, music). To support the hypothesis of a procedural deficit, Ullman and Pierpont (2005) list various deficits associated with SLI, such as processing of syntax, morphology, and nonlinguistic deficits (temporal and

[1] We are here referring to temporal processing with respect to sequencing, that is, to larger time scales than those proposed in Tallal's hypothesis of a rapid spectrotemporal processing deficit. Interestingly, the review of Tallal and Gaab (2006), which discusses the benefits of musical training on language and literacy skills, also indicates that musical training may improve sequencing skills and attention, which may in turn influence directly (or via rapid spectrotemporal processing) the processing of linguistic components (e.g., syllables) as well as language and literacy skills.

rhythmic processing).[2] Our study was further motivated by Goswami's (2011) recently proposed temporal sampling (oscillatory) framework for developmental dyslexia and, by extension, for SLI. Also referring to the dynamic attending theory (Large & Jones, 1999), this framework explains phonological and other observed deficits via a deficit in temporal coding and attention.

The present study investigated the potential influence of a musical rhythmic prime on the performance in a subsequent language task. We contrasted two musical primes (short musical excerpts played by percussion instruments), for which meter extraction was either easy or difficult (referred to as *regular* or *irregular* prime, respectively). In the experimental session, each music presentation was followed by a block of experimental trials of the language task that investigated syntax processing (i.e., procedure adapted from Kotz et al., 2005). Children were asked to make grammaticality judgments on auditorily presented sentences that were syntactically either correct or incorrect. If the rhythmicity of the musical prime can influence temporal attention (e.g., via internal oscillators), and if this influence holds over the temporal delay to the language task (i.e., music and language were not presented simultaneously), then performance should be better after the regular primes than the irregular ones (notably by reinforcing processes underlying phonological processing, speech segmentation, and syntax processing).

The present study tested both children with SLI (Experiment 1A) and children with dyslexia (Experiment 1B). Children suffering from these language-learning impairments have normal range nonverbal intelligence, adequate opportunity to learn, and do not present any neurological and sensory disorders. The children in the SLI group were characterized by a failure to develop age-appropriate receptive and/or expressive language skills since early childhood. The children in the dyslexic group were characterized by literacy deficits; in particular, the tested children were diagnosed with phonological or mixed dyslexia (not surface dyslexia). Whereas the dyslexic children did not present comorbid SLI, some of the SLI children also displayed literacy difficulties (as it is often observed; Brizzolara et al., 2011; Catts et al., 2005). Whether dyslexia and SLI are qualitatively distinct disorders or can be considered as two points on a continuum is still matter of debate (Bishop & Snowling, 2004). Our study was not designed to address this issue, but aimed to investigate whether musical primes can influence language processing in the presence of syntactic and phonological disorders as well as rhythmic processing deficits. Given that syntactic disorders are more systematically present in SLI than in dyslexia (Bishop & Snowling, 2004; Catts et al., 2005), a greater impact of musical priming could be expected on the grammaticality judgments for children with SLI than for children with dyslexia.

Method

Participants

Experiment 1A included SLI children, and Experiment 1B included dyslexic children. For each patient group, we included two specifically tailored groups of control children that were matched for either chronological age (CA) or reading age (RA). Average RA was based on reading scores obtained with a standardized reading test, the Alouette test, which focuses on decoding mechanisms by requiring children to read sentences without semantic support (Lefavrais, 1965). All children were French monolinguals. None exhibited auditory deficits, as shown in the clinical assessment. None reported musical activity. None of the children in the control groups reported a history of written or spoken language impairments.

All SLI and dyslexic children were recruited from a neuropediatric hospital unit, a special school for severe language and learning disorders, or a speech therapist office. Diagnosis of a language deficit and general neurological assessments were made by neuropsychologists or speech therapists (see details below). The SLI and dyslexic children were not diagnosed as mentally retarded and did not show nonverbal deficits. They were not diagnosed with additional learning difficulties (e.g., dyspraxia, attentional deficits, autistic spectrum disorder, or other neurological or psychiatric disorders), except as indicated otherwise below. The evaluations were based on a variety of French neuropsychological and language tests,[3] with pathological scores being defined as scores that are at least 2 standard deviations inferior to the population mean.

The experiment was approved by the French ethics committee Comité de Protection de Personnes and informed consent was obtained by the participants and their parents.

