SCUOLA DI DOTTORATO
UNIVERSITÀ DEGLI STUDI DI MILANO-BICOCCA

Dipartimento di / Department of

Psicologia

Dottorato di Ricerca in / PhD program Psicologia, linguistica e neuroscienze cognitive
Ciclo / Cycle 32

Curriculum in (se presente / if it is) Mente, cervello e comportamento

Neural entrainment, hierarchical processing, and morphosyntactic and rhythmic predictions in typical development, in Developmental Dyslexia, and in Developmental Language Disorder

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ANNO ACCADEMICO / ACADEMIC YEAR 2018/2019

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Abstract

This work investigates prediction mechanisms and neural entrainment in children as the possible elements underlying both rhythmic and morphosyntactic processing. Both rhythmic meter and language are organized in hierarchical structures in which elements are ordered following specific rules (Fitch and Martins, 2014). Knowledge of these rules triggers compulsive expectancies regarding incoming material; these are assumed to be fundamental for efficient language and rhythmic processing and for reading (Guasti et al., 2017; Grüter, Rohde and Schafer, 2014; Miyake, Onishi and Pöppel, 2004; Persici et al., 2019).

In this work we hypothesized that better hierarchical processing abilities in rhythm may transfer to the language domain, and that deficits in hierarchical processing may lead to language and/or reading disorders. To test whether abilities in making structure-based predictions correlate across domains, we investigated the abilities to infer the arrival of morphosyntactic and rhythmic material in groups of children with typical language development (TD) with or without musical training, and in participants with Developmental Dyslexia (DD). Results confirmed our hypotheses, as they showed better structure-based predictions in musician children than in non-musician TD children, and in TD children than in DD children. Results also suggested that efficiency of processing strategies improves with age.

Secondly, we hypothesized that individual differences in strength of timing and content structure-based predictions may be the result of individual differences in the efficiency and precision with which brain oscillations entrain to auditory stimuli ('neural entrainment'). To address these hypotheses, we tested the neural responses of TD children and of children with Developmental Language Disorder (DLD) in an experimental paradigm that was designed to elicit different metrical (hierarchical) interpretations. Results showed that all children were sensitive to hierarchical structures, and that individual differences in neural activity predicted individual differences in syntactic performance. Importantly, results also suggested that children with DLD might have atypical oscillatory activity in the gamma frequency band, which is important for hierarchical processing (Ding et al., 2017).

In line with Fiveash et al. (submitted) and in Ladányi, Persici, et al. (submitted), we propose that neural oscillatory activity plays a key role in supporting the processing of both surface-level features and of syntactic structures in both musical rhythm and language, through an enhancement of structure-based prediction abilities; individual differences in

neural entrainment will lead to individual differences in strength of predictions, which in turn will lead to individual differences in language and rhythm performance.

The evidence presented in this work indicates that neural oscillatory activity gives an important insight into the language abilities of children and suggests that studying neural responses to rhythm in infancy may help predict the later development of language/reading disorders. Furthermore, our results suggest that musical training has positive effects on hierarchical processing, and that musical interventions centered on rhythm may enhance mechanisms of neural entrainment and timing, as well as hierarchical processing skills.

Abstract – italiano

Il presente lavoro indaga i meccanismi di predizione e di sincronizzazione neurale nei bambini, sulla base dell'ipotesi che questi possano essere elementi rilevanti nei processi di elaborazione ritmica e morfosintattica. Sia il metro ritmico che il linguaggio sono organizzati in strutture gerarchiche in cui gli elementi sono ordinati secondo regole specifiche (Fitch & Martins, 2014). La conoscenza di queste regole porta alla formazione automatica di aspettative riguardo al materiale in arrivo; queste aspettative sono ritenute fondamentali per il processamento efficiente del linguaggio e del ritmo, così anche come per la lettura (Guasti et al., 2017).

In questa tesi abbiamo ipotizzato che migliori capacità di elaborazione gerarchica nel ritmo possano portare a migliori capacità di processamento di strutture gerarchiche nel linguaggio e che deficit in queste abilità possano portare allo sviluppo di disturbi del linguaggio e/o della lettura. Per valutare se le abilità nel fare previsioni strutturali correlino tra ritmo e il linguaggio, abbiamo studiato e confrontato le capacità di predire materiale linguistico (sulla base di informazioni morfosintattiche) e materiale ritmico in gruppi di bambini a sviluppo tipico (in inglese, TD) con o senza formazione musicale e in partecipanti con dislessia evolutiva (in inglese, DD). I risultati hanno confermato le nostre ipotesi, in quanto hanno mostrato predizioni strutturali migliori nei musicisti rispetto ai non-musicisti nel gruppo dei tipici e migliori predizioni strutturali nei TD rispetto ai bambini con dislessia. Inoltre, i risultati suggeriscono miglioramenti nell'efficienza delle strategie di processamento con l'aumentare dell'età.

In secondo luogo, abbiamo ipotizzato che differenze individuali nella forza e nella efficienza con cui si fanno predizioni temporali e di contenuto possano dipendere da differenze individuali nell'efficienza e nella precisione dei meccanismi neurali di sincronizzazione delle oscillazioni cerebrali rispetto agli stimoli uditivi. Per testare queste ipotesi, abbiamo analizzato le risposte neurali di bambini TD e di bambini affetti da disturbo evolutivo del linguaggio (in inglese, DLD) in un paradigma sperimentale progettato per suscitare diverse interpretazioni metriche (e quindi gerarchiche). I risultati hanno mostrato che tutti i bambini erano sensibili alle caratteristiche metriche degli stimoli e che le differenze individuali nell'attività neurale predicevano le prestazioni in compiti sintattici. Inoltre, i risultati hanno suggerito che i bambini con DLD potrebbero avere attività oscillatoria atipica nella banda di frequenza gamma (che, secondo gli studi in letteratura (p.es., Ding et al., 2017), è importante per l'elaborazione gerarchica).

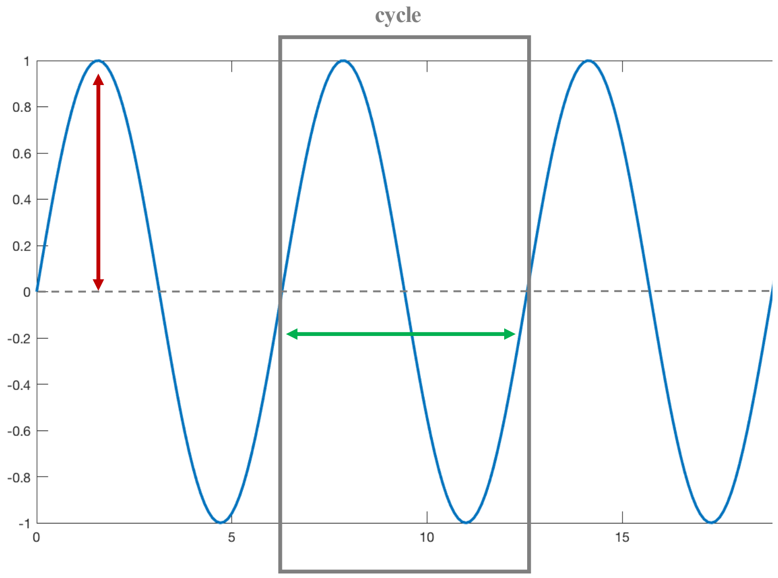
In accordo con Ladányi, Persici, et al. (in revisione), sosteniamo che l’attività oscillatoria a livello neurale possa svolgere un ruolo chiave nel supportare il processamento degli elementi di base e delle strutture gerarchiche, sia nel ritmo che nel linguaggio, e che questo supporto passi attraverso il miglioramento delle predizioni strutturali. Sosteniamo, quindi, che migliori capacità di sincronizzazione neurale si traducano in migliori capacità di predizione strutturale e che queste, a loro volta, possano influenzare positivamente l’elaborazione ritmica e linguistica.

Le evidenze presentate in questo lavoro rimarcano l’importanza dello studio dell’attività oscillatoria cerebrale nei bambini piccoli e suggeriscono la possibilità di utilizzare questi paradigmi nell’infanzia per poter predire il futuro sviluppo di disturbi del linguaggio e/o della lettura. Inoltre, gli studi qui riportati sottolineano come la formazione musicale sia importante per il miglioramento dei processi di elaborazione linguistica e suggeriscono che l’uso di attività ritmiche, in particolare, possa giocare un ruolo fondamentale nel trattamento dei disturbi del linguaggio e della lettura.

Chapter 1

1.1 Introduction

The ability to accurately perceive rhythmic features is not only important for music perception, but also for language acquisition and for reading. Research using behavioral (Holliman, Wood, & Sheehy, 2010) and electrophysiological (Strait, Hornickel, & Kraus, 2011) methods has shown that how well children read is linked to their degree of sensitivity to speech rhythm. Speech rhythm is conveyed by the amplitude envelope (i.e., the changes in the amplitude of a sound over time; see Figure 1 and 2B) and by the information about speech rhythm, tempo, and stress that it contains (Myers, Lense, & Gordon, 2019). The accurate perception of the modulations of the amplitude envelope is fundamental for language acquisition (e.g., Gervain & Werker, 2013), and for speech segmentation and processing (Bion, Benavides-Varela, & Nespor, 2011). In fact, sensitivity to the suprasegmental features of speech is thought to facilitate grouping of strong (accented) and weak (non-accented) syllables, word recognition and, by consequence, vocabulary acquisition (Newman, Ratner, Jusczyk, Jusczyk, & Dow, 2006) and reading development (Metsala & Walley, 1998).



Amplitude:
Distance between origin of the wave and its crest (or trough);

Period:
time required to complete one cycle;

Frequency:
Number of cycles per second (Hz).

Figure 1. Characteristics of a periodic wave: amplitude, period, cycle, and frequency.

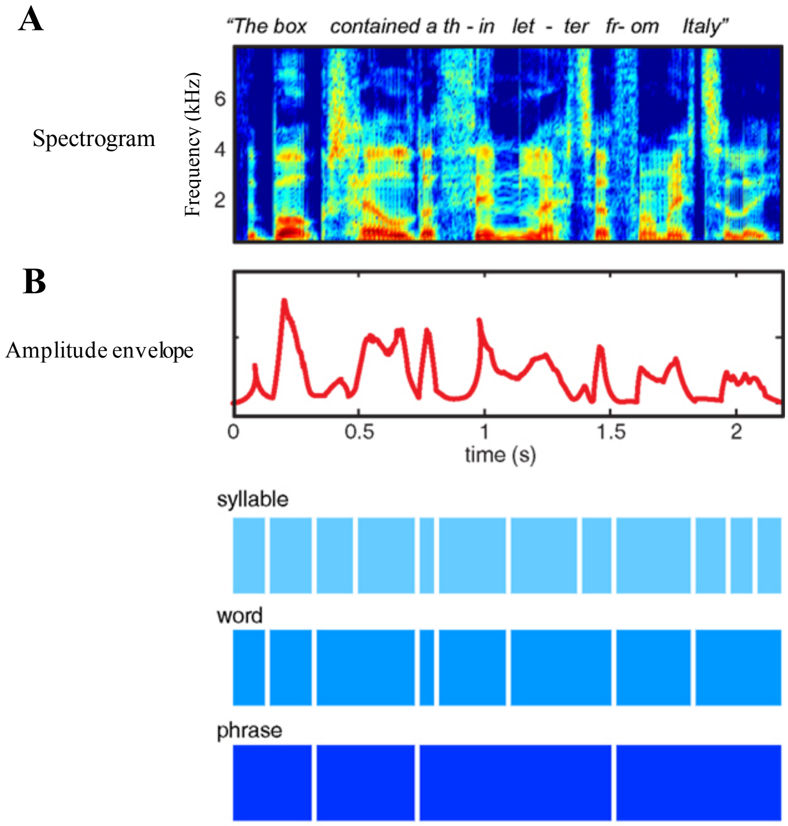


Figure 2. Representations of the acoustic speech signal: spectrogram (A) and amplitude envelope (B) are represented on the top portion of the figure. The spectrogram shows the spectrum of the sound frequencies over time; the colors (from darker to brighter) indicate the amplitude of the sounds (from lower to higher). Adapted from Peelle & Davis (2012).

However, reading skills (and their early precursors) are not only dependent on the ability to perceive the rhythmic features of speech, but are also associated with more general rhythm perception abilities. In fact, studies have shown that preschool children with better musical rhythm perception skills show enhanced phonological awareness and better early reading abilities (Anvari, Trainor, Woodside, & Levy, 2002; Degé & Schwarzer, 2011; Douglas & Willatts, 1994; Grube, Kumar, Cooper, Turton, & Griffiths, 2012; Moritz, Yampolsky, Papadelis, Thomson, & Wolf, 2013). This is interesting, because, though speech and music have similarities, they also have distinctive features: both have sequences of sounds that unfold in time and that are processed based on the analysis of the temporal structure in which sounds are organized and on fine temporal distinctions (Patel, 2008); however, music most often relies on metrical units with isochronous inter-onset intervals, whereas speech is characterized by a grid of more variable temporal units (metrical vs. non-metrical patterns: Essens & Povel, 1985). If better reading skills were only a direct consequence of better speech rhythm abilities, metrical perception should not explain unique variance (above and over that of non-metrical perception) in phonological and reading skills. On the contrary, Ozernov-Palchik, Wolf, and Patel (2018) showed that individual differences in *metrical* processing predict individual differences in letter-sound knowledge above IQ, auditory working memory, phonological awareness, and non-metrical processing; moreover, in their study only metrical processing was associated with early literacy measures. These results suggest that musical rhythm may be particularly useful for the development of language and reading skills.

Interestingly, associations with language and literacy measures are also found in rhythmic production. Woodruff Carr, White-Schwoch, Tierney, Strait, and Kraus (2014) showed that the accuracy with which children synchronize their movements to an acoustic rhythmic stimulus predicts their performance in phonological awareness and sentence repetition, a task which requires not only adequate auditory processing and short-term memory skills, but also access to the grammatical structure of the sentence that is repeated (Klem et al., 2015). This finding suggests that the benefits of enhanced rhythm skills may not only pertain to the prosodic and phonological characteristics of speech, but also extend to syntactic skills.

In line with this idea, in a study with 5- to 7-year-olds, Gordon et al. (2015) showed that individual differences in rhythm discrimination abilities explained individual differences in expressive grammar performance; the children who better differentiated between identical and different rhythmic patterns also showed better grammar skills.

In addition, studies with adults have shown that syntactic dependencies in music and language are processed using the same cognitive and neural mechanisms (Patel, 2008). The processing of harmonic syntactic violations affects the syntactic processing of sentences, when presented simultaneously (Slevc, Rosenberg, & Patel, 2009), but not their semantic processing (Hoch, Poulin-Charronnat, & Tillmann, 2011); on the other hand, the processing of syntactic violations in language– but not other types of violations – affects harmonic syntactic processing (Kunert, Willems, & Hagoort, 2016; Steinbeis & Koelsch, 2008). Furthermore, electrophysiological studies show that neural responses to syntactic violations in language are reduced if violations to harmony are also present (Stefan Koelsch, Gunter, Wittfoth, & Sammler, 2005), which suggests shared neural responses between harmonic and syntactic processing.

Though most studies focused on the comparison between harmony and linguistic syntax, more recent studies have shown associations between rhythmic and language syntactic processing (Sun, Liu, Zhou, & Jiang, 2018). Why would rhythm and linguistic syntax be linked? Rhythm and language are both constituted by temporal regularities organized at multiple hierarchical levels. The term 'hierarchy' here is used to refer to a tree-like structure in which lower levels are incorporated into higher levels and in which elements are ordered according to specific rules (Fitch, 2017). In music, regularly timed basic units are perceptually grouped and organized into a hierarchical structure (see Figure 3) called 'meter' (Lerdahl & Jackendoff, 1983). Meter also involves the perception of the beat, which serves as an anchor "around which other [rhythmic] events are organized" (Iversen, Repp, & Patel, 2009:58). Though beats are often cued by physical cues, the hierarchical interpretation of a sequence of tones is a process that takes place automatically and unconsciously, regardless of whether or not tones are accented (Bolton, 1894).

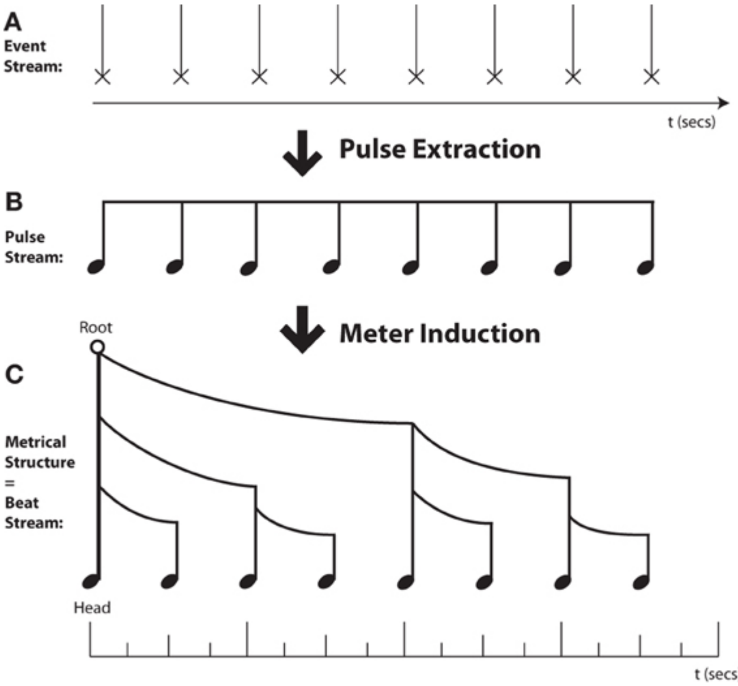


Figure 3. Hierarchical structure in music. From Fitch (2013).

Just like rhythm, language is also constituted by elements that are ordered following a hierarchical structure and specific rules (Lashley, 1951) (see Figure 4).

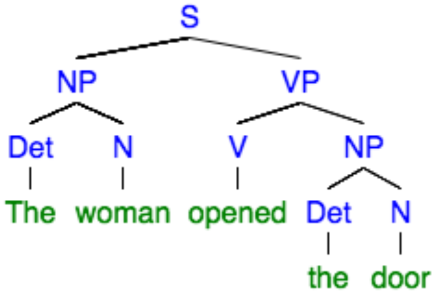


Figure 4. Hierarchical structure in language.

The continuous exposure and processing of hierarchical structures in one domain may benefit the processing of hierarchical structures in other domains. To investigate this hypothesis, studies have compared language performance between musicians and non-musicians. Results have shown that adult musicians do not only show enhanced auditory processing in relation to musical stimuli (Koelsch, Schröger, & Tervaniemi, 1999), but also in relation to language. More specifically, advantages in musicians are found in important linguistic domains such as syllable (Zuk et al., 2013) and speech sound discrimination (Bidelman, Weiss, Moreno, & Alain, 2014; Kempe, Thoresen, Kirk, Schaeffler, & Brooks, 2012), rhythmic grouping (Boll-Avetisyan, Bhatara, Unger, Nazzi, & Höhle, 2016), metrical processing (Marie, Magne, & Besson, 2011), timing discrimination (Sares, Foster, Allen, & Hyde, 2018), speech segmentation (François, Jaillet, Takerkar, & Schön, 2014), neural encoding of speech processing (Musacchia, Sams, Skoe, & Kraus, 2007), and hierarchical syntactic structure acquisition (Brod & Opitz, 2012). Moreover, neuroimaging studies have shown that musicians have greater grey matter volume in motor, auditory, and visual-spatial brain regions (Gaser & Schlaug, 2003; Schneider, Scherg, & Dosch, 2002), as well as in the corpus callosum (Schlaug, Lutz, Huang, Staigeri, & Steinmetz1, 1995), which is important for stimulus integration processes between brain hemispheres. Importantly, an fMRI study published in 2014 has further shown that musicians recruit language brain areas in processing rhythm (Herdener et al., 2014), which suggests again similarities between rhythmic and language processing.

Interestingly, the language advantages found in adults with several years of musicianship are also found in children: even those children who have received only a few years of musical training show enhanced auditory processing (Habibi, Cahn, Damasio, & Damasio, 2016), speech sound sensitivity (Strait, O'Connell, Parbery-Clark, & Kraus, 2014), verbal ability (Forgeard, Winner, Norton, & Schlaug, 2008), and syntactic processing (Jentschke & Koelsch, 2009).

Intervention studies have also provided evidence that a few months of musical training already produce positive effects on language and literacy skills (see also Tallal & Gaab (2006) and Tierney & Kraus (2013) for a review). School-age children show benefits in phonological awareness already after four or five months of musical training (Degé & Schwarzer, 2011; Moritz et al., 2013; Patscheke, Degé, & Schwarzer, 2019) and in reading abilities after only four weeks (Taub & Lazarus, 2012; see also Moreno et al., 2009). Testing children after nine months of training showed enhanced word decoding skills (Rautenberg, 2015), and better speech segmentation (François, Chobert, Besson, & Schön, 2013); phoneme processing and vocabulary development improvements (Linnavalli, Putkinen, Lipsanen, Huotilainen, & Tervaniemi, 2018) also appeared after two years. Interestingly, one month of musical training was enough for Zhao and Kuhl (2016) to see advances in temporal information (foreign syllable structure) processing in infants. The finding that short-term exposure to music is already beneficial suggests that structural brain changes may not be necessary for language and literacy benefits to appear.

Relevantly, recent rhythmic priming studies have shown that, after hearing regular rhythmic primes, typically-developing (TD) children show enhanced grammar task performance (Bedoin, Brisseau, Molinier, Roch, & Tillmann, 2016; Chern, Tillmann, Vaughan, & Gordon, 2018; Ladányi, Lukács, & Gervain, submitted; Przybylski et al., 2013). It should be noted that it was again the regularity of the stimuli that positively affected the children's grammaticality judgements, not the exposure to any kind of rhythmic structure; this suggests that the mechanisms involved in musical rhythm are specifically important for adequate language processing.

The effect of musical training on language and literacy skills also has clinical relevance. In fact, an increasingly large body of literature has found that worse rhythm perception and production skills are found in populations with reading deficits (dyslexia), grammar deficits (Specific Language Impairment: SLI, or 'Developmental Language Disorder': DLD), and speech and motor impairments, such as stuttering and Developmental Coordination Disorder. The next section of this chapter will focus specifically on the evidence of associations between rhythm and language and reading skills in dyslexia and DLD.

1.2 Dyslexia

Developmental Dyslexia (DD) is a disorder characterized by deficits in reading and spelling, which do not depend on neurological impairments or other cognitive deficits. Rates with which this disorder is found in the population oscillate between 3 and 17%, depending on the language and on the definition of reading disorder adopted (Lindgren, De Renzi, & Richman, 1985). Though this disorder was once assumed to depend on a phonological deficit only (found across languages: Ziegler & Goswami, 2005), more recent studies have also shown impaired morphosyntactic processing of complex structures (Cantiani, Lorusso, Perego, Molteni, & Guasti, 2015; Rispens & Been, 2007), and reduced sensitivity to syntactic violations (Sabisch, Hahne, Glass, Von Suchodoletz, & Friederici, 2006; see Chapter 3 for more details).

Besides linguistic deficits, increasingly more studies have shown that children with dyslexia show deficits in tasks requiring sensorimotor synchronization (Colling, Noble, & Goswami, 2017; Dellatolas, Watier, Le Normand, Lubart, & Chevrie-Muller, 2009; Overy, Nicolson, Fawcett, & Clarke, 2003; Thomson & Goswami, 2008). In fact, children with dyslexia are reported to have difficulties in synchronizing their taps to auditory stimuli, significantly more so than their typically developing peers. These rhythmic deficits cannot only be linked to motor difficulties, as children with dyslexia also show worse rhythmic perception in both music (Flaugnacco et al., 2014; Goswami, Huss, Mead, Fosker, & Verney, 2013; Huss, Verney, Fosker, Mead, & Goswami, 2011; Lee, Sie, Chen, & Cheng, 2015; Muneaux, Ziegler, Truc, Thomson, & Goswami, 2004; Thomson & Goswami, 2008) and language (e.g., stress detection: Goswami, Mead, et al., 2013; Leong, Hämäläinen, Soltész, & Goswami, 2011). Specifically, individuals with dyslexia seem to have impaired processing of amplitude envelope cues. As already mentioned, the amplitude envelope contains information regarding speech duration, rhythm, tempo and stress (Kotz, Ravignani, & Fitch, 2018; Myers et al., 2019) that is fundamental for accurate speech perception; if the envelope is degraded, speech can be unintelligible (Ghitza, 2012).

Particularly problematic for individuals with dyslexia seems to be rise time information processing (i.e., the rate at which amplitude modulations change) (Goswami et al., 2016; Huss et al., 2011; Leong et al., 2011; Thomson, Fryer, Maltby, & Goswami, 2006); rise time information is crucial for speech segmentation and comprehension, as it allows the tracking of the envelope onset and therefore the temporal segmentation of the speech stream into syllables. In a study with typically-developing (TD) children and children with Developmental Dyslexia (DD), Goswami and colleagues (2002) showed that children with

DD are significantly less sensitive to modulations of rise time information than TD peers. In fact, the performance in a beat-detection task that required participants to differentiate between slow- and fast-modulated sound envelopes changed as a function of reading level and was significantly worse in the dyslexia group. Significantly worse sensitivity to rise time information in dyslexia was further confirmed in successive studies that tested both children (Richardson, Thomson, Scott, & Goswami, 2004; Thomson & Goswami, 2008) and adults (Thomson et al., 2006), and that focused on a variety of different languages, including Spanish (Molinaro, Lizarazu, Lallier, Bourguignon, & Carreiras, 2016), French (Muneaux et al., 2004), English (Pasquini, Corriveau, & Goswami, 2007), Hungarian (Surányi et al., 2009), and Chinese (Wang, Huss, Hämäläinen, & Goswami, 2012).

According to the Temporal Sampling Framework by Goswami (2011), inefficient processing of rise time information in dyslexia depends on atypical entrainment of brain oscillations to speech. The term 'neural entrainment' refers to stimulus-induced changes in the phase of the oscillations that are produced by the firing of sets of neurons and by the alternation of their excitation and inhibition states (see Figure 5). Exposure to auditory stimuli causes the reorganization of the phase of the neural oscillations (Penny, Kiebel, Kilner, & Rugg, 2002) and their temporal alignment (phase-locking; see Figure 5).

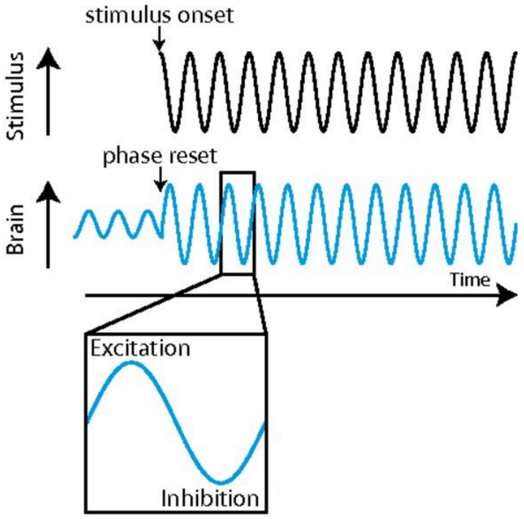


Figure 5. Phase-resetting of neural oscillations caused by the exposure to auditory stimuli. Adapted from (Henry & Obleser, 2012)

Crucially, electroencephalography (EEG) and magnetoencephalography (MEG) studies have shown that, when we hear someone speak, our cortical activity is entrained at multiple levels concurrently (Luo, Wang, Poeppel, Simon, & Ding, 2006), both at the basic elements of language (phones: Di Liberto, O'Sullivan, & Lalor, 2015), and at higher levels of the hierarchical structure (Ding et al., 2017) (see Figure 6). This process is thought to be crucial for speech decoding, processing, and comprehension (Ahissar et al., 2001; Ding et al., 2017; Ghitza, 2012; Henry & Obleser, 2012; Luo & Poeppel, 2007). Any deficits in this ability are thought to lead to impaired phonological processing, syntactic processing, speech comprehension, and reading.

Evidence in favor of the hypothesis that dyslexia might be associated with inefficient neural entrainment to speech, and more specifically to the speech envelope and at the accented syllable rate (~2 Hz), has been provided in recent studies using electrophysiological methods (Leong & Goswami, 2014; Molinaro et al., 2016; Power, Colling, Mead, Barnes, & Goswami, 2016). Importantly, this deficit is found across languages and does not depend on the rhythmic properties of the language spoken by the population with dyslexia studied, as it has been shown both in a stress-timed language like English (Power et al., 2016) and in a syllable-timed language like Spanish (Molinaro et al., 2016). Atypical entrainment may be the cause of inefficient encoding of suprasegmental information, which in turn may produce the syntactic deficits that have been shown in dyslexia (Marshall, Harcourtbrown, Ramus, & Van Der Lely, 2009; B. Sabisch et al., 2006). Crucially, atypical entrainment in dyslexia is also shown to non-speech stimuli (Cutini, Szucs, Mead, Huss, & Goswami, 2016; Frey, François, Chobert, Besson, & Ziegler, 2019). Interestingly, Cutini et al. (2016) showed that TD and DD children's neural oscillations entrained to amplitude-modulated noise delivered at 2 Hz (the syllable rate) and 40 Hz (the phonetic rate); however, neural entrainment at 2 Hz was atypical in DD children.

Importantly, the processing deficits encountered in dyslexia do not appear to recover with the sole passage of time: as mentioned previously in this section, even adults with dyslexia show deficits in rhythmic synchronization and perception (Pasquini et al., 2007; Thomson et al., 2006), and atypical entrainment to speech (Molinaro et al., 2016) and to non-speech stimuli (Hämäläinen, Rupp, Soltész, Szücs, & Goswami, 2012; Lizarazu et al., 2015; Soltész, Szűcs, Leong, White, & Goswami, 2013). However, the deficits associated with dyslexia *do* seem to benefit from musical training. In fact, studies show that musicians with dyslexia have both better auditory temporal processing (Bishop-Liebler, Welch, Huss, Thomson, & Goswami, 2014) and better amplitude information processing (Zuk et al., 2017) as compared to non-musicians with dyslexia. These observations have led to the idea that applying rhythm training at an early age may bring about benefits for children with reading impairments.

Intervention studies that compared rhythm training with other activities have shown that only the children who receive a rhythm training later show improved language and reading skills (Bonacina, Cancer, Lanzi, Lorusso, & Antonietti, 2015; Flaugnacco et al., 2015; Habib et al., 2016; Overy, 2003; Thomson, Leong, & Goswami, 2013). These results have been interpreted as suggesting that rhythmic stimulation may enhance neural entrainment and, by consequence, speech and language processing. Moreover, the fact that neural oscillations also entrain to the level of syntactic structures in language (Ding, Melloni, Zhang, Tian, & Poeppel, 2015) suggests that rhythmic stimulation may not only be beneficial to phonological processing and segmentation processes in dyslexia, but also to syntactic processing. Crucially, Przybylski and colleagues (2013) showed that even short presentation of rhythmic primes positively affects sentence grammatical processing in children with dyslexia. Altogether, these studies suggest that rhythm training may be a useful approach for the rehabilitation of language and reading skills in population with reading deficits, and advocate for the need to add rhythm stimulation to the more traditional therapeutic methods centered around language (Schön & Tillmann, 2015).

Figure 6. Neural oscillations entrained to speech. Oscillations in the gamma band (in green) entrain to phonemes, oscillations in theta (in blue) entrain to syllables; delta has been shown to be relevant for prosodic information (cf. Soltész et al., 2013). Adapted from Meyer (2018).

1.3 Specific Language Impairment (SLI) or Developmental Language Disorder (DLD)

Specific Language Impairment (SLI; Leonard, 1998), now also referred to as Developmental Language Disorder (DLD; Bishop, 2017), is a disorder characterized by deficits in language comprehension and/or production which can persist in adult life (Bishop, 2017; Clegg, Hollis, Mawhood, & Rutter, 2005; Leonard, 1998) and which do not follow from brain injury, acquired or degenerative neurological disease, hearing loss, intellectual disability or autism spectrum disorder.