Experiment 1A: SLI children and control groups. Twelve SLI children (8 boys, average CA: 9 years 6 months, SD = 23 months, range: 6 years 6 months – 12 years 11 months; average RA: 7 years 8 months, SD = 17 months, range: 6 years 2 months – 10 years 11 months) were included in Experiment 1A. Eight SLI children were diagnosed with a phonological–syntactic syndrome (de Weck & Rosat, 2003) with verbal expression mainly affected at phonological, syntactic, and semantic levels as assessed by various batteries including at least word and pseudoword repetition, naming, morphosyntactic production, and phonemic fluency (see footnote 3). Four SLI children had both verbal expression and comprehension disorders, as assessed by vocabulary tests, morphosyntactic tests, and comprehension of sentences (ELO, EVIP, ECOSSE, N-EEL; see footnote 3). Four of the SLI children were diagnosed with dyslexia, and one child was diagnosed with attention-deficit/hyperactivity disorder, but he received methylphenidate treatment.

Twenty control children were matched to the SLI children: Twelve (seven boys) were matched for CA with the SLI children

[2] Neural correlates of the procedural component in Ullman's (2001, 2004) "declarative/procedural" model have been associated with the frontal/basal-ganglia circuitry. In further support, Ullman and Pierpont (2005) review data of SLI suggesting neural abnormalities of at least two structures: the frontal cortex and the basal ganglia.

[3] BALE (Batterie Analytique du Langage Ecrit: a series of tests investigating reading, spelling, and metaphonological skills in French), ELO (Evaluation du Langage Oral: a series of tests assessing language production and comprehension of words and sentences), N-EEL (Nouvelles Epreuves pour l'Examen du Langage: a set of tests designed to assess language in children ages from 3 years 7 months to 8 years 7 months), Déno 48 (a French naming test), TCG (a verbal production test requiring 3- to 9-year-old children to induce the end of a perceived sentence on the basis of pictures), TVAP (Test de Vocabulaire Actif et Passif: 3- to 8-year-old children are required to define words), EDEI-R (Echelles Différentielles d'Efficience Intellectuelle—Forme Révisée: a series of tests to assess intellectual efficiency in 3- to 9-year-old children), NEPSY (a Developmental NEuroPSYchological Assessment designed for 3- to 12-year-old children).

(CA controls; average CA: 9 years 5 months, *SD* = 20 months, range: 6 years 6 months – 11 years 11 months); eight (4 boys) were matched for RA with the SLI children (RA controls; average RA: 7 years 2 months, *SD* = 11 months, range: 6 years 6 months – 8 years 8 months).[4]

Experiment 1B: Dyslexic children and control groups. Ten dyslexic children (6 boys, average CA: 9 years 9 months, *SD* = 10 months, range: 8 years 6 months – 10 years 10 months, average RA: 7 years 7 months, *SD* = 10 months, range: 6 years 6 months – 8 years 10 months) were included in Experiment 1B. None of the children was diagnosed with SLI, but all were diagnosed with dyslexia: Eight children were diagnosed with phonological dyslexia, a clinical subtype characterized by dramatic impairment of the analytic, nonlexical procedure in both reading and spelling, as reflected by poor pseudoword reading, lexicalization errors, and frequent phonologically implausible reading and spelling errors, but few difficulties in reading and spelling (regular and irregular) familiar words (Castles & Coltheart, 1993; Manis, Seidenberg, Doi, McBride-Chang, & Petersen, 1996; Rowse & Wilshire, 2007). Phonological dyslexia is also characterized by poor performance on tests of phonological awareness (in the absence of SLI), which contrasts this form of dyslexia from surface dyslexia (Hanley & Gard, 1995). Two children were diagnosed with mixed dyslexia, defined by impairments in an analytic nonlexical procedure and a lexical reading procedure.

Eighteen control children were included in Experiment 1B: 10 (five boys) were matched for CA with the dyslexic children (average CA: 9 years 10 months, *SD*: 10 months, range: 8 years 6 months – 10 years 10 months); eight (4 boys) were matched for RA with the dyslexic children (average RA: 7 years 8 months, *SD* = 12 months, range: 6 years 6 months – 8 years 10 months) Note that the data of 10 of these 18 control children had been also included in the control groups of Experiment 1A.

Materials

Musical stimuli. Two 32-s musical sequences were constructed. The two sequences contained the same number of tones, but they differed in their rhythmic structure so that it was either relatively easy or difficult to extract the underlying meter (referred to as regular vs. irregular prime sequences; see Figure 1; http://www-crnl.univ-lyon1.fr/bt-sound.html).[5] The sequences were played by two percussion instruments (i.e., a tam-tam at 175 Hz and a maracas at 466 Hz). Each instrumental line was composed of a section of eight beats of 500 ms, which was repeated eight times to form the prime sequence.

The regular prime sequence had a simple rhythmic structure with interonset intervals of 250 ms, 500 ms, 750 ms, or 1,000 ms and one unit of 375 ms followed by 125 ms (i.e., creating an interval of 500 ms). The chaining of the interonset intervals (in milliseconds) over time for each instrument was 500, 750, 250, 500, 500, 750, 250, 500 for the tam-tam (see first line in Figure 1 top) and 375, 125, 500, 250, 250, 500, 500, 500, 1,000 for the maracas (see second line in Figure 1 top). To extract the metrical structure, listeners needed to find regular subdivisions of 125 ms and then 250 ms, and build a hierarchy with the main beat every 500 ms, followed by another hierarchy level at 1,000 ms. The hierarchy was reinforced by the simultaneous presentation of events played by the two instruments on six of the eight beats in the pattern. We selected the tempo of 500 ms based on the developmental work by McAuley, Jones, Holub, Johnston, and Miller (2006) on entrainment; they reported that the spontaneous motor tempo of children from 8 to 10 years of age lies at about 521 ms (±61).

The irregular prime sequence had a rhythmic structure with interonset intervals of 125 ms, 250 ms, 375 ms, 500 ms, 625 ms, 750 ms, or 1,375 ms. The chaining of the interonset intervals (in ms) over time for each instrument was 625, 375, 375, 500, 375, 375, 1,375 for the tam-tam (see first line in Figure 1 bottom) and 375, 125, 750, 250, 625, 375, 500, 1,000 for the maracas (see second line in Figure 1 bottom). The chaining of these intervals in the pattern allowed the extraction of a regular subdivision at 125 ms, but the temporal occurrence of events as well as the less frequent simultaneous presentations of events played by the two instruments (i.e., three times) made it more difficult to build a hierarchical metrical organization of beats.

Linguistic stimuli. The material was composed of 96 French sentences that were grammatically either correct (48) or incorrect (48). We first created 48 correct sentences and derived from each correct sentence an incorrect sentence. The violations used were of three different types (Gunter, Friederici, & Schriefers, 2000): gender agreement (**Le* caméra filme les danseurs [*The$_{\text{(masculine)}}$ camera$_{\text{(feminine)}}$ is filming the dancers]), number agreement (*Laura *ont* oublié son violon [*Laura$_{\text{(3rd person, singular)}}$ have$_{\text{(3rd person, plural)}}$ forgotten her violin]), and person agreement (*Les baguettes *sommes* en bois [*Drumsticks$_{\text{(3rd person, plural)}}$ are$_{\text{(2nd person, plural)}}$ made of wood]). The violation of gender agreement affected the nominal group and the other violations affected the verbal group. Each type of syntactic violation was represented by eight sentences. Grammatical and ungrammatical sentences were composed of an average of 6.1 words (range = 4–8) and an average of 8.29 syllables (range = 6–11); their duration was on average 2,300 ms (±353).

To avoid that a given participant listened to the same sentence in its grammatically correct and incorrect version, we split the 96 sentences into two lists (A and B) of 48 sentences. A grammatically correct sentence (presented in List A) was matched in number of words, number of syllables, number of letters, and the words' lexical frequency (based on the standard frequency index in

[4] We acknowledge that the matching of reading age was not complete between the reading age of the patient group and of the RA control group. This was due to one SLI child with a higher reading age (131 months) than his/her peers, and we missed including such a performant child in the RA control group. Removing this SLI child dropped the standard deviation to 13, thus comparable to the RA control group (note that the group remains matched to the CA group, with an average age of 9.43 years 5.18 months, *SD* = 23). An overall ANOVA without this child confirmed the data pattern of the entire group (notably the main effect of musical prime), $F(1, 28) = 16.04$, $MSE = 10.67$, $p = .0004$.

[5] Fourteen nonmusician adults listened to the sequences (presented in counterbalanced order) and judged on a scale from 1 to 10 how regular they found each sequence (from 1 = *very irregular* to 10 = *very regular*) and how easy they would find it to dance with each sequence (from 1 = *very difficult* to 10 = *very easy*). The results clearly indicated the intended difference between regular and irregular conditions: Average perceived regularity was significantly stronger for the regular sequence (9.5 ± 0.73) than for the irregular sequence (3.31 ± 2.33, $p < .0001$). Averaged ease to dance with the sequence was also significantly stronger for the regular sequence (9.0 ± 1.67) than for the irregular sequence (3.0 ± 1.93, $p < .0001$).