Recent studies have shown that, like children with DD, children with DLD show deficits in amplitude envelope and rise time information processing (Corriveau, Pasquini, & Goswami, 2007; Goswami et al., 2016; Richards & Goswami, 2015); as mentioned above, these are fundamental for the adequate acquisition and development of vocabulary, phonological awareness, reading, and speech stress processing (Corriveau et al., 2007; Cumming, Wilson, Leong, Colling, & Goswami, 2015; Richards & Goswami, 2015).

Moreover, DLD has been associated with difficulties in both speech and music rhythm processing (Bedoin et al., 2016; Cumming et al., 2015; Sallat & Jentschke, 2015) and synchronization. In fact, significantly worse performance in prosody perception (Fisher, Plante, Vance, Gerken, & Glattke, 2007; Richards & Goswami, 2019; Beate Sabisch, Hahne, Glass, von Suchodoletz, & Friederici, 2009; Wells & Peppé, 2003) and in rhythmic sensorimotor synchronization tasks (which required participants to tap in time with the beat) has been shown in this group (Corriveau & Goswami, 2009; Cumming et al., 2015), though visible differences with TD children seem to be constrained to the particular task used (cf. Vuolo, Goffman, & Zelaznik, 2017; Zelaznik et al., 2012). Interestingly, Weinert (1992) found that impaired processing of rhythm is also associated with impaired processing of prosody in DLD, and suggested that both would be the consequence of inefficient processing of temporal cues. As in dyslexia, deficits in temporal perception are thought to be caused by an underlying impairment in neural entrainment (Goswami et al. 2016).

The finding that neural oscillations can be influenced by the frequency of external auditory cues led to the idea that rhythmic simulations may enhance entrainment (for the same mechanisms discussed in the Dyslexia section of this chapter), and, as a consequence, grammatical processing. Again, recent findings provide support for these theories, as children with DLD profit from the presentation of rhythmic primes by showing enhanced grammaticality judgements (Bedoin et al., 2016; Ladányi, Lukács, et al., submitted;

Przybylski et al., 2013). It should be noted that, in all of these studies, enhanced performance was found after the regular rhythmic primes, and not after irregular or neutral sounds. These findings suggest that rhythm and language processing may be tightly linked and support the hypothesis that rhythm may be a useful tool in therapy for remediation of language disorders (Ladányi, Persici, Fiveash, Tillmann, & Gordon, submitted).

1.4 Neural entrainment as the possible underlying cause of dyslexia and DLD

The associations between rhythm and language and literacy skills (see Table 1) outlined in the previous sections have given rise to several theories, including the Dynamic Attending Theory (DAT: Jones, 2019; Jones & Boltz, 1989; Large & Jones, 1999), the Temporal Sampling Framework (Goswami, 2011), the Sound Envelope processing, synchronization, and entrainment to the Pulse (SEP: Fujii & Wan, 2014), the Precise Auditory Timing Hypothesis (PATH: Tierney & Kraus, 2014), and the Overlap, Precision, Emotion, Repetition, Attention hypothesis (OPERA: Patel, 2011). As highlighted in Fiveash, Bedoin, and Tillmann (submitted), the shared aspects among these theories are the emphasized roles of fine-grained auditory processing (without which signal processing would be impossible), sensorimotor coupling (the involvement of sensory and motor areas in both speech and music: Chen, Penhune, & Zatorre, 2008; Fujioka, Trainor, Large, & Ross, 2012; Glanz Iljina et al., 2018; Möttönen, Dutton, & Watkins, 2013), and neural oscillations.

As mentioned in previous sections, neuron firing resulting in oscillations entrains to and is affected by external auditory cues that are regular and therefore predictable. In music, such elements constitute, for instance, the beat; in language, an example is stress. According to the DAT (Jones, 2019; Jones & Boltz, 1989; Large & Jones, 1999), the entrainment process facilitates auditory input structuring by allocating increased attention to important time points along the auditory stimulus. The role of hiearchically organized oscillations in speech processing has also been emphasized (Ding et al., 2015; Giraud & Poeppel, 2012). Nested oscillations entrained at different timescales to the speech stream would facilitate matching between acoustic patterns and linguistic units and, by consequence, decoding (Ghitza, 2011).

In line with the concepts of sensorimotor coupling and neural oscillation, studies have shown that even when individuals do not move, both auditory and motor cortices are activated during speech/language and rhythm processing (Chen et al., 2008; Grahn & Brett, 2007; Harding, Sammler, Henry, Large, & Kotz, 2019). Based on these premises, Kotz, Schwartze, and Schmidt-Kassow (2009) proposed that the network that may underlie the processing of predictable sensory cues, such as beat in rhythm and stress in language, would be the pre-SMA-basal ganglia circuit, which involves frontal (dorsolateral prefrontal cortex), the supplementary motor area (SMA), and basal ganglia regions. Research with primates has shown that the basal ganglia is where oscillations in the beta frequency band originate from (Merchant & Bartolo, 2018). Beta oscillations appear to be important for rhythmic processing (Fujioka et al., 2012), are thought to reflect the coupling of the activity of distant brain regions (Bartolo, Prado, & Merchant, 2014), and to play a role in predictive sensory processing (Arnal & Giraud, 2012; Leventhal et al., 2012). The results found in primates suggest that similar functions may be carried out by the basal ganglia in humans. More specifically, the whole pre-SMA-basal ganglia circuit is thought to regulate the entrainment of the neural oscillations to auditory stimuli and to enhance predictions about future structural events (Kotz et al., 2009).

In linguistic processing the ability to predict incoming input may not only restrict to the rhythmic properties of speech (e.g., stress), but also involve more complex units. As already discussed, language is constituted by elements that are ordered following a hierarchical structure (Lashley, 1951), just like rhythm (see Figures 3 and 4); oscillations are also hierarchically organized, and they are entrained to speech at different timescales. According to the Metric Binding Hypothesis (Jones, 2019), it is the internal entrainment and 'binding' of multiple nested oscillations the mechanism that supports meter processing and that enhances temporal predictions. Given the similarities between language and rhythm, it is possible to hypothesize that the same process favors hierarchical processing in language. This idea is supported by studies showing entrainment of neural oscillations not only to the basic elements of the hierarchical structure such as beats and stress, but also to higher levels such as meter in music (Nozaradan, Peretz, Missal, & Mouraux, 2011) and syntactic structures in language (Ding et al., 2015), even though they are not physically present or cued in the stimulus (Tal et al., 2017).

Since efficient entrainment to rhythm and language is thought to enhance predictions, differences in efficiency of entrainment should correspond to differences in prediction skills. Advantages following from better neural entrainment may not only be found in *predictive timing* mechanisms (Friston, 2005), that is, in temporal predictions, but may also correspond to improved *predictive coding* (Friston, 2005), or the ability to predict *what* will happen next (Jones & Boltz, 1989; Stefan Koelsch, Vuust, & Friston, 2019). Since predictions are fundamental for efficient structural processing, improved prediction skills should correspond to better syntactic and rhythmic processing.

To conclude, as proposed in Fiveash et al. (submitted) and in Ladányi, Persici, et al. (submitted), fine-grained auditory processing, oscillatory brain networks, and sensorimotor coupling may form a network that supports the processing of both surface-level features and syntactic structures in both musical rhythm and language (see Figure 7). Deficits in rhythmic and language processing in populations with dyslexia and DLD may stem from deficits in timing mechanisms, as a result of impaired fine-grained auditory processing, impaired neural entrainment, and/or impaired sensorimotor coupling in the brain. As a consequence, individual differences in language performance should correspond, cognitively, to individual differences in efficiency of prediction-making mechanisms in rhythm, and neurally, to individual differences in entrainment. Chapter 2, 3, and 4 of this work will investigate the hypothesis that individual differences in prediction skills in music correspond to individual differences in prediction skills in language; Chapter 2 will focus on typically-developing children, Chapter 3 on children with DD, and Chapter 4 on children who have received early and continuous exposure to music. Chapter 5 will focus on the investigation of neural measures of rhythmic processing in typically developing children and on individual differences in rhythmic entrainment and grammar performance. Chapter 6 will investigate the same process in a population with grammatical impairments, that is, in children with DLD.

Table 1

List of studies investigating rhythm in dyslexia and developmental language disorder

		Age	**Task**	**Evidence for atypical rhythm?**
Dyslexia	Colling, Noble, & Goswami (2017)	9-10 years	- Beat perception - Tapping task	Yes
	Cutini, Szűcs, Mead, Huss, & Goswami (2016)	12 years	- Neural entrainment to amplitude-modulated noise	Yes (2 Hz)
	Frey, François, Chobert, Besson, & Ziegler (2018)	10 years	- Neural processing of speech sounds in silence, noise, and envelope conditions	Yes

Goswami et al. (2002)	11 years	- Beat detection in amplitude-modulated sounds	Yes
Goswami et al. (2010)	7-13 years	Amplitude envelope onset (rise time) discrimination	Yes
Goswami, Huss, Mead, Fosker, & Verney (2013)	8-14 years	- Beat perception	Yes
Goswami, Mead, Fosker, Huss, Barnes, & Leong (2013)	9 years	- Syllable stress discrimination	Yes
Goswami et al. (2016)		- Discrimination of amplitude rise time - Temporal modulations of nursery rhymes	- Yes - No but impaired acoustic learning during the experiment from low-pass filtered targets
Hämäläinen, Rupp, Soltész, Szücs, & Goswami (2012)	19-29 years	Amplitude-modulated white noise	Yes at 2 Hz
Huss, Verney, Fosker, Mead, & Goswami (2011)	8-13 years	Amplitude envelope rise time perception	Yes
Lee, Sie, Chen, & Cheng (2015)	9-12 years	rhythmic imitation	Yes
Leong & Goswami (2014)	< 40 years, mean: 22 yrs	rhythmic detection to identify amplitude-modulated nursery rhyme sentences	Yes
Leong, Hämäläinen, Soltész, & Goswami (2011)	17-41 years	Amplitude envelope onset (rise time) perception and syllable stress detection	Yes
Lizarazu et al. (2015)	children: 8 – 14 years; adults: 17-44 years	auditory neural synchronization	Yes
Molinaro, Lizarazu, Lallier, Bourguignon, & Carreiras (2016)	children: 8-14 years; adults: 22 – 37 years	neural synchronization to spoken sentences (MEG)	Yes
Muneaux, Ziegler, Truc, Thomson, & Goswami (2004)	11 years	Beat perception (slope)	Yes
Overy (2000)	6-7 years	- Rhythm discrimination - Tempo discrimination - Meter reproduction	Yes, especially in meter reproduction

	Overy, Nicolson, Fawcett, & Clarke (2003)	7-11 years	tests of timing skills (rhythm copying, rhythm discrimination, song rhythm, tempo copying, tempo discrimination, song beat)	Yes
	Pasquini, Corriveau, & Goswami (2007)	19-27 years	rise time perception and temporal order judgement	Yes
	Persici, Stucchi, & Arosio (2019)	9-11 years	Tapping	Yes
	Power, Colling, Mead, Barnes, & Goswami (2016)	12-14 years	Neural entrainment to speech syllables	Yes
	Soltész, Szücs, Leong, White, & Goswami (2013)	mean: 25.8 years	Neural entrainment to tones presented at 2 or 1.5 Hz	Yes
	Surányi et al. (2009)	8-9 years	Amplitude envelope rise time discrimination	Yes
	Thomson, Fryer, Maltby, & Goswami (2006)	18-31 years	- Basic auditory processing tasks (rise time, duration, and intensity discrimination) - Tempo discrimination - Tapping (uni- and bimanual)	- Yes - No - Yes but only in the inter-tap-interval variability
	Thomson & Goswami (2008)	10 years	- Rhythmic discrimination - paced and unpaced finger tapping	- No - Yes
	Wang, Huss, Hämäläinen, & Goswami (2012)	9-10 years	Basic auditory processing tasks (rise time, duration, and intensity discrimination)	Yes
	Zuk et al. (2017)	18-36 years	speech syllable discrimination	Yes
DLD	Bedoin et al. (2016)	9-11 years	Rhythm discrimination	Yes
	Corriveau & Goswami (2009)	7-11 years	Paced and unpaced tapping	Yes in the paced condition
	Corriveau, Pasquini, & Goswami (2007)	7-11 years	amplitude envelope rise time and sound duration perception	Yes
	Cumming, Wilson, Leong, Colling, & Goswami (2015)	6-12 years	- beat detection - tapping - speech/music task	Yes, especially in tapping
	Goswami et al. (2016)	9 years	- Discrimination of amplitude rise time	Yes

			Temporal modulations of nursery rhymes	
	Richards & Goswami (2015)	8-12 years	stress perception task	Yes
	Richards & Goswami (2019)	6-11 years	- stress pattern disruptions	Yes
	Sabisch, Hahne, Glass, von Suchodoletz, & Friederici (2009)	8-10 years	syntactic processing with prosody disruptions	Yes
	Sallat & Jentschke (2015)	4-5 years	rhythmic-melodic perception task	Yes
	Vuolo et al. (2017)	4-5 years	tapping and bimanual clapping	Yes but only in the bimanual clapping task
	Weinert (1992)	5-8 years	Rhythmic discrimination	Yes
	Wells & Peppé (2003)	8 years	Prosody perception	Yes
	Zelaznik & Goffman (2010)	6-8 years	tapping and drawing to a metronome	Yes (but no in the timing skill in the manual domain)
	Chang, Chow, Wieland, & McAuley (2016)	6-11 years	auditory rhythm discrimination task	Yes
	Falk, Müller, & Dalla Bella (2015)	8-16 years	finger tapping	Yes

Note. Adapted from Ladányi, Persici, et al. (submitted)

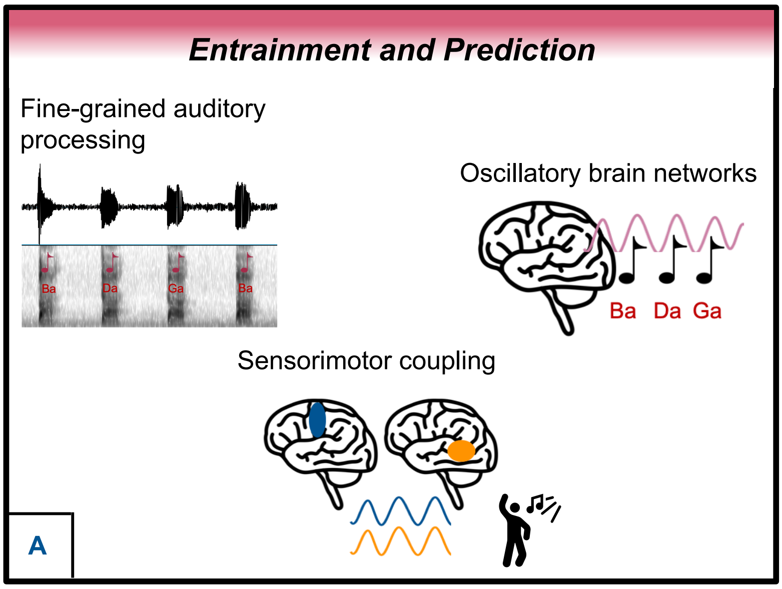


Figure 7. Shared mechanisms for musical rhythm and language processing. Adapted from Ladányi, Persici, et al. (submitted)

1.5 References

Ahissar, E., Nagarajan, S., Ahissar, M., Protopapas, A., Mahncke, H., & Merzenich, M. M.