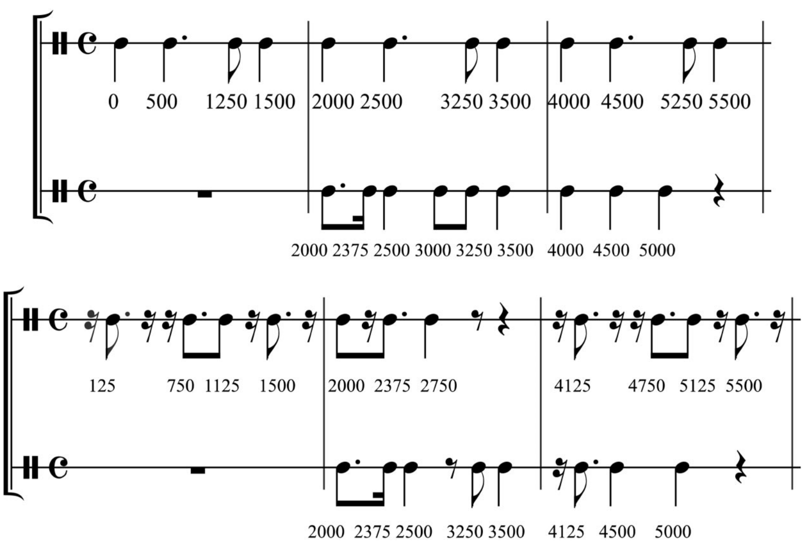

Figure 1. Musical score of the beginning of the regular prime (top) and the irregular prime (bottom). The timelines under each score part indicate the onsets of each note (in milliseconds).

MANULEX, which is a database on words in children books; Lété, Sprenger-Charolles, & Colé, 2004) with another correct sentence (presented in List B). Based on these lists, two experimental sets were constructed: (1) 24 grammatically correct sentences chosen from List A and 24 grammatically incorrect sentences from List B and (2) 24 grammatically correct sentences chosen from List B and 24 grammatically incorrect sentences from List A. Each participant worked on one of the sets. Sentences were spoken by a female native speaker of French at a natural speed of production.

Apparatus

Musical sequences were built and recorded by Finale software. Instruments were chosen from the instruments bank MakeMusic GM and played by synthesizers "49 orchestra" for the tam-tam sound and "41 standard" for the maracas sound. Sentences were recorded with a Røde NT1 microphone in a sound-attenuated booth and normalized in intensity using Audacity software. The experiment was run on PsyScope software (Cohen, MacWhinney, Flatt, & Provost, 1993) and participants used the USB Button Box developed for this software. Musical sequences and linguistic sentences were presented over headphones (SONY MDR V300).

Procedure

The 48 sentences were presented by blocks of six sentences, with the constraint that each block contained three grammatically correct sentences and three incorrect sentences. Before each of the eight blocks, one of the two rhythmic prime sequences was presented (with four blocks preceded by a regular prime and four by an irregular prime). The order of the primes and the blocks as well as the order of the sentences in each block were randomized for each participant.

Participants were asked to listen to the music and were shown a picture on the computer screen (a black-and-white drawing, which represented, e.g., a guitar playing music). At the end of the prime sequence, a blue exclamation mark appeared on the screen to indicate the beginning of the sentence. Participants were asked to judge the grammaticality of the sentences. To facilitate the understanding of the required grammaticality judgment, the experimenter explained to the children that two dragons pronounced the sentences: one who was never wrong and one who was always wrong. At the end of the sentence, two pictures of dragons were presented on the screen: a dragon who looked satisfied and a dragon who looked puzzled. Participants answered by pressing one of two buttons on the response box, one below each dragon. The next sentence was triggered by the experimenter. At the beginning, the organization of an experimental trial was illustrated with one grammatically correct sentence.

Data Analyses

Performance was analyzed with signal detection theory calculating discrimination sensitivity with d' and response bias with c for each participant and for each prime condition.[6] These analyses are based on the proportions of hits (i.e., proportion of correct responses for ungrammatical sentences, p[hits]) and false alarms (i.e., errors for grammatical sentences, p[FAs]) after regular and irregular primes. d' is defined as z(p[hits]) – z(p[FAs]), and response bias c as $-0.5[z(\text{p[hits]}) * z(\text{p[FAs]})]$; see Macmillan and Creelman (1991) for more details. d' and c were analyzed by two analyses of variance (ANOVAs) with musical prime (regular, irregular) as the within-participant factor and group (children with language disorders, CA controls, RA controls) as the between-participants factor. The factor children with language disorders referred to SLI children in Experiment 1A and dyslexic children in Experiment 1B. To estimate effect sizes, we calculated partial η^2 (Cohen, 1988). We further performed supplementary ANOVAs

[6] The correction of the d' and c measures used .01 for cases without false alarms and .99 for the maximum number of hits.

including gender as an additional between-participants factor, but neither the main effect of gender nor its interactions with one of the other factors reached significance (*p*s > .13).

Results and Discussion

Experiment 1A (SLI Children)

For d' (see Figure 2 left, and Table 1), the main effect of group was significant, $F(2, 29) = 8.19$, $p = .002$, $MSE = 4.77$, partial $\eta^2 = .36$. As expected, CA controls performed better than SLI children and RA controls, $F(1, 29) = 15.96$, $p = .0004$, partial $\eta^2 = .36$, whereas these two latter groups did not differ in their performance level, $p = .89$. Note that performance for SLI children was above chance level after the regular prime ($p = .004$) and after the irregular prime ($p = .03$). It is most interesting that the main effect of musical prime was significant, $F(1, 29) = 15.02$, $p = .0005$, $MSE = 0.67$, partial $\eta^2 = .34$, and it did not interact with group, $p = .68$. For all participant groups, performance was better after the regular musical prime than after the irregular musical prime.

The analysis of *c* (see Table 2) revealed that this effect of musical prime was not accompanied by a difference in response bias *c*. Only the main effect of group was significant, $F(2, 29) = 4.31$, $p = .03$, $MSE = 0.83$, partial $\eta^2 = .23$, but not the main effect of musical prime, $p = .43$, nor their interaction, $p = .34$.

Additional analyses without the four SLI children who were also diagnosed with dyslexia replicated the outcome of the entire group: Notably, they confirmed a significant main effect of music for d', $F(1, 21) = 6.45$, $MSE = 0.71$, $p = .02$, partial $\eta^2 = .23$, and its absence for *c*, $p = .51$.

Given the large age range among patients and their CA matched controls, we ran two further analyses: The difference in d' for regular and irregular prime did not correlate with age, $r(30) = .07$; and we removed the three youngest SLI children and their matched CA controls as well as the oldest one (in each group), leading to a reduced age range (SLI, $n = 8$: average CA = 9 years 11 months, $SD = 14.53$ months, range = 8 years 4 months − 11 years 10 months; CA controls, $n = 8$: average CA = 9 years 10 months, $SD = 13.38$ months, range = 8 years 4 months − 11 years 4 months), but confirming the outcome of the entire participant groups (i.e., main effect of musical prime), $F(1, 21) = 20.57$, $p = .0002$, and of group, $F(2, 21) = 10.98$, $p = .0005$, but no interaction, $p = .99$.

In sum, Experiment 1A showed that children's grammaticality judgments were influenced by the metricality of the musical prime preceding the language presentation: Performance was better after the regular musical prime than after the irregular prime. Although the performance level of SLI children was lower than that of the CA-matched control children, the SLI children also benefited from

Table 1
d′ Data Pattern of Experiments 1A and 1B Averaged Over Participants, by Musical Prime (Regular, Irregular)

Group	Average *d′*		*SE*	
	Regular prime	Irregular prime	Regular prime	Irregular prime
Experiment 1A				
SLI children	1.64	0.9	0.45	0.37
CA controls	3.89	3.29	0.58	0.59
RA controls	1.9	0.84	0.49	0.43
Experiment 1B				
Dyslexic children	3.8	2.66	0.66	0.52
CA controls	4.47	3.9	0.42	0.63
RA controls	2.84	2.33	0.53	0.75

Note. SLI = specific language impairment; CA = chronological age-matched control; RA = reading age-matched control.