(2001). Speech comprehension is correlated with temporal response patterns recorded from auditory cortex. *Proceedings of the National Academy of Sciences of the United States of America*, *98*(23), 13367–13372. https://doi.org/10.1073/pnas.201400998

Anvari, S. H., Trainor, L. J., Woodside, J., & Levy, B. A. (2002). Relations among musical skills, phonological processing, and early reading ability in preschool children. *Journal of Experimental Child Psychology*, *83*(2), 111–130. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/12408958

Arnal, L. H., & Giraud, A. L. (2012). Cortical oscillations and sensory predictions. *Trends in Cognitive Sciences*. https://doi.org/10.1016/j.tics.2012.05.003

Bartolo, R., Prado, L., & Merchant, H. (2014). Information processing in the primate basal ganglia during sensory-guided and internally driven rhythmic tapping. *Journal of Neuroscience*, *34*(11), 3910–3923. https://doi.org/10.1523/JNEUROSCI.2679-13.2014

Bedoin, N., Brisseau, L., Molinier, P., Roch, D., & Tillmann, B. (2016). Temporally regular musical primes facilitate subsequent syntax processing in children with Specific Language Impairment. *Frontiers in Neuroscience*, *10*(JUN), 1–11. https://doi.org/10.3389/fnins.2016.00245

Bidelman, G. M., Weiss, M. W., Moreno, S., & Alain, C. (2014). Coordinated plasticity in brainstem and auditory cortex contributes to enhanced categorical speech perception in musicians. *The European Journal of Neuroscience*, *40*(4), 2662–2673. https://doi.org/10.1111/ejn.12627

Bion, R. A. H., Benavides-Varela, S., & Nespor, M. (2011). Acoustic markers of prominence influence infants' and adults' segmentation of speech sequences. *Language and Speech*, *54*(1), 123–140. https://doi.org/10.1177/0023830910388018

Bishop-Liebler, P., Welch, G., Huss, M., Thomson, J. M., & Goswami, U. (2014). Auditory temporal processing skills in musicians with dyslexia. *Dyslexia*, *20*(3), 261–279. https://doi.org/10.1002/dys.1479

Bishop, D. V. M. (2017, November 1). Why is it so hard to reach agreement on terminology? The case of developmental language disorder (DLD). *International Journal of Language and Communication Disorders*. Wiley Blackwell. https://doi.org/10.1111/1460-6984.12335

Boll-Avetisyan, N., Bhatara, A., Unger, A., Nazzi, T., & Höhle, B. (2016). Effects of experience with L2 and music on rhythmic grouping by French listeners. *Bilingualism*, *19*(5), 971–986. https://doi.org/10.1017/S1366728915000425

Bolton, T. L. (1894). Rhythm. *American Journal of Psychology*, *6*, 145–238.

Bonacina, S., Cancer, A., Lanzi, P. L., Lorusso, M. L., & Antonietti, A. (2015). Improving reading skills in students with dyslexia: The efficacy of a sublexical training with rhythmic background. *Frontiers in Psychology*, *6*(OCT). https://doi.org/10.3389/fpsyg.2015.01510

Brod, G., & Opitz, B. (2012). Does it really matter? Separating the effects of musical training on syntax acquisition. *Frontiers in Psychology*, *3*(DEC). https://doi.org/10.3389/fpsyg.2012.00543

Cantiani, C., Lorusso, M. L., Perego, P., Molteni, M., & Guasti, M. T. (2015). Developmental Dyslexia With and Without Language Impairment: ERPs Reveal Qualitative Differences in Morphosyntactic Processing. *Developmental Neuropsychology*, *40*(5), 291–312. https://doi.org/10.1080/87565641.2015.1072536

Chen, J. L., Penhune, V. B., & Zatorre, R. J. (2008). Listening to musical rhythms recruits motor regions of the brain. *Cerebral Cortex (New York, N.Y. : 1991)*, *18*(12), 2844–2854. https://doi.org/10.1093/cercor/bhn042

Chern, A., Tillmann, B., Vaughan, C., & Gordon, R. L. (2018). New evidence of a rhythmic priming effect that enhances grammaticality judgments in children. *Journal of Experimental Child Psychology*, *173*, 371–379. https://doi.org/10.1016/j.jecp.2018.04.007

Clegg, J., Hollis, C., Mawhood, L., & Rutter, M. (2005). Developmental language disorders--a follow-up in later adult life. Cognitive, language and psychosocial outcomes. *Journal of Child Psychology and Psychiatry, and Allied Disciplines*, *46*(2), 128–149. https://doi.org/10.1111/j.1469-7610.2004.00342.x

Colling, L. J., Noble, H. L., & Goswami, U. (2017). Neural entrainment and sensorimotor synchronization to the beat in children with developmental dyslexia: An EEG study. *Frontiers in Neuroscience*, *11*(JUL). https://doi.org/10.3389/fnins.2017.00360

Corriveau, K. H., & Goswami, U. (2009). Rhythmic motor entrainment in children with speech and language impairments: Tapping to the beat. *Cortex*, *45*(1), 119–130. https://doi.org/10.1016/j.cortex.2007.09.008

Corriveau, K. H., Pasquini, E., & Goswami, U. (2007). Basic Auditory Processing Skills and Specific Language Impairment: A New Look at an Old Hypothesis. *Journal of Speech, Language, and Hearing Research*, *50*, 647–666. https://doi.org/10.1044/1092-4388(2007/046

Cumming, R., Wilson, A., Leong, V., Colling, L. J., & Goswami, U. (2015). Awareness of

Rhythm Patterns in Speech and Music in Children with Specific Language Impairments. *Frontiers in Human Neuroscience*, *9*, 672. https://doi.org/10.3389/fnhum.2015.00672

Cutini, S., Szucs, D., Mead, N., Huss, M., & Goswami, U. (2016). Atypical right hemisphere response to slow temporal modulations in children with developmental dyslexia. *NeuroImage*, *143*, 40–49. https://doi.org/10.1016/j.neuroimage.2016.08.012

Degé, F., & Schwarzer, G. (2011). The effect of a music program on phonological awareness in preschoolers. *Frontiers in Psychology*, *2*, 124. https://doi.org/10.3389/fpsyg.2011.00124

Dellatolas, G., Watier, L., Le Normand, M. T., Lubart, T., & Chevrie-Muller, C. (2009). Rhythm reproduction in kindergarten, reading performance at second grade, and developmental dyslexia theories. *Archives of Clinical Neuropsychology*, *24*(6), 555–563. https://doi.org/10.1093/arclin/acp044

Di Liberto, G. M., O'Sullivan, J. A., & Lalor, E. C. (2015). Low-Frequency Cortical Entrainment to Speech Reflects Phoneme-Level Processing. *Current Biology : CB*, *25*(19), 2457–2465. https://doi.org/10.1016/j.cub.2015.08.030

Ding, N., Melloni, L., Yang, A., Wang, Y., Zhang, W., & Poeppel, D. (2017). Characterizing Neural Entrainment to Hierarchical Linguistic Units using Electroencephalography (EEG). *Frontiers in Human Neuroscience*, *11*, 481. https://doi.org/10.3389/fnhum.2017.00481

Ding, N., Melloni, L., Zhang, H., Tian, X., & Poeppel, D. (2015). Cortical tracking of hierarchical linguistic structures in connected speech. *Nature Neuroscience*, *19*(1), 158–164. https://doi.org/10.1038/nn.4186

Douglas, S., & Willatts, P. (1994). The relationship between musical ability and literacy skills. *Journal of Research in Reading*, *17*(2), 99–107. https://doi.org/10.1111/j.1467-9817.1994.tb00057.x

Essens, P. J., & Povel, D. J. (1985). Metrical and nonmetrical representations of temporal patterns. *Perception & Psychophysics*, *37*(1), 1–7. https://doi.org/10.3758/BF03207132

Fisher, J., Plante, E., Vance, R., Gerken, L. A., & Glattke, T. J. (2007). Do children and adults with language impairment recognize prosodic cues? *Journal of Speech, Language, and Hearing Research*, *50*(3), 746–758. https://doi.org/10.1044/1092-4388(2007/052)

Fitch, W. T. (2013). Rhythmic cognition in humans and animals: distinguishing meter and pulse perception. *Frontiers in Systems Neuroscience*, *7*. https://doi.org/10.3389/fnsys.2013.00068

Fitch, W. T. (2017). Empirical approaches to the study of language evolution. https://doi.org/10.3758/s13423-017-1236-5

Fiveash, A., Bedoin, N., & Tillmann, B. (submitted). Rhythmic processing of music and language: A review and implications for developmental disorders.

Flaugnacco, E., Lopez, L., Terribili, C., Montico, M., Zoia, S., & Schön, D. (2015). Music Training Increases Phonological Awareness and Reading Skills in Developmental Dyslexia: A Randomized Control Trial. *PLOS ONE*, *10*(9), e0138715. https://doi.org/10.1371/journal.pone.0138715

Flaugnacco, E., Lopez, L., Terribili, C., Zoia, S., Buda, S., Tilli, S., … Schön, D. (2014). Rhythm perception and production predict reading abilities in developmental dyslexia. *Frontiers in Human Neuroscience*, *8*, 392. https://doi.org/10.3389/fnhum.2014.00392

Forgeard, M., Winner, E., Norton, A., & Schlaug, G. (2008). Practicing a Musical Instrument in Childhood is Associated with Enhanced Verbal Ability and Nonverbal Reasoning. *PLoS ONE*, *3*(10), e3566. https://doi.org/10.1371/journal.pone.0003566

François, C., Chobert, J., Besson, M., & Schön, D. (2013). Music training for the development of speech segmentation. *Cerebral Cortex*, *23*(9), 2038–2043. https://doi.org/10.1093/cercor/bhs180

François, C., Jaillet, F., Takerkar, S., & Schön, D. (2014). Faster sound stream segmentation in musicians than in nonmusicians. *PLoS ONE*, *9*(7). https://doi.org/10.1371/journal.pone.0101340

Frey, A., François, C., Chobert, J., Besson, M., & Ziegler, J. C. (2019). Behavioral and electrophysiological investigation of speech perception deficits in silence, noise and envelope conditions in developmental dyslexia. *Neuropsychologia*, *130*, 3–12. https://doi.org/10.1016/J.NEUROPSYCHOLOGIA.2018.07.033

Friston, K. (2005). A theory of cortical responses. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *360*(1456), 815–836. https://doi.org/10.1098/rstb.2005.1622

Fujii, S., & Wan, C. Y. (2014, October 13). The role of rhythm in speech and language rehabilitation: The SEP hypothesis. *Frontiers in Human Neuroscience*. Frontiers Media S. A. https://doi.org/10.3389/fnhum.2014.00777

Fujioka, T., Trainor, L. J., Large, E. W., & Ross, B. (2012). Internalized timing of isochronous sounds is represented in neuromagnetic β oscillations. *The Journal of*

Neuroscience : The Official Journal of the Society for Neuroscience, *32*(5), 1791–1802. https://doi.org/10.1523/JNEUROSCI.4107-11.2012

Gaser, C., & Schlaug, G. (2003). *Brain Structures Differ between Musicians and Non-Musicians*. Retrieved from https://www.jneurosci.org/content/jneuro/23/27/9240.full.pdf

Ghitza, O. (2011). Linking speech perception and neurophysiology: Speech decoding guided by cascaded oscillators locked to the input rhythm. *Frontiers in Psychology*, *2*(JUN). https://doi.org/10.3389/fpsyg.2011.00130

Ghitza, O. (2012). On the role of theta-driven syllabic parsing in decoding speech: intelligibility of speech with a manipulated modulation spectrum. *Frontiers in Psychology*, *3*, 238. https://doi.org/10.3389/fpsyg.2012.00238

Giraud, A.-L., & Poeppel, D. (2012). Cortical oscillations and speech processing: emerging computational principles and operations. *Nature Neuroscience*, *15*(4), 511–517. https://doi.org/10.1038/nn.3063

Glanz Iljina, O., Derix, J., Kaur, R., Schulze-Bonhage, A., Auer, P., Aertsen, A., & Ball, T. (2018). Real-life speech production and perception have a shared premotor-cortical substrate. *Scientific Reports*, *8*(1), 8898. https://doi.org/10.1038/s41598-018-26801-x

Gordon, R. L., Shivers, C. M., Wieland, E. A., Kotz, S. A., Yoder, P. J., & Devin Mcauley, J. (2015). Musical rhythm discrimination explains individual differences in grammar skills in children. *Developmental Science*, *18*(4), 635–644. https://doi.org/10.1111/desc.12230

Goswami, U. (2011). A temporal sampling framework for developmental dyslexia. *Trends in Cognitive Sciences*, *15*(1), 3–10. https://doi.org/10.1016/J.TICS.2010.10.001

Goswami, U., Cumming, R., Chait, M., Huss, M., Mead, N., Wilson, A. M., … Fosker, T. (2016). Perception of filtered speech by children with developmental dyslexia and children with specific language impairments. *Frontiers in Psychology*, *7*(MAY). https://doi.org/10.3389/fpsyg.2016.00791

Goswami, U., Huss, M., Mead, N., Fosker, T., & Verney, J. P. (2013). Perception of patterns of musical beat distribution in phonological developmental dyslexia: Significant longitudinal relations with word reading and reading comprehension. *Cortex*, *49*(5), 1363–1376. https://doi.org/10.1016/J.CORTEX.2012.05.005

Goswami, U., Mead, N., Fosker, T., Huss, M., Barnes, L., & Leong, V. (2013). Impaired perception of syllable stress in children with dyslexia: A longitudinal study. *Journal of Memory and Language*, *69*(1), 1–17. https://doi.org/10.1016/J.JML.2013.03.001

Goswami, U., Thomson, J., Richardson, U., Stainthorp, R., Hughes, D., Rosen, S., & Scott, S. K. (2002). Amplitude envelope onsets and developmental dyslexia: A new hypothesis. *Proceedings of the National Academy of Sciences*, *99*(16), 10911–10916. https://doi.org/10.1073/pnas.122368599

Grahn, J. A., & Brett, M. (2007). Rythm in Motor Areas of the Brain. *Journal of Cognitive Neuroscience*, *19*(5), 893–906.

Grube, M., Kumar, S., Cooper, F. E., Turton, S., & Griffiths, T. D. (2012). Auditory sequence analysis and phonological skill. *Proceedings of the Royal Society B: Biological Sciences*, *279*(1746), 4496–4504. https://doi.org/10.1098/rspb.2012.1817

Habib, M., Lardy, C., Desiles, T., Commeiras, C., Chobert, J., & Besson, M. (2016). Music and dyslexia: A new musical training method to improve reading and related disorders. *Frontiers in Psychology*, *7*(JAN). https://doi.org/10.3389/fpsyg.2016.00026

Habibi, A., Cahn, B. R., Damasio, A., & Damasio, H. (2016). Neural correlates of accelerated auditory processing in children engaged in music training. *Developmental Cognitive Neuroscience*, *21*. https://doi.org/10.1016/j.dcn.2016.04.003

Hämäläinen, J. A., Rupp, A., Soltész, F., Szücs, D., & Goswami, U. (2012). Reduced phase locking to slow amplitude modulation in adults with dyslexia : An MEG study. *NeuroImage*, *59*(3), 2952–2961. https://doi.org/10.1016/j.neuroimage.2011.09.075

Harding, E. E., Sammler, D., Henry, M. J., Large, E. W., & Kotz, S. A. (2019). Cortical tracking of rhythm in music and speech. *NeuroImage*, *185*(October 2018), 96–101. https://doi.org/10.1016/j.neuroimage.2018.10.037

Henry, M. J., & Obleser, J. (2012). Frequency modulation entrains slow neural oscillations and optimizes human listening behavior. *Proceedings of the National Academy of Sciences of the United States of America*, *109*(49), 20095–20100. https://doi.org/10.1073/pnas.1213390109

Herdener, M., Humbel, T., Esposito, F., Habermeyer, B., Cattapan-Ludewig, K., & Seifritz, E. (2014). Jazz Drummers Recruit Language-Specific Areas for the Processing of Rhythmic Structure. *Cerebral Cortex*, *24*(3), 836–843. https://doi.org/10.1093/cercor/bhs367

Hoch, L., Poulin-Charronnat, B., & Tillmann, B. (2011). The influence of task-irrelevant music on language processing: Syntactic and semantic structures. *Frontiers in Psychology*, *2*(JUN). https://doi.org/10.3389/fpsyg.2011.00112

Holliman, A. J., Wood, C., & Sheehy, K. (2010). The contribution of sensitivity to speech rhythm and non-speech rhythm to early reading development. *Educational Psychology*, *30*(3), 247–267. https://doi.org/10.1080/01443410903560922

Huss, M., Verney, J. P., Fosker, T., Mead, N., & Goswami, U. (2011). Music, rhythm, rise time perception and developmental dyslexia: Perception of musical meter predicts reading and phonology. *Cortex*, *47*(6), 674–689. https://doi.org/10.1016/J.CORTEX.2010.07.010

Iversen, J. R., Repp, B. H., & Patel, A. D. (2009). Top-down control of rhythm perception modulates early auditory responses. *Annals of the New York Academy of Sciences*, *1169*, 58–73. https://doi.org/10.1111/j.1749-6632.2009.04579.x

Jentschke, S., & Koelsch, S. (2009). Musical training modulates the development of syntax processing in children. *NeuroImage*, *47*(2), 735–744. https://doi.org/10.1016/j.neuroimage.2009.04.090

Jones, M. R. (2019). *Time will tell: A theory of Dynamic Attending*. New York: Oxford University Press.

Jones, M. R., & Boltz, M. (1989). Dynamic Attending and Responses to Time. *Psychological Review*, *96*(3), 459–491. https://doi.org/10.1037/0033-295X.96.3.459

Kempe, V., Thoresen, J. C., Kirk, N. W., Schaeffler, F., & Brooks, P. J. (2012). Individual Differences in the Discrimination of Novel Speech Sounds: Effects of Sex, Temporal Processing, Musical and Cognitive Abilities. *PLoS ONE*, *7*(11). https://doi.org/10.1371/journal.pone.0048623

Klem, M., Melby-Lervåg, M., Hagtvet, B., Lyster, S. A. H., Gustafsson, J. E., & Hulme, C. (2015). Sentence repetition is a measure of children's language skills rather than working memory limitations. *Developmental Science*, *18*(1), 146–154. https://doi.org/10.1111/desc.12202

Koelsch, S, Schröger, E., & Tervaniemi, M. (1999). Superior pre-attentive auditory processing in musicians. *Neuroreport*, *10*(6), 1309–1313. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/10363945

Koelsch, Stefan, Gunter, T. C., Wittfoth, M., & Sammler, D. (2005). Interaction between Syntax Processing in Language and in Music: An ERP Study. *Journal of Cognitive Neuroscience*, *17*(10), 1565–1577. https://doi.org/10.1162/089892905774597290

Koelsch, Stefan, Vuust, P., & Friston, K. (2019). Predictive Processes and the Peculiar Case of Music. *Trends in Cognitive Sciences*, *23*(1), 63–77. https://doi.org/10.1016/j.tics.2018.10.006

Kotz, S. A., Ravignani, A., & Fitch, W. T. (2018). Special Issue: Time in the Brain The Evolution of Rhythm Processing. *Trends in Cognitive Sciences*, *22*(10), 896–910.

https://doi.org/10.1016/j.tics.2018.08.002

Kotz, S. A., Schwartze, M., & Schmidt-Kassow, M. (2009). Non-motor basal ganglia functions: A review and proposal for a model of sensory predictability in auditory language perception. *Cortex*, *45*(8), 982–990. https://doi.org/10.1016/j.cortex.2009.02.010

Kunert, R., Willems, R. M., & Hagoort, P. (2016). Language influences music harmony perception: Effects of shared syntactic integration resources beyond attention. *Royal Society Open Science*, *3*(2). https://doi.org/10.1098/rsos.150685

Ladányi, E., Lukács, Á., & Gervain, J. (submitted). Rhythmic priming in children with and without Specific Language Impairment.

Ladányi, E., Persici, V., Fiveash, A., Tillmann, B., & Gordon, R. L. (submitted). Is atypical rhythm a risk factor for speech and language disorders?

Large, E. W., & Jones, M. R. (1999). The dynamics of attending: How people track time-varying events. *Psychological Review*. https://doi.org/10.1037/0033-295X.106.1.119

Lashley, K. S. (1951). The problem of serial order in behavior. *Cerebral Mechanisms in Behavior: The Hixon Symposium*, (7), 112–135. https://doi.org/10.1016/j.humov.2007.04.001

Lee, H.-Y., Sie, Y.-S., Chen, S.-C., & Cheng, M.-C. (2015). The Music Perception Performance of Children with and without Dyslexia in Taiwan. *Psychological Reports*, *116*(1), 13–22. https://doi.org/10.2466/15.28.PR0.116k15w8

Leonard, L. B. (1998). *Children with Specific Language Impairment*. Cambridge, MA: MIT Press.

Leong, V., & Goswami, U. (2014). Impaired extraction of speech rhythm from temporal modulation patterns in speech in developmental dyslexia. *Frontiers in Human Neuroscience*, *8*, 96. https://doi.org/10.3389/fnhum.2014.00096

Leong, V., Hämäläinen, J., Soltész, F., & Goswami, U. (2011). Rise time perception and detection of syllable stress in adults with developmental dyslexia. https://doi.org/10.1016/j.jml.2010.09.003

Lerdahl, F., & Jackendoff, R. (1983). *A generative theory of tonal music*. MIT Press.

Leventhal, D. K., Gage, G. J., Schmidt, R., Pettibone, J. R., Case, A. C., & Berke, J. D. (2012). Basal ganglia beta oscillations accompany cue utilization. *Neuron*, *73*(3), 523–536. https://doi.org/10.1016/j.neuron.2011.11.032

Lindgren, S. D., De Renzi, E., & Richman, L. C. (1985). Cross-national comparisons of developmental dyslexia in Italy and the United States. *Child Development*, *56*(6), 1404–

1417. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/3878269

Linnavalli, T., Putkinen, V., Lipsanen, J., Huotilainen, M., & Tervaniemi, M. (2018). Music playschool enhances children’s linguistic skills. *Scientific Reports*, *8*(1), 8767. https://doi.org/10.1038/s41598-018-27126-5

Lizarazu, M., Lallier, M., Molinaro, N., Bourguignon, M., Paz-Alonso, P. M., Lerma-Usabiaga, G., & Carreiras, M. (2015). Developmental evaluation of atypical auditory sampling in dyslexia: Functional and structural evidence. *Human Brain Mapping*, *36*(12), 4986–5002. https://doi.org/10.1002/hbm.22986

Luo, H., & Poeppel, D. (2007). Phase Patterns of Neuronal Responses Reliably Discriminate Speech in Human Auditory Cortex. *Neuron*, *54*(6), 1001–1010. https://doi.org/10.1016/j.neuron.2007.06.004

Luo, H., Wang, Y., Poeppel, D., Simon, J. Z., & Ding, N. (2006). Concurrent Encoding of Frequency and Amplitude Modulation in Human Auditory Cortex : MEG Evidence Concurrent Encoding of Frequency and Amplitude Modulation in Human Auditory Cortex : MEG Evidence. *Journal of Neurophysiology*, *96*(5), 2712–2723. https://doi.org/10.1152/jn.01256.2005

Marie, C., Magne, C., & Besson, M. (2011). Musicians and the metric structure of words. *Journal of Cognitive Neuroscience*, *23*(2), 294–305. https://doi.org/10.1162/jocn.2010.21413

Marshall, C. R., Harcourtbrown, S., Ramus, F., & Van Der Lely, H. K. J. (2009). The link between prosody and language skills in children with specific language impairment SLI andor dyslexia. *International Journal of Language and Communication Disorders*, *44*(4), 466–488. https://doi.org/10.1080/13682820802591643

Merchant, H., & Bartolo, R. (2018, March 1). Primate beta oscillations and rhythmic behaviors. *Journal of Neural Transmission*. Springer-Verlag Wien. https://doi.org/10.1007/s00702-017-1716-9

Metsala, J. L., & Walley, A. C. (1998). Spoken vocabulary growth and the segmental restructuring of lexical representations: Precursors to phonemic awareness and early reading ability. In J. L. Metsala & L. C. Ehri (Eds.), *Word recognition in beginning literacy* (pp. 89–120). Mahwah, NJ, US: Lawrence Erlbaum Associates, Inc.

Meyer, L. (2018, October 1). The neural oscillations of speech processing and language comprehension: state of the art and emerging mechanisms. *European Journal of Neuroscience*. Blackwell Publishing Ltd. https://doi.org/10.1111/ejn.13748

Molinaro, N., Lizarazu, M., Lallier, M., Bourguignon, M., & Carreiras, M. (2016). Out-of-synchrony speech entrainment in developmental dyslexia. *Human Brain Mapping*, *37*(8), 2767–2783. https://doi.org/10.1002/hbm.23206

Moreno, S., Marques, C., Santos, A., Santos, M., Castro, S. L., & Besson, M. (2009). Musical Training Influences Linguistic Abilities in 8-Year-Old Children: More Evidence for Brain Plasticity. *Cerebral Cortex*, *19*(3), 712–723. https://doi.org/10.1093/cercor/bhn120

Moritz, C., Yampolsky, S., Papadelis, G., Thomson, J. M., & Wolf, M. (2013). Links between early rhythm skills, musical training, and phonological awareness. *Reading and Writing*, *26*(5), 739–769. https://doi.org/10.1007/s11145-012-9389-0

Möttönen, R., Dutton, R., & Watkins, K. E. (2013). Auditory-motor processing of speech sounds. *Cerebral Cortex (New York, N.Y. : 1991)*, *23*(5), 1190–1197. https://doi.org/10.1093/cercor/bhs110

Muneaux, M., Ziegler, J. C., Truc, C., Thomson, J., & Goswami, U. (2004). Deficits in beat perception and dyslexia: evidence from French. *Neuroreport*, *15*(8), 1255–1259. https://doi.org/10.1097/01.wnr.0000127459.31232.c4

Musacchia, G., Sams, M., Skoe, E., & Kraus, N. (2007). Musicians have enhanced subcortical auditory and audiovisual processing of speech and music. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(40), 15894–15898. https://doi.org/10.1073/pnas.0701498104

Myers, B. R., Lense, M. D., & Gordon, R. L. (2019). Pushing the Envelope : Developments in Neural Entrainment to Speech and the Biological Underpinnings of Prosody Perception. *Brain Sciences*, *9*, 70. https://doi.org/10.3390/brainsci9030070

Newman, R., Ratner, N. B., Jusczyk, A. M., Jusczyk, P. W., & Dow, K. A. (2006). Infants' early ability to segment the conversational speech signal predicts later language development: a retrospective analysis. *Developmental Psychology*, *42*(4), 643–655. https://doi.org/10.1037/0012-1649.42.4.643

Nozaradan, S., Peretz, I., Missal, M., & Mouraux, A. (2011). Tagging the neuronal entrainment to beat and meter. *Journal of Neuroscience*, *31*(28), 10234–10240. https://doi.org/10.1523/JNEUROSCI.0411-11.2011

Overy, K. (2003). Dyslexia and music: From timing deficits to musical intervention. *Annals of the New York Academy of Sciences*, *999*, 497–505. https://doi.org/10.1196/annals.1284.060

Overy, K., Nicolson, R. I., Fawcett, A. J., & Clarke, E. F. (2003). Dyslexia and music: Measuring musical timing skills. *Dyslexia*, *9*(1), 18–36.

https://doi.org/10.1002/dys.233

Ozernov-Palchik, O., Wolf, M., & Patel, A. D. (2018). Relationships between early literacy and nonlinguistic rhythmic processes in kindergarteners. *Journal of Experimental Child Psychology*, *167*, 354–368. https://doi.org/10.1016/j.jecp.2017.11.009

Pasquini, E. S., Corriveau, K. H., & Goswami, U. (2007). Auditory Processing of Amplitude Envelope Rise Time in Adults Diagnosed With Developmental Dyslexia. *Scientific Studies of Reading*, *11*(3), 259–286. https://doi.org/10.1080/10888430701344280

Patel, A. D. (2008). *Music, Language, and the Brain*.

Patel, A. D. (2011). Why would musical training benefit the neural encoding of speech? The OPERA hypothesis. *Frontiers in Psychology*, *2*(JUN). https://doi.org/10.3389/fpsyg.2011.00142

Patscheke, H., Degé, F., & Schwarzer, G. (2019). The effects of training in rhythm and pitch on phonological awareness in four- to six-year-old children. *Psychology of Music*, *47*(3), 376–391. https://doi.org/10.1177/0305735618756763

Peelle, J. E., & Davis, M. H. (2012). Neural oscillations carry speech rhythm through to comprehension. *Frontiers in Psychology*. https://doi.org/10.3389/fpsyg.2012.00320

Penny, W. D., Kiebel, S. J., Kilner, J. M., & Rugg, M. D. (2002, August 1). Event-related brain dynamics. *Trends in Neurosciences*. Elsevier Ltd. https://doi.org/10.1016/S0166-2236(02)02202-6

Power, A. J., Colling, L. J., Mead, N., Barnes, L., & Goswami, U. (2016). Neural encoding of the speech envelope by children with developmental dyslexia. *Brain and Language*, *160*. https://doi.org/10.1016/j.bandl.2016.06.006

Przybylski, L., Bedoin, N., Krifi-Papoz, S., Herbillon, V., Roch, D., Léculier, L., … Tillmann, B. (2013). Rhythmic auditory stimulation influences syntactic processing in children with developmental language disorders. *Neuropsychology*, *27*(1), 121–131. https://doi.org/10.1037/a0031277

Rautenberg, I. (2015). The effects of musical training on the decoding skills of German-speaking primary school children. *Journal of Research in Reading*, *38*(1), 1–17. https://doi.org/10.1111/jrir.12010

Richards, S., & Goswami, U. (2015). Auditory processing in specific language impairment (SLI): Relations with the perception of lexical and phrasal stress. *Journal of Speech, Language, and Hearing Research*, *58*(4), 1292–1305. https://doi.org/10.1044/2015_JSLHR-L-13-0306

Richards, S., & Goswami, U. (2019). Impaired Recognition of Metrical and Syntactic

Boundaries in Children with Developmental Language Disorders. *Brain Sciences*, *9*(2), 33. https://doi.org/10.3390/brainsci9020033

Richardson, U., Thomson, J. M., Scott, S. K., & Goswami, U. (2004). Auditory Processing Skills and Phonological Representation in Dyslexic Children. *Dyslexia*, *10*, 215–233. https://doi.org/10.1002/dys.276

Rispens, J., & Been, P. (2007). Subject–verb agreement and phonological processing in developmental dyslexia and specific language impairment (SLI): a closer look. *International Journal of Language & Communication Disorders*, *42*(3), 293–305. https://doi.org/10.1080/13682820600988777

Sabisch, B., Hahne, A., Glass, E., Von Suchodoletz, W., & Friederici, A. D. (2006). Auditory language comprehension in children with developmental dyslexia: Evidence from event-related brain potentials. *Journal of Cognitive Neuroscience*, *18*(10), 1676–1695. https://doi.org/10.1162/jocn.2006.18.10.1676

Sabisch, Beate, Hahne, C. A., Glass, E., von Suchodoletz, W., & Friederici, A. D. (2009). Children with specific language impairment: The role of prosodic processes in explaining difficulties in processing syntactic information. *Brain Research*, *1261*, 37–44. https://doi.org/10.1016/J.BRAINRES.2009.01.012

Sallat, S., & Jentschke, S. (2015). Music Perception Influences Language Acquisition: Melodic and Rhythmic-Melodic Perception in Children with Specific Language Impairment. *Behavioural Neurology*, *2015*, 1–10. https://doi.org/10.1155/2015/606470

Sares, A. G., Foster, N. E. V., Allen, K., & Hyde, K. L. (2018). Pitch and time processing in speech and tones: The effects of musical training and attention. *Journal of Speech, Language, and Hearing Research*, *61*(3), 496–509. https://doi.org/10.1044/2017_JSLHR-S-17-0207

Schlaug, G., Lutz, J., Huang, Y., Staigeri, J. F., & Steinmetz1, H. (1995). Increased corpus callosum size in musicians. *Neuropsychologia*, *33*(8), 1047–1055. Retrieved from http://www.brainmusic.org/EducationalActivitiesFolder/Schlaug_CCmus1995.pdf

Schneider, P., Scherg, M., & Dosch, H. G. (2002). Morphology of Heschl's gyrus reflects enhanced activation in the auditory cortex of musicians. *Nature Neuroscience*, *5*(7), 688–694. https://doi.org/10.1038/nn871