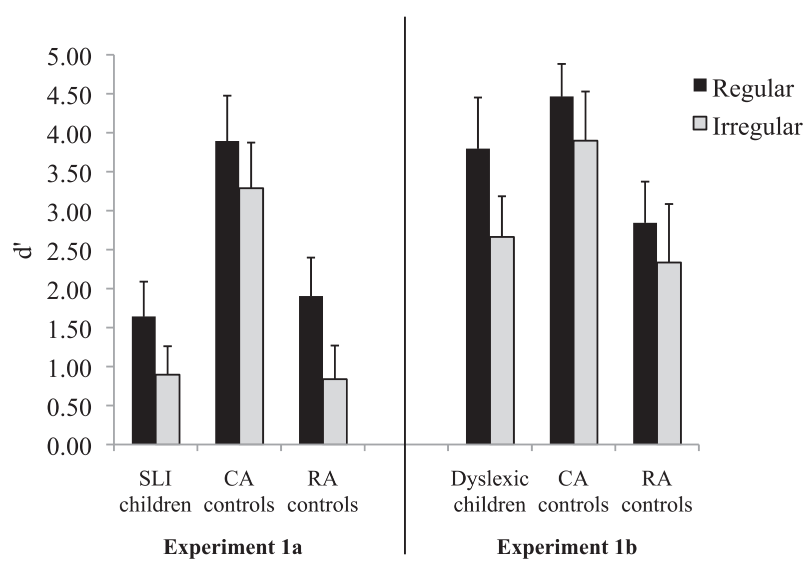

Figure 2. d' data pattern of Experiments 1A and 1B averaged over participants, presented as a function of the musical prime (regular, irregular) and the participant groups: specific language impairment (SLI) children in Experiment 1A, dyslexic children in Experiment 1B, with their respective control groups matched for chronological age (CA) and reading age (RA). Error bars indicate between-participants standard errors.

Table 2
c Data Pattern of Experiments 1A and 1B Averaged Over Participants, by Musical Prime (Regular, Irregular)

Group	Mean		*SE*	
	Regular prime	Irregular prime	Regular prime	Irregular prime
Experiment 1A				
SLI children	0.29	0.42	0.21	0.15
CA controls	−0.26	−0.56	0.31	0.26
RA controls	0.15	0.03	0.11	0.09
Experiment 1B				
Dyslexic children	−0.39	−0.15	0.27	0.27
CA controls	−0.21	−0.72	0.32	0.23
RA controls	0.14	−0.25	0.28	0.30

Note. SLI = specific language impairment; CA = chronological age-matched control; RA = reading age-matched control.

the regularity of the musical prime. Furthermore, response biases were overall relatively small, even though SLI children showed a bias to respond "grammatical" and CA controls a bias to respond "ungrammatical." However, this group difference may be related to expertise with language or an effect of schooling. Most important, bias was not significantly modulated by the type of musical prime.

Experiment 1B (Dyslexic Children)

For d' (see Figure 2 and Table 1), the main effect of musical prime fell just short of significance, $F(1, 25) = 3.91$, $p = .059$, $MSE = 1.92$, partial $\eta^2 = .14$, but it showed, as for Experiment 1A, that performance was better after the regular musical prime than after the irregular musical prime. This effect did not interact with group, $p = .75$. The main effect of group was only marginally significant, $F(2, 25) = 2.56$, $p = .097$, $MSE = 4.55$, partial $\eta^2 = .17$, but also suggested that CA controls performed better than dyslexic children and RA controls, whereas these latter two groups showed comparable performance levels. For the dyslexic children, the analysis of c did not reveal any significant effects, $ps > .18$ (see Table 2).

In sum, the findings of Experiment 1B observed for dyslexic children and their matched control groups were in agreement with the result patterns observed in Experiment 1A for SLI children and their matched control groups: Even though the main effect fell just short of significance in Experiment 1B, performance after the regular prime was also better than after the irregular prime for all participant groups.

General Discussion

The present study investigated whether musical primes can influence children's performance in a subsequent language task, which focused on syntax processing. The musical primes differed in their temporal (metric) structures, being either regular or irregular. As predicted, we observed better performance after the regular prime than after the irregular prime. This difference was observed for children with developmental language deficits (SLI, dyslexia) and their matched control groups. Interestingly, the previously reported temporal processing deficits in children with developmental language disorders, notably deficits in rhythm and meter processing (Corriveau & Goswami, 2009; Thomson & Goswami, 2008; see also Huss, Verney, Fosker, Mead, & Goswami, 2011), did not hinder the influence of the prime's temporal structure on the subsequent language task. Even SLI and dyslexic children processed the temporal differences in the two musical primes and the regular prime with its metrical structure benefits to the grammaticality judgments compared with the irregular prime. The effect size for this benefit of the regular prime over the irregular prime (as indicated by partial η^2) was higher for the children with SLI than for the children with dyslexia (.34 vs. .14). Although we have to acknowledge that we tested fewer dyslexic children than SLI children ($n = 10$ vs. $n = 12$), supplementary analyses on the SLI group (reducing the sample size by focusing on a narrower age range, separating by gender as well as subsampling) confirmed the significance pattern for this patient group.[7] The more pronounced benefit of the SLI group may be linked to the stronger syntactic disorder in the case of SLI compared with dyslexia (e.g., Catts et al., 2005). In particular, SLI children tested in the current task showed weaker performance in the grammaticality task (average $d' = 1.27$) than did the dyslexic children (average $d' = 3.23$).