Schön, D., & Tillmann, B. (2015). Short-and long-term rhythmic interventions: perspectives for language rehabilitation. *Annals of the New York Academy of Sciences*, *1337*, 32–39. https://doi.org/10.1111/nyas.12635

Slevc, L. R., Rosenberg, J. C., & Patel, A. D. (2009). Making psycholinguistics musical:

Self-paced reading time evidence for shared processing of linguistic and musical syntax. *Psychonomic Bulletin & Review*, *16*(2), 374–381. https://doi.org/10.3758/16.2.374

Soltész, F., Szűcs, D., Leong, V., White, S., & Goswami, U. (2013). Differential Entrainment of Neuroelectric Delta Oscillations in Developmental Dyslexia. *PLoS ONE*, *8*(10), e76608. https://doi.org/10.1371/journal.pone.0076608

Steinbeis, N., & Koelsch, S. (2008). Shared neural resources between music and language indicate semantic processing of musical tension-resolution patterns. *Cerebral Cortex (New York, N.Y. : 1991)*, *18*(5), 1169–1178. https://doi.org/10.1093/cercor/bhm149

Strait, D. L., Hornickel, J., & Kraus, N. (2011). Subcortical processing of speech regularities underlies reading and music aptitude in children. *Behavioral and Brain Functions*, *7*(1), 44. https://doi.org/10.1186/1744-9081-7-44

Strait, D. L., O'Connell, S., Parbery-Clark, A., & Kraus, N. (2014). Musicians' enhanced neural differentiation of speech sounds arises early in life: Developmental evidence from ages 3 to 30. *Cerebral Cortex*, *24*(9), 2512–2521. https://doi.org/10.1093/cercor/bht103

Sun, L., Liu, F., Zhou, L., & Jiang, C. (2018). Musical training modulates the early but not the late stage of rhythmic syntactic processing. *Psychophysiology*, *55*(2), 1–10. https://doi.org/10.1111/psyp.12983

Surányi, Z., Csépe, V., Richardson, U., Thomson, J. M., Honbolygó, F., & Goswami, U. (2009). Sensitivity to rhythmic parameters in dyslexic children: A comparison of Hungarian and English. *Reading and Writing*, *22*(1), 41–56. https://doi.org/10.1007/s11145-007-9102-x

Tal, I., Large, E. W., Rabinovitch, E., Wei, Y., Schroeder, C. E., Poeppel, D., & Zion Golumbic, E. (2017). Neural Entrainment to the Beat: The "Missing-Pulse" Phenomenon. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *37*(26), 6331–6341. https://doi.org/10.1523/JNEUROSCI.2500-16.2017

Tallal, P., & Gaab, N. (2006). Dynamic auditory processing, musical experience and language development. *Trends in Neurosciences*, *29*(7), 382–390. https://doi.org/10.1016/j.tins.2006.06.003

Taub, G. E., & Lazarus, P. J. (2012). The effects of training in timing and rhythm on reading achievement. *Contemporary Issues in Education Research*, *5*(4), 343–350. https://doi.org/https://doi.org/10.19030/cier.v5i4.7598

Thomson, J. M., Fryer, B., Maltby, J., & Goswami, U. (2006). Auditory and motor rhythm awareness in adults with dyslexia. *Journal of Research in Reading*, *29*(3), 334–348. https://doi.org/10.1111/j.1467-9817.2006.00312.x

Thomson, J. M., & Goswami, U. (2008). Rhythmic processing in children with developmental dyslexia: Auditory and motor rhythms link to reading and spelling. *Journal of Physiology-Paris*, *102*, 120–129. https://doi.org/10.1016/j.jphysparis.2008.03.007

Thomson, J. M., Leong, V., & Goswami, U. (2013). Auditory processing interventions and developmental dyslexia: A comparison of phonemic and rhythmic approaches. *Reading and Writing*, *26*(2), 139–161. https://doi.org/10.1007/s11145-012-9359-6

Tierney, A., & Kraus, N. (2013). *Music training for the development of reading skills*. *Progress in Brain Research* (1st ed., Vol. 207). Elsevier B.V. https://doi.org/10.1016/B978-0-444-63327-9.00008-4

Tierney, A., & Kraus, N. (2014). Auditory-motor entrainment and phonological skills: Precise auditory timing hypothesis (PATH). *Frontiers in Human Neuroscience*, *8*(NOV). https://doi.org/10.3389/fnhum.2014.00949

Vuolo, J., Goffman, L., & Zelaznik, H. N. (2017). Deficits in Coordinative Bimanual Timing Precision in Children With Specific Language Impairment. https://doi.org/10.1044/2016_JSLHR-L-15-0100

Wang, H. L. S., Huss, M., Hämäläinen, J. A., & Goswami, U. (2012). Basic auditory processing and developmental dyslexia in Chinese. *Reading and Writing*, *25*(2), 509–536. https://doi.org/10.1007/s11145-010-9284-5

Weinert, S. (1992). Deficits in acquiring language structure: The importance of using prosodic cues. *Applied Cognitive Psychology*, *6*(6), 545–571. https://doi.org/10.1002/acp.2350060607

Wells, B., & Peppé, S. (2003). Intonation abilities of children with speech and language impairments. *Journal of Speech, Language, and Hearing Research*, *46*(1), 5–20. https://doi.org/10.1044/1092-4388(2003/001)

Woodruff Carr, K., White-Schwoch, T., Tierney, A. T., Strait, D. L., & Kraus, N. (2014). Beat synchronization predicts neural speech encoding and reading readiness in preschoolers. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(40), 14559–14564. https://doi.org/10.1073/pnas.1406219111

Zelaznik, H. N., Vaughn, A. J., Green, J. T., Smith, A. L., Hoza, B., & Linnea, K. (2012). Motor timing deficits in children with Attention-Deficit/Hyperactivity disorder. *Human*

Movement Science, *31*(1), 255–265. https://doi.org/10.1016/J.HUMOV.2011.05.003

Zhao, T. C., & Kuhl, P. K. (2016). Musical intervention enhances infants' neural processing of temporal structure in music and speech. *Proceedings of the National Academy of Sciences of the United States of America*, *113*(19), 5212–5217. https://doi.org/10.1073/pnas.1603984113

Ziegler, J. C., & Goswami, U. (2005). Reading Acquisition, Developmental Dyslexia, and Skilled Reading Across Languages: A Psycholinguistic Grain Size Theory. *Psychological Bulletin*, *131*(1), 3–29. https://doi.org/10.1037/0033-2909.131.1.3

Zuk, J., Bishop-Liebler, P., Ozernov-Palchik, O., Moore, E., Overy, K., Welch, G., & Gaab, N. (2017). Revisiting the "Enigma" of Musicians With Dyslexia: Auditory Sequencing and Speech Abilities. *Journal of Experimental Psychology: General*, *146*(4), 495–511. https://doi.org/10.1037/xge0000281

Zuk, J., Ozernov-Palchik, O., Kim, H., Lakshminarayanan, K., Gabrieli, J. D. E., Tallal, P., & Gaab, N. (2013). Enhanced syllable discrimination thresholds in musicians. *PLoS ONE*, *8*(12), 1–8. https://doi.org/10.1371/journal.pone.0080546

Chapter 2

Rhythmic and morphosyntactic predictions in children with typical language development

2.1 Introduction

As mentioned in Chapter 1, associations between individual differences in rhythm and language skills, as well as between rhythm and literacy, are consistently found in the literature. Furthermore, short- (e.g., Chern, Tillmann, Vaughan, & Gordon, 2018), mid- (e.g., Degé & Schwarzer, 2011) and long-term (Musacchia, Sams, Skoe, & Kraus, 2007) exposure to rhythm and music seems to positively affect language and reading performance. As proposed in the Atypical Rhythm Risk Hypothesis (Ladányi, Persici, Fiveash, Tillmann, & Gordon, submitted), deficits in rhythm and timing may lead to atypical speech and language development. This idea is supported by the finding that musical rhythm and speech/language processing activate brain networks that are thought to regulate the synchronization of neural oscillations with auditory stimuli, a process that is thought to be important for efficient language processing (Kotz, Schwartze, & Schmidt-Kassow, 2009).

Relevantly to grammar, neural oscillations are not only entrained to the basic levels of beats and syllables, but also to higher-level structures such as syntactic phrases in language (Ding, Melloni, Zhang, Tian, & Poeppel, 2015). As discussed in Ladányi et al., (submitted), higher-level structure processing in language might be rendered possible by the same binding mechanism that is assumed to support efficient meter processing, that is the entrainment of multiple nested neural oscillators (cf. Metric Binding Hypothesis, Jones 2019). Efficient entrainment among multiple oscillators at multiple levels of the structure is thought to support an increase in attention allocation to specific parts of the signal (Large & Jones, 1999), and thus to improve temporal predictions and processing. As discussed in Chapter 1, more efficient entrainment may not only enhance predictive timing mechanisms (i.e., predictions of *when* an event will occur; Friston, 2005), but also improve our predictions about *what* will occur next (or *predictive coding*; Friston, 2005) (Jones & Boltz, 1989; Koelsch, Vuust, & Friston, 2019).

Predictions are thought to be vital for efficient language processing and reading. Building expectations allows to restrict the number of possible alternatives for incoming input and therefore make both processing and reading faster and less costly in terms of computational efforts (Grüter, Rohde, & Schafer, 2014; Guasti, Pagliarini, & Stucchi, 2017). The use of expectations to process language is a phenomenon observed not only in adults, but in children as well (Borovsky, Elman, & Fernald, 2012), and it has been shown using a variety of different methods, including eye-tracking and ERPs. For instance, Dahan, Swingley, Tanenhaus, and Magnuson (2000) and Lew-Williams & Fernald (2007) have shown that native speakers of Romance languages, both adults and young children, anticipate an incoming noun based on the gender features of specific preceding linguistic elements. More specifically, in those two studies authors investigated the expectations triggered by the processing of definite articles, which in Romance languages are marked for gender and number in agreement with the nouns they introduce (see (1a)). Participants were presented with pictures of objects with nouns of different gender (see Figure 1) and listened to DPs introducing one of the two objects; results showed that participants converged on target objects after hearing the determiner but before hearing the target noun. These anticipatory effects were interpreted as the result of a two-step process: (i) the processing of the gender features of the determiners and (ii) the automatic triggering of expectations about the features of successive input. The existence of expectations in these processes is confirmed in studies using EEG, in which violations of gender agreement between determiners and nouns are observed to elicit specific neural responses associated with expectation violation (Barber, Salillas, & Carreiras, 2004; Gunter, Friederici, & Schriefers, 2000).

In Romance languages another example of gender agreement is offered by clitic pronouns. In Italian, specifically, direct object clitic pronouns are weak monosyllabic morphemes that are bound to a verb host, which they can either precede (when the verb is finite) or be attached to (when the verb is nonfinite). Like determiners, direct object clitics are marked for grammatical gender (besides number and person) and agree with their antecedent. Interestingly, in sentences with a right dislocated antecedent, as (1b), the processing of the clitic triggers automatic expectations about features of the right dislocated antecedent. A study with French (Léger et al., 2015) has shown that in a situation in which participants are required to look at pictures of objects with nouns of different gender and to listen to sentences with clitics with a right dislocated antecedent (as in (1b)), participants converge on the target object after hearing the clitic but before hearing the target noun.

1. a. Paolo mangia la forchetta
Paolo eat-3PRS.SG. the.DET.SG.F. fork.SG.F.
‘Paolo is eating the apple.’

b. Paolo la mangia velocemente, la forchetta
Paolo the.CL.SG.F. eat-3PRS.SG. quickly the.SG.F.fork.SG.F.
‘Paolo is eating the apple’

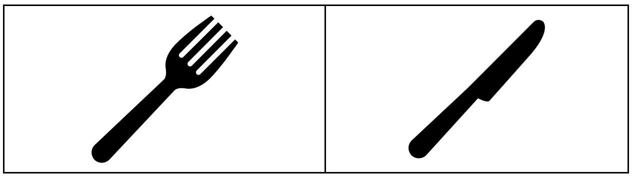


Figure 1. Picture of objects with nouns of different gender: *forchetta* “fork” (feminine, in Italian) and *coltello* “knife” (masculine).

Articles and direct object clitics are particularly interesting because of their vulnerability in speech and language disorders. Clitics, in particular, are acquired relatively late in typical development (Guasti, 1993): Italian monolingual children start to produce them at around age two years and occasionally omit them up to five years (Caprin & Guasti, 2009). Difficulties in the production of direct object clitics have been found across different languages (cf. Varlokosta et al., 2016), in second language learners (Grondin & White, 1996; Müller, Crysmann, & Kaiser, 1996; Müller & Hulk, 2001; Schmitz & Müller, 2008), and in speech and language disorders such as aphasia (e.g., Miceli, Silveri, Romani, & Caramazza, 1989), DLD (for Italian, Bortolini et al., 2006) and Developmental Dyslexia (for Italian, Arosio, Pagliarini, Perugini, Barbieri, & Guasti, 2016). Even their comprehension is problematic for children when they are used in a discourse where more than one possible antecedent is available (Pirvulescu & Strik, 2014). This difficulty also affects the ability to use gender marking to identify referents: as shown by Dispaldro, Ruggiero, and Scali (2015), Italian children correctly identify referents based on clitic gender marking with an accuracy of only 65% at 4;6 years; this rate increases up to 80% between 5;0 and 6;0, but does not reach adult performance up until 7;5 years.

However, once they are fully acquired, both articles and clitics can be used in typical development to infer properties of the linguistic material that will follow. As discussed above, both can be used to infer an upcoming noun, for instance, based on their gender features and the notion that they must agree. The finding that their encounter builds the expectation of encountering a noun with the same features has been shown in comprehension with a variety of different methods, in adults (Rossi, Kroll, & Dussias, 2014), as well as in children (Léger et al., 2015). If individual differences in rhythm and language depend on degree of neural entrainment and, by consequence, on strength of prediction skills, morphosyntactic processing tasks measuring gender-triggered expectations should also show individual differences.

Whether the encounter of gender-marked determiners, and the expectations that follow from it, differ in any way from encountering gender-marked clitic pronouns is not clear. It should be reminded that, although definite determiners and direct object clitics have the same phonological form in Italian (and French), they also differ on a number of levels, including their syntactic and sematic features, their acquisition trajectories (clitics are acquired later than articles), and their status as clinical markers in language disorders (see Chapter 3 for more details on their use in dyslexia and DLD).

Moreover, it is not clear whether type of gender information available plays any role in triggering stronger or weaker expectations about following nouns. In Italian gender information is not only lexically encoded in nouns; phonological and semantic cues can also be available. In fact, a noun ending in -*a* most often signals feminine gender, while nouns ending in -*o* are usually masculine. Furthermore, nouns can also be used to denote animate entities with a specific biological gender (for instance, ‘cow’ vs. ‘bull’). This information, which, in Italian, is prototypically conveyed by masculine and feminine nouns, respectively, provides individuals with one more cue to infer the lexical gender of the noun, i.e., the biological gender of the denoted referents. Though previous studies have tested gender-triggered expectations, it is still under debate whether type of gender information affects the efficient establishment of grammatical relations (cf. Caffarra & Barber, 2015; Holmes & Segui, 2004) and the individuals’ ability to anticipate incoming input.

2.2 The present study

Though rhythm and grammar skills have more and more often been compared in recent literature, the link between them is still unclear. Here, we propose that individual differences in the two domains may come as a consequence of individual differences in neural entrainment, which in turn affects structure-based prediction skills. If this is true, better anticipation skills in one domain should correspond to better predictions in the other. In rhythm, we expect efficient anticipation skills to translate into smaller synchronization errors in sensorimotor synchronization tasks, due to efficient structure processing and expectation building; in language, efficient predictions should correspond to faster processes of anticipation of incoming nouns based on the features of preceding linguistic elements.

In the present study we investigated these questions using a tapping task and two morphosyntactic tasks. Tapping tasks are adequate to test prediction skills, because a synchronized action (the tap) requires not only prediction of *when* the next event will happen (Fraisse & Repp, 2012; Miyake, Onishi, & Pöppel, 2004), but also the preparation for an action and the anticipation of the movement and effect associated with that action. The negative asynchrony consistently found in tapping tasks, even in adults and musicians, is thought to reflect this anticipatory process (Aschersleben, 2002). This idea is further confirmed by the fact that positive asynchronies (taps in delay), on the contrary, are rarely found: if asynchronies were due to wrong temporal estimates only, early and late responses should be found with equal proportions. Temporal predictions in rhythmic structures are thought to be supported by the perception of the beat, the regular pulse around which rhythms are organized perceptually (thus constituting the 'meter'). Beats can also be accompanied by physical cues, such as accents; however, their perception seems to take place regardless: even sequences of regularly spaced and unaccented tones tend to be interpreted as metrically organized in sets of two or three (Bolton, 1894), at least in western countries. Though beats are perceived regardless of whether or not they are physically conveyed in the stimulus, their presence may help younger participants give a stronger metric interpretation to the rhythmic sequences they are exposed to, and help them organize their motor synchronization behaviors more efficiently, in accordance with their expectations about the upcoming beats. In our study we investigated this idea by presenting children with both stressed and unstressed rhythmic patterns in a special type of tapping task (a warning-imperative task), which required only one response per trial as a response to a warning, and therefore granted more passive exposure to the stimuli before any movement was required. In addition, to test whether performance improved as a function of age (which we expected, because adults are usually found to be more precise in their sensorimotor synchronization behaviors (McAuley, Jones, Holub, Johnston, & Miller, 2006)), we compared the performance of children in this task with that of adults.

For language, we used a determiner and a clitic processing tasks. Both were used to investigate whether anticipation skills in morphosyntactic processing are affected by type of preceding element and/or type of gender information available. As mentioned, while researchers agree on the notion that gender information triggers the expectation of a gender-agreeing noun, there is no consensus regarding whether gender cue type affects processing (cf. Caffarra & Barber, 2015; Holmes & Segui, 2004). Moreover, though processing of these elements is expected to be improved in older children than in younger ones, it is not known whether the strategies used for efficient processing of these elements and their features differ at different points of the developmental course.

In sum, the present study investigated structure-based predictions, that is, predictions that are triggered automatically and unconsciously after processing elements that contain combinatory features, with the assumption that individual differences in these tasks may follow from individual differences in neural entrainment. Participants' prediction skills will be compared across two domains, rhythm and language, using behavioral tasks. In rhythm, we expected the presence of physical accents to boost anticipation skills. In language, we expected to see a different use of gender information type and an advantage when the all cues were available. Finally, to test whether prediction strategies might develop and/or change across development in either domain, we analyzed the performance of child participants of different age groups and compared it with a group of adults.

2.2.1 Methods

Participants

61 children typically-developing (TD) Italian monolingual children aged between 4 and 12 years participated in the study. Participants were recruited from public schools in the Milan metropolitan area and did not have any diagnosed or reported speech problems. Children were divided into three age groups: preschoolers (n = 13, age range in years: 4;5-6;2, mean: 5.4, SD: 0.6), elementary schoolers (n = 33, age range: 8;5-11;3, mean: 9.9, SD: 0.9), and middle schoolers (n = 15, age range: 11;4-12;2, mean: 11.8, SD: 0.3). To make sure that elementary and middle schoolers did not have any reading deficits, the reading abilities of school-aged children were tested in a standardized word and pseudoword reading test (DDE-2; Sartori, Job, & Tressoldi, 2007). The two tests consisted of four lists of word or pseudowords presented in order of increasing difficulty. Participants' accuracy and speed were standardized for age based on the normative data provided in Sartori et al., (2007). Mean z-scores for each subgroup and in total are reported in Table 1; note that all scores show a performance in line with the normative data (though slightly worse) and within 1.5

SD from the mean of each age group (same criterium for group assignment (TD/with dyslexia) used in Chapter 3). Children were compared to a control group of 10 adults with no speech, language, or reading deficits (age range in years: 19-55; mean age: 27.5, SD: 12.5).

All participants had age-appropriate nonverbal IQ, normal or corrected-to-normal vision, and no hearing deficits. The study was approved by the ethics committee of the University of Milano – Bicocca (protocol number: 199_2018bis).

Table 1

Child participants' characteristics and reading scores

	Total	*Preschool*	*Elementary*	*Middle*
N	61	13	33	15
Mean age in years	9.4 (2.4)	5.4 (0.6)	9.9 (0.9)	11.8 (0.3)
Word reading (z-scores):				
Accuracy	-0.11 (0.72)	/	-0.11 (0.77)	-0.07 (0.61)
Speed	-0.51 (0.52)	/	-0.66 (0.53)	-0.42 (0.50)
Pseudoword reading (z-scores):				
Accuracy	-0.21 (0.78)	/	-0.16 (0.70)	-0.71 (0.62)
Speed	-0.44 (0.72)	/	-0.62 (0.51)	-0.61 (0.64)

Note. Preschoolers were not tested in the reading tests, because they were not able to read yet. For all the other participants, z-scores were calculated in reference to the normative data provided in Sartori et al. (2007). Lower performance than standard is indicated by negative values in both accuracy and RTs data. Standard deviations from the mean are given in parentheses.

Materials

Warning imperative task (tapping). Rhythmic abilities were tested in a warning-imperative task (WIT; Pagliarini, Maffioli, Molteni, & Stucchi, 2016; Walter, Cooper, Aldridge, McCallum, & Winter, 1964), first presented in Pagliarini (2016). In this experiment, participants listened to a series of rhythmically regular sequences of pure tones with a frequency of 440 Hz, 8 millisecond (ms) rise and fall times, and 200 ms steady-state duration. Tones were played with an inter-onset-interval (IOI) of 750 ms, for a resulting tempo of 80 beats per minute (bpm), and were arranged in sequences of eight tones. Each sequence had a duration of 6000 ms and was repeated ten times. At random points throughout each sequence, participants heard one *warning sound*, which alerted them to be ready to tap in time with the following tone (the *imperative*). Warning sounds were created by adding an 880 Hz beep to the basic sound and were randomly distributed throughout the sequence. Tone sequences (thus consisting of six basic tones, one warning tone, and one imperative tone) appeared in two conditions: in condition 1 (unstressed) all beeps had the same intensity; in condition 2 (stressed condition), there was an alternation between stronger and weaker tones, the latter having half the intensity of the former, 4 ms rise and fall times, and 100 ms steady-state duration. The result of this alternation was the perception of a physical accent on every other tone, which was supposed to generate a metrical interpretation of the pattern as having a beat on the first tone of each pair (see Figure 2). We included both conditions because, though we expected participants to form metrical interpretations of the signal regardless of whether or not physical accents were present (Bolton, 1894), we hypothesized that the presence of physical accents would help our participants, especially the younger ones, perform the task.

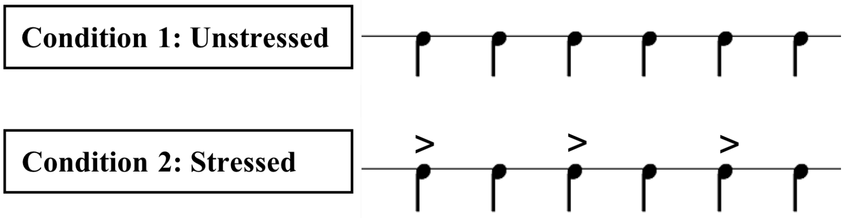
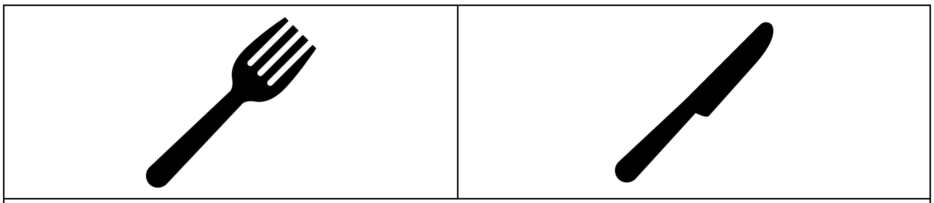


Figure 2. Rhythmic conditions in the warning imperative task. Note that the accented pattern was conveyed through an intensity reduction on the second tone of each pair, not through an intensity increase on the first tone.

Determiner processing task. In the determiner processing task participants were presented with two pictures on a computer screen and listened to a sentence telling them about a character touching one of the two objects represented in the pictures. One picture depicted the referent of a noun of masculine gender, the other one of feminine gender. In each sentence, the noun describing the picture was preceded by a gender-marked determiner (in agreement with the noun) and a phonologically opaque adjective, as in Figure 3).



🔊	Pinky	tocca	il	grande	coltello
	Pinky	touch-3PRS.SG.	the.SG.M	big	knife.SG.M.

‘Pinky will quickly touch the big knife

Figure 3. In the determiner processing tasks participants were presented with two pictures, one associated with a prototypical noun of feminine gender (e.g., *forchetta* “fork”, on the left side), the other associated with a prototypical noun of masculine gender (e.g., *coltello* “knife”. Upon the presentation of the pictures, a sentence containing gender-marked determiners (here, masculine) cueing the arrival of an agreeing noun (*coltello* “knife”, masculine) was played.

The prototypical nouns associated with the target and competitor pictures were drawn from basic vocabulary words that are familiar to school-aged children (selected from Marconi, Ott, Pesenti, Ratti, & Tavella, 1994); target and competitor nouns had the same number, syllable length (ranging from two to four syllables), and animacy category (human vs. inanimate) and had similar frequency. Each item pair belonged to one of three conditions, which differed for the type of gender information of the prototypical nouns associated with the pictures. In Condition 1 (Grammar, G), the target noun and competitor were phonologically opaque (i.e., ended in -e) and the referent was an inanimate object; therefore, only the grammatical lexical information of gender was available. In Condition 2 (Grammar-Phonology, GP), the referent was still an inanimate object, but the noun endings were either in -o or -a (which most often signal masculine and feminine gender, respectively). Therefore, they not only contained a grammatical information of gender, but also a phonological marking. Finally, in Condition 3 (Grammar-Phonology-Semantics, GPS), nouns were also associated with a semantic information of the biological gender of their referents, in that they referred to a human character (e.g., *mago* ‘wizard’, ending in -o and having a masculine grammatical gender, besides denoting a masculine human entity). In this condition, we expected participants to benefit from the automatic and unconscious activation of stereotypical knowledge associated with nouns referring to people (see Garnham, Oakhill, & Reynolds, 2002; Oakhill, Garnham, & Reynolds, 2005), and therefore to make faster predictions.

Conditions included six pairs of nouns each, for a total of 18 items, all of which had the same onset time in the sentence. Items were presented following a pseudorandomized order. The ability to recognize the noun referents was controlled in a denomination task before the administration of the determiner processing task. During this denomination task, children were shown pictures and asked to name them; the same pictures were later used in the two language experimental tasks. All participants scored *within* 2 SD from the mean of each age group; therefore, all participants could be included in later analyses. The experimental items were preceded by nine practice trials to make sure participants understood the task (see the Appendix). Accuracy and response times (RTs) in the determiner processing task were recorded and analyzed. RTs were further compared across conditions and groups.

Clitic processing task. The clitic processing task was the same as the one used in Persici, Stucchi, and Arosio (2019). As in the determiner processing task, participants were shown two pictures while they listened to a sentence. Target and competitor pictures were matched and assigned a gender cue condition; sentences were created following Léger, Prévost, and Tuller (2015). In each, a third-person singular clitic pronoun was followed by an agreeing right-dislocated postverbal Determiner Phrase (DP), as in (2). The following gender-marked noun was preceded by a verb and an adverb, so as to provide participants with more time to converge on the target picture.

2. Pinky la tocca velocemente, la forchetta
   Pinky CL.SG.M touch-3PRS.SG. quickly, the.SG.F fork.SG.F
   ‘Pinky will quickly touch the fork’

Participants were shown a total of 18 items with the same onset time, six for each condition, appearing in pseudorandomized order. The experimental items were preceded by five practice trials to make sure participants understood the task (see the Appendix). We measured accuracy (to make sure participants were able to perform the task) and analyzed and compared RTs across conditions and groups.

Procedure

Warning imperative task (tapping task). Half of the participants were first tested in this task, the other half was first tested in one of the language anticipation tasks. During the warning imperative task, participants sat in front of a computer screen and wore headphones. Before the test started, they were instructed to pay attention to the rhythmic sequences presented auditorily. After a habituation phase, participants had to click the mouse in time with the beat following a warning sound (i.e., the imperative; see Figure 4). Customized scripts and the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997; Kleiner et al., 2007) in Matlab (The Mathworks, Inc., 2017) were used to create and present the task. The time lag between the participant's response and the beat (i.e., the milliseconds interspersed between the beat and the participant's tap or vice versa) or synchronization error in each trial was recorded and analyzed.

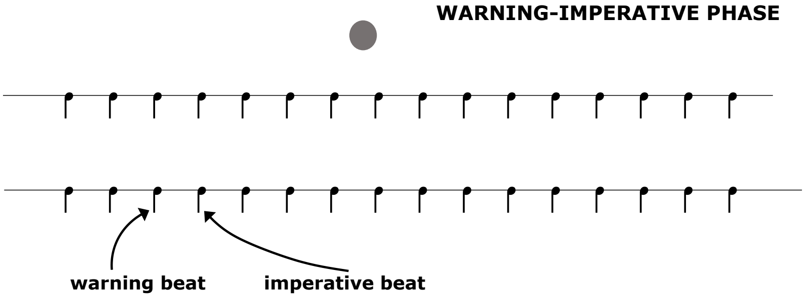


Figure 4. Warning-imperative task. Participants were required to tap in time with the beat following the warning sound (i.e., in time with the imperative beat). Tones were played with an IOI of 750 ms. Adapted from Pagliarini et al. (2016).

Determiner and clitic processing tasks. Participants performed the two language tasks in two separate sessions that took place within one month from one another. Before each started, children were instructed to carefully look at the pictures that would appear on the computer screen and to listen to the sentences played through the headphones. After that, they were required to identify, as quickly as possible, the correct noun referent of the sentence by selecting one of the two pictures on the screen. The tasks were created and played using customized scripts and the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997; Kleiner et al., 2007) in Matlab (The Mathworks, Inc., 2017). Responses were given by pressing either L (for the picture on the right side) or S (for the one on the left side) on the computer keyboard. Accuracy and response times were analyzed and compared.

2.2.2 Data analysis and results

Warning imperative tapping task

Individual Matlab output txt files were merged and re-organized in Matlab and then imported in R (R Development Core Team, 2016) using customized scripts. Twenty-two participants were removed, because their data was either missing or invalid (i.e., at least 60% of their responses was beyond the IOI of 750 ms; for this reason, the final sample included 49 participants, with only three participants in the preschool group[1], 29 participants in the elementary school group, seven children in the middle school group, and 10 adults. All responses above four standard deviations from zero were considered outliers and substituted with the median value of the previous and following two responses. Since middle schoolers were tested in a previous version of this task that included only five items, we analyzed only the first five items for all participants.

The remaining data were analyzed in a Linear Mixed-Effects Model (LMM) in R (R Development Core Team, 2016; lmer function in the "lme4" package, Bates et al., 2015). The model included Age group (preschool vs. elementary vs. middle school vs. adults), Condition (1 – unstressed vs. 2 – stressed), and Item (from 1 to 5) as fixed effects, Subject as random effect, and Synchronization error (measured in milliseconds) as the dependent variable. Posthoc tests after significant interactions were run using the function “testInteractions” in package “phia” (De Rosario-Martinez, 2015).

Results showed no significant main effects of Age group ($p = .405$), of Condition ($p = .761$), or Item ($p = .249$). However, they did show a significant Age group × Condition interaction ($F(3, 405) = 4.742$, $p = .003$). Post-hoc tests showed a significant difference between the stressed and unstressed rhythmic condition in the middle school group only ($\chi^2_{(1)} = 11.792$, $p <.001$), with the stressed condition being the one in which middle schoolers’ taps were more synchronized. The unstressed rhythmic condition seemed to be particularly problematic for middle schoolers: only in this condition their performance was

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[1] Removing preschoolers from the dataset does not significantly affect the results of the analyses presented in this section.

significantly worse than that of all of the other groups (as compared to preschoolers: $\chi^2_{(1)} = 3.946$, $p = .047$; to elementary schoolers: $\chi^2_{(1)} = 4.965$, $p = .026$; to adults: $\chi^2_{(1)} = 5.924$, $p = .015$). However, it should be noted that this group had a very limited sample size (n = 7) and these results may rather depend on individual differences than on group differences.