Our finding is in agreement with previous work that has shown beneficial effects of a metrical musical stimulus (e.g., a marching rhythm) on syntax processing in patients with basal ganglia lesions or Parkinson's disease (Kotz & Gunter, 2012; Kotz et al., 2005). For these patients—similar to the SLI and dyslexic children—deficits in temporal processing have been reported (Schwartze et al., 2011). Overall temporal processing is impaired but not fully abolished. The decreased functionality may particularly affect language processing, which requires sequencing and segmentation (such as syntax here), because rhythmic and metrical structures are less strongly implemented in language than in music. Most important, the impaired system can be activated by the musical stimuli with its clear metrical structure. The regular events in the musical prime provide predictable cues that may allow boosting and entraining internal oscillators, which then benefit the sequencing and temporal segmentation at the sentence level, thus favoring syntax processing. The regular prime improved children's grammaticality judgments (in comparison to the irregular prime); this is even for SLI children for whom previous work has suggested a sequencing deficit (Weinert, 1992) or a more general procedural deficit (Ullman & Pierpont, 2005). This deficit has been attributed to impaired processing of grammatical structures and temporal sequences—whether language (syntax, morphology, phonology) or music (Corriveau & Goswami, 2009; Ullman, 2001; Ullman & Pierpont, 2005). Ullman and Pierpont (2005) reviewed evidence for neural abnormalities in frontal cortex and basal ganglia, both having been associated with structural processing (e.g., Grahn, 2009). Based on Ullman's declarative and procedural memory model, Nicolson and Fawcett (2007) have further extended this framework and discussed SLI and dyslexia

[7] We ran 12 additional ANOVAs subsampling the SLI group and its matched CA group down to 10 children each. Each of these analyses confirmed a main effect of musical prime ($ps < .002$) and group ($ps < .02$), but no interaction.

together with other various developmental disorders in terms of procedural learning difficulties.

Kotz et al. (2009) reviewed two pathways involved in nonmotor functions, such as sequencing (i.e., formation of sensory predictions, segmentation of incoming auditory streams, syntax processing) and temporal attention: a basal–ganglia–pre-supplementary motor area (SMA) circuitry and a cerebellar–thalamic–pre-SMA pathway. These pathways would be involved in the perception of sensory predictable cues (such as beats in metrical structures) and the synchronization between internal oscillators and external (stimulus) regularities (as suggested by the dynamic attending theory; Jones, 1976). Deficits in one of the pathways, such as in patients with basal ganglia lesions, can lead to syntactic processing deficits (e.g., Frisch, Kotz, von Cramon, & Friederici, 2003; Kotz et al., 2003). The stimulation of the system with highly regular stimuli (e.g., musical sequences in Kotz et al., 2005), which may be more efficient even for the impaired pathway, or via the alternative pathway would allow compensating a sequencing deficit in sentence processing. This led Kotz et al. (2005) to promote metrical stimulation as a therapeutic tool. For developmental language disorders, it has been reported that SLI and dyslexia include abnormalities in regions of the frontal cortex (in particular Broca's area and premotor regions), with additional abnormalities in a corticostriatal network in SLI and a corticocerebellar network in dyslexia (see Nicolson & Fawcett, 2007, for a review). One may now speculate that these anomalies would thus affect one of the two pathways involved in sequencing and temporal attention, and that a temporally regular (external) stimulation would benefit in particular the unimpaired one, thus allowing the boosting of sequencing capacities.

The metrical prime also benefited the control groups in our experiments: The clearly established regular temporal structure in the musical material had a positive impact on syntactic processing in children in the subsequent language task, whether they experienced language difficulties or not. Based on Jones's framework of dynamic attending (e.g., Jones & Boltz, 1989), the hypothesis is that the metrical structure of the musical material allows orienting attention over time and allows developing expectations about the temporal occurrence of a next event, which then facilitates processing, segmentation, and integration. As speech is inherently tied to time and requires temporal processing and cognitive sequencing (see Kotz & Schwartze, 2010), this modulation of temporal attention benefits both the healthy and impaired brain. The observed performance differences further suggest the importance of rhythm processing in language processing. They can be linked to previous work suggesting that rhythm processing deficits lead to deficits in language processing by, for example, impairing suprasegmental information processing (e.g., Corriveau & Goswami, 2009; Thomson & Goswami, 2008). Although our present results cannot provide evidence for sequencing deficiencies to be the core of language deficits in SLI and dyslexia (an interesting question that was not directly assessed in this study), they suggest that this kind of cognitive mechanism can be improved—relatively quickly (and at least on an interim basis)—by nonlinguistic stimuli, which results in improved processing of syntactic information.

For basal ganglia patients (Kotz et al., 2005), the effect of the musical prime was shown in the restoration of an ERP component (the P600 following the perception of syntactic violations) that was reported as missing in previous work (Kotz et al., 2003). For the developmental language disorders investigated in the present study, the effect of the musical prime was confirmed in the comparison of two prime types (regular, irregular), thus showing a relative facilitation between the two conditions: regular versus irregular. However, this comparison does not yet allow conclusions about compensatory benefits of the regular prime in comparison to children's performance without music. The rationale of our experimental design followed previous linguistic and musical priming research: studying first relative facilitation and then investigating costs and benefits compared with a baseline condition. Due to difficulties in determining adequate baseline conditions (see Jonides & Mack, 1984, and Tillmann, Janata, Birk, & Bharucha, 2003, for discussions of this difficulty for language and music materials) and the not-yet-known temporal persistence of the musical prime effect over time (thus potentially contaminating a silent baseline condition), our study started by investigating the possibility whether musical metrical structures may influence subsequent language processing. Now that this influence has been observed (even though as relative facilitation), future research needs to study the potential, compensatory benefits of music on language performance by including the comparison with a potential baseline condition (e.g., using meaningless noise or environmental sound scenes) or by following an alternative approach, as done via ERP measurements in Kotz et al. (2005). For example, Sabisch et al. (2006) reported delayed or missing anterior negativities for the processing of syntactic and prosodic structures in dyslexic children compared with controls. If a metrically regular prime benefits syntax processing, the delay of the anterior negativity should be reduced or should vanish (compared with that of the control children).

Our study provides new evidence that can be integrated in the temporal sampling framework recently proposed by Goswami (2011) for dyslexia and by extension for SLI. Speech processing requires processing of amplitude envelopes at a rather low frequency (reflecting the sequential rate of syllables and words).[8] The temporal sampling framework, which highlights that oscillatory networks of neurons provide synchronous activity over different frequency bands, suggests impaired temporal sampling of the input at low-frequency oscillatory mechanisms (i.e., theta and delta rhythms, covering 1.5 to 10 Hz) in children with developmental language disorders. Evidence can be found in impaired processing of slow-frequency modulations at 2 Hz (Witton et al., 1998) and impaired tapping performance to a beat (particularly at 2 Hz; Thomson & Goswami, 2008) in dyslexic children (see also Hämäläinen, Rupp, Soltész, Szücs, & Goswami, 2012). Together with the dynamic attending theory (e.g., Jones & Boltz, 1989) postulating internal oscillators guiding attention over time, Goswami (2011) suggests that the impaired rhythmic entrainment leads to difficulties in develop-

[8] In natural speech, syllables occur about every 200 ms, with stressed syllables about every 500 ms (i.e., corresponding to a rate of 2 Hz). This corresponds to the tempo of our musical primes, which was chosen based on McAuley et al. (2006) for the tested age group's preferred spontaneous tempo. This leads to the need for future studies to manipulate the base tempo of the regular and irregular musical primes to investigate whether there might be some specificity related to frequency ranges.

ing attention over time, leading to deficits in syllabic segmentation and other sequential processes. This aspect allows integration of other approaches of developmental language disorders that focus on attention, such as the sluggish attention-shifting hypothesis (Facoetti et al., 2010; Hari & Renvall, 2001). Goswami discusses the potential benefits of therapeutic interventions or educational practices based on rhythm and music as those might "entrain the Theta and Delta oscillatory networks that are (by hypotheses) impaired in dyslexia" (p. 9). In particular, she suggests that remediation based on rhythm and music (e.g., matching syllable patterns to metrical structures in singing, playing instruments, or moving in time, working with metrical poetry, or singing nursery rhymes) might impact language development and be particularly beneficial in developmental language disorders. Together with this framework and other data showing positive effects of a musical activity program (including rhythm skills) on phonological skills and spelling performance (Overy, 2000) and also of exposure to musical primes on syntactic processing (e.g., Kotz et al., 2005), our study provides new grounds and motivations for further testing the benefit of rhythmic stimulation on language processing and its underlying mechanisms. Providing evidence for cross-domain effects (from music to language) over time is encouraging and multiplies the possibilities of using rhythmic stimulation in training or remediation programs, in addition to accentuating rhythmic structures in linguistic material itself (at the same time, as in poetry). This perspective could also exploit the motivational advantages and pleasantness that musical material might provide in a rehabilitation setting, beyond its stimulating effect for impaired temporal processing networks. Future adaptations need to test the potential impact and benefit of the prior presentation of strongly metrical musical material on various linguistic subsequent tasks, which require segmentation processes (see Bedoin et al., 2012, for a reading task).

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