Finally, as Figure 5 shows, the within-group error variation seems to be particularly large in preschoolers and to reduce in older participants. This is expected, because children are usually more variable in their taps as compared to adults (McAuley et al., 2006). To analyze whether variability was in fact significantly different between preschoolers and older groups, we obtained the coefficient of variation (CV)[2] of the absolute value of the synchronization error for each group and then compared it across groups by running an ANOVA test and pairwise comparisons of adjusted means (Tukey correction, package "lsmeans"; Lenth, 2016). Results showed a larger CV in preschoolers (mean: 107.9) than in the other groups (elementary: 61.9; middle: 81.28; adults: 61.4), though the only difference approaching statistical significance was between the CV of preschoolers and that of elementary schoolers ($p = .077$). The fact that differences are significant if means are not adjusted for group size (preschool vs. elementary: $p = .017$, preschool vs. adults: $p = .026$) suggests that the absence of differences reported above depends on the very limited size of the preschool and adult groups. Taken together, these results suggest a smaller error variability in older groups than in younger ones, though these findings should be confirmed in larger groups of participants.

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[2] The coefficient of variation was calculated by dividing the standard deviation by the mean and multiplying the result by 100.

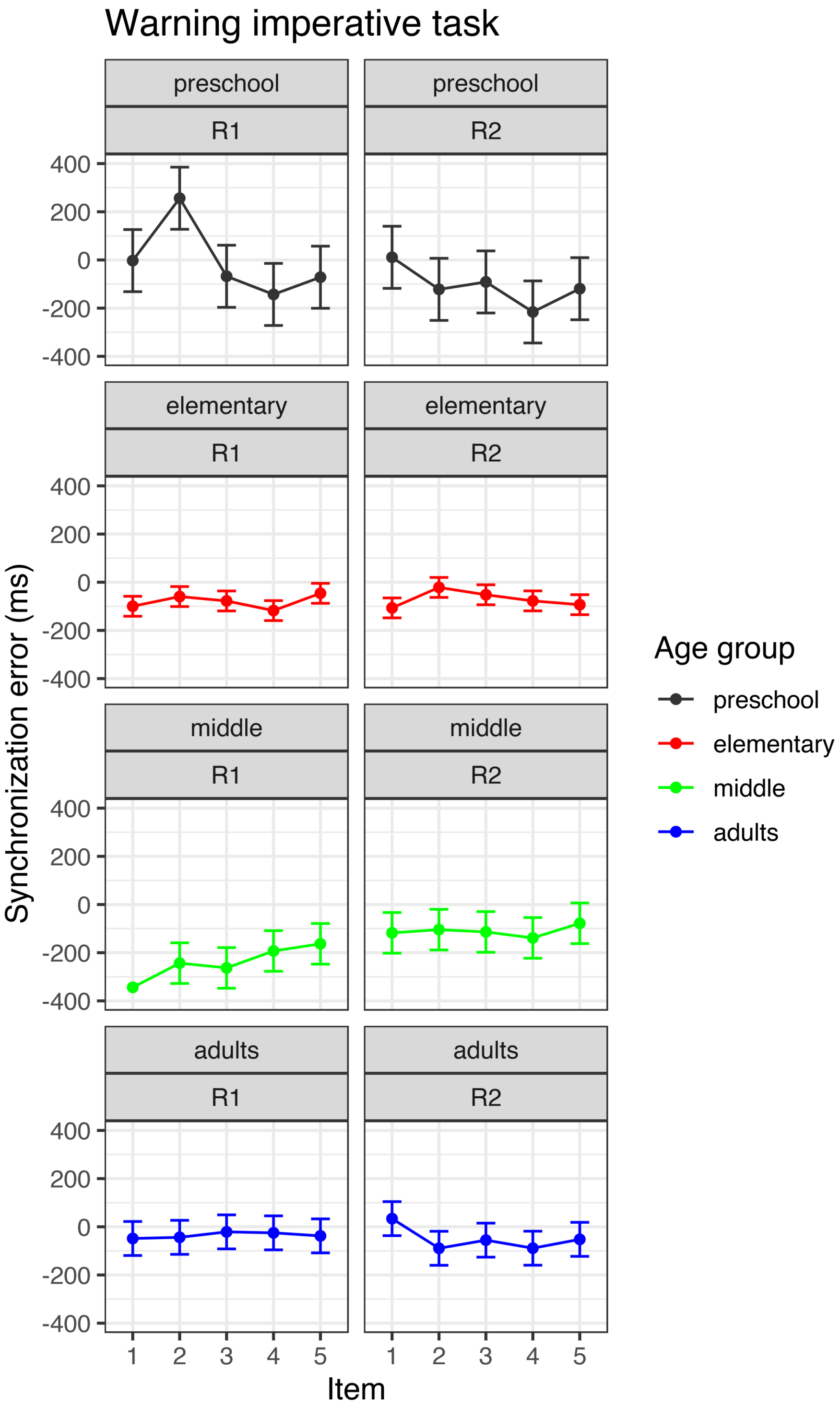

Figure 5. Synchronization error by item in the warning imperative task. Each row shows the performance of each individual age group in the two conditions (R1 = unstressed, R2 = stressed). The zero represents the onset of the imperative tone: the closer responses are to 0, the smaller the asynchrony. Any response below or above 0 is given early or late, respectively, with respect to the beat. Model effects were plotted using the r packages "effects" (Fox & Weisberg, 2019) and "ggplot2" (Wickham, 2016).

Determiner processing task

To minimize data handling errors, output Matlab txt files were imported in and prepared for R through loops using customized scripts. Item 10 was removed from the analysis because of a methodological error. Accuracy in this task was at ceiling (98.4 %). Pictures and sentence were supposed to appear simultaneously, but in order to reduce possible discrepancies in timing between picture and sentence playout across trials, response times were calculated both from the moment in which pictures appeared on the screen (t1), and from the moment the sentence was played (t0). Final response times for each participant were obtained by calculating the mean between the two.

Response times that had been given either too early (100 milliseconds after the onset of the determiner at 1 second or earlier) or too late (three seconds later than the offset of the longest noun) were considered invalid and therefore substituted with NA. The remaining RTs were analyzed in a LMM in R (R Development Core Team, 2016; lmer function in the "lme4" package, Bates et al., 2015).

As in the warning imperative task, children (n = 61) were divided into three age groups: preschool (13 children), elementary school (n = 33), and middle school (n= 15), and were compared with a group of adults (n = 10). Thus, the final model included Age group (preschool, elementary, middle, adults) and Condition (1, 2, 3) as fixed effects, and Subject and Item as random effects. Results showed significant effects of Group ($F(3, 67.05) = 18.992$, $p < .001$) and Condition ($F(2, 15.82) = 6.388$, $p = .009$), and a significant Age Group × Condition interaction ($F(6, 1112.04) = 30.546$, $p < .001$). Post-hoc tests showed significant differences between conditions only in middle schoolers and adults. More specifically, while middle schoolers showed a significant difference between conditions 2 and 3 ($\chi^2_{(1)} = 4.400$, $p = .036$), adults showed significant differences between all conditions (condition 1 vs. 2: $\chi^2_{(1)} = 32.701$, $p < .001$; condition 1 vs. 3: $\chi^2_{(1)} = 126.679$, $p < .001$; condition 2 vs. 3: $\chi^2_{(1)} = 33.624$, $p < .001$). Unexpectedly, they were fastest in the most difficult condition, i.e., in condition 1 (see Figure 6).

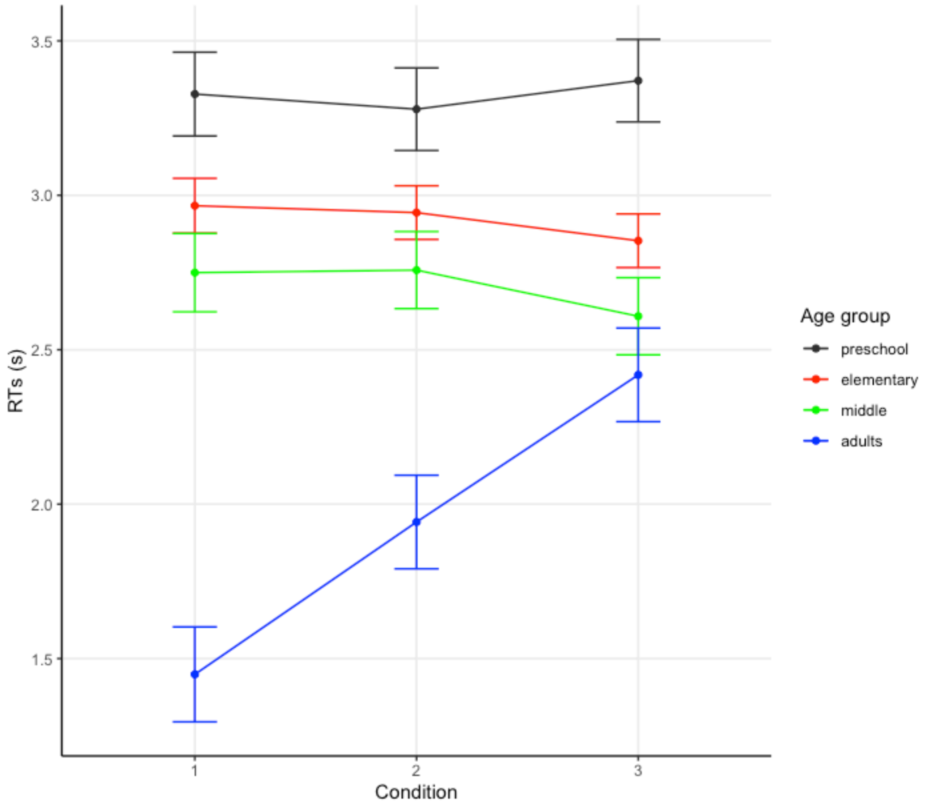

Figure 6. Response times (s) in the determiner processing task in the three conditions (1 G, 2 GP, and 3 GPS) by group (preschool in black, elementary in red, middle in green, and adults in blue).

Clitic processing task

Matlab output txt files were imported in and prepared for R through loops using customized scripts. As in the determiner processing task, item 10 was removed from the analysis because of a methodological error. All children were able to perform this task, as shown by their very high accuracy rate (99.1%). Response times in the clitic processing task were calculated as in the determiner processing task. In addition, all responses given before 200 milliseconds from the onset of the clitic pronoun at 1900 ms (and thus before 100 ms after the onset of the vowel disambiguating the gender information of the clitic (either -a or -o)) were considered invalid: any response below this threshold had to have been given before participants had processed the clitic pronoun. Furthermore, we excluded those responses given after 2 seconds from the onset of the final DP, because such a delay indicated that participants had not understood the task or that they were distracted.

As in the determiner processing task, the remaining RTs in the clitic processing task were analyzed in an LMM that included Age group and Condition as fixed effects, and Subject and Item as random effects.

Results showed a main effect of Age group (*F*(3, 66.97) = 21.169, $p < .001$). No significant effect of Condition was found ($p = .145$). Posthoc tests showed significantly slower RTs in preschoolers as compared to the other three groups (as compared to elementary: z = 4.908, $p < .001$; to middle school: z = 5.059, $p < .001$; to adults: z = 7.336, $p < .001$), and slower RTs in the elementary (z = 4.098, $p < .001$) and middle schoolers (z = 2.843, $p = .023$) as compared to adults. Elementary and middle school groups showed similar response times in this task ($p = .741$). See Figure 7.

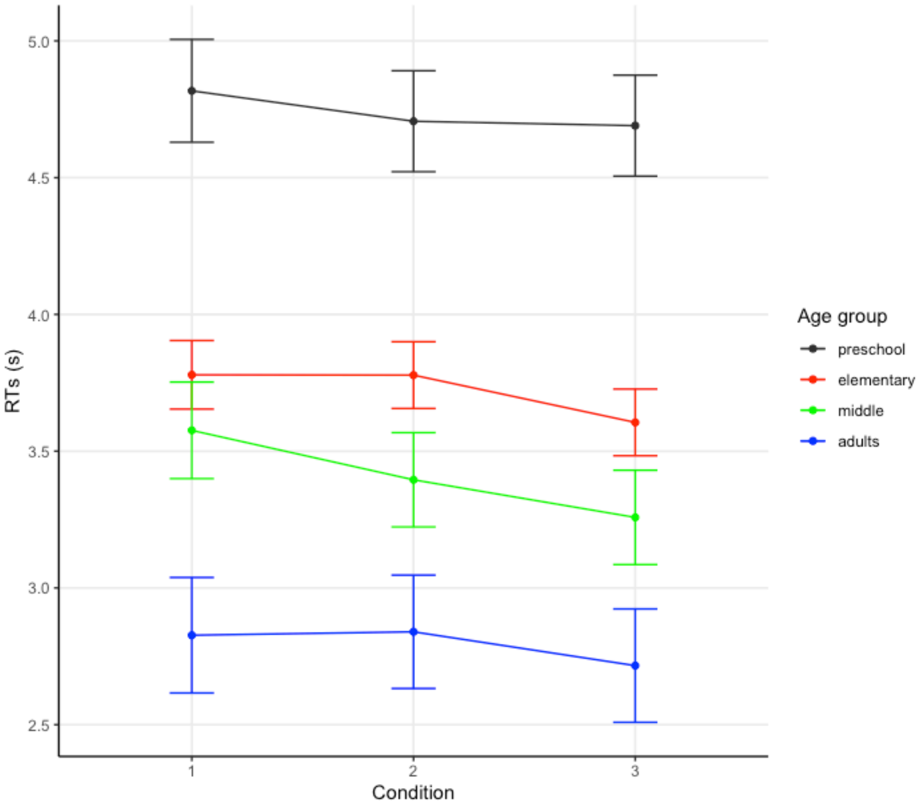

Figure 7. Response times (s) in the clitic processing task in the three conditions (1 G, 2 GP, and 3 GPS) by group (preschool in black, elementary in red, middle in green, and adults in blue).

To further investigate the participants' anticipation skills, we also performed additional analyses, this time with the ratio of anticipatory responses on the total as the dependent variable. First, we assigned a score of 1 to the responses given before or within 100 ms after the onset of the DP, and a score of 0 to all the other responses. The resulting 'anticipation scores' were then analyzed in a Generalized Linear Mixed Model (GLMM) with Age group and Condition as predictors, and Subject and Item as random effects. Likelihood ratio tests showed significant effects of Age group ($\chi^2_{(3)} = 36.798$, $p < .001$) and of Condition ($\chi^2_{(2)} = 6.968$, $p = .031$), and a significant Age group × Condition interaction ($\chi^2_{(11)} = 46.881$, $p < .001$). After significant main effects, we ran post hoc tests with the Tukey correction. Tests showed a significantly higher anticipation ratio in condition 3 (GPS) than in condition 1 (z = 2.438, $p = .039$), as a general trend across participants. Finally, significant differences were found between the preschoolers and all of the other groups in each of the three conditions (see Table 2 and Figure 8).

Table 2
Contrasts between the anticipatory response ratio in preschoolers and in the other groups by condition.

Condition	**Contrasts**	**z value**	**p value**
Condition 1	preschoolers vs. elementary schoolers	-3.792	.008
	preschoolers vs. middle schoolers	-3.707	.011
	preschoolers vs. adults	-4.957	< .001
Condition 2	preschoolers vs. elementary schoolers	-3.286	.047
	preschoolers vs. middle schoolers	-3.838	.007
	preschoolers vs. adults	-4.853	< .001
Condition 3	preschoolers vs. elementary schoolers	-3.939	.005
	preschoolers vs. middle schoolers	-4.273	.001
	preschoolers vs. adults	-4.773	< .001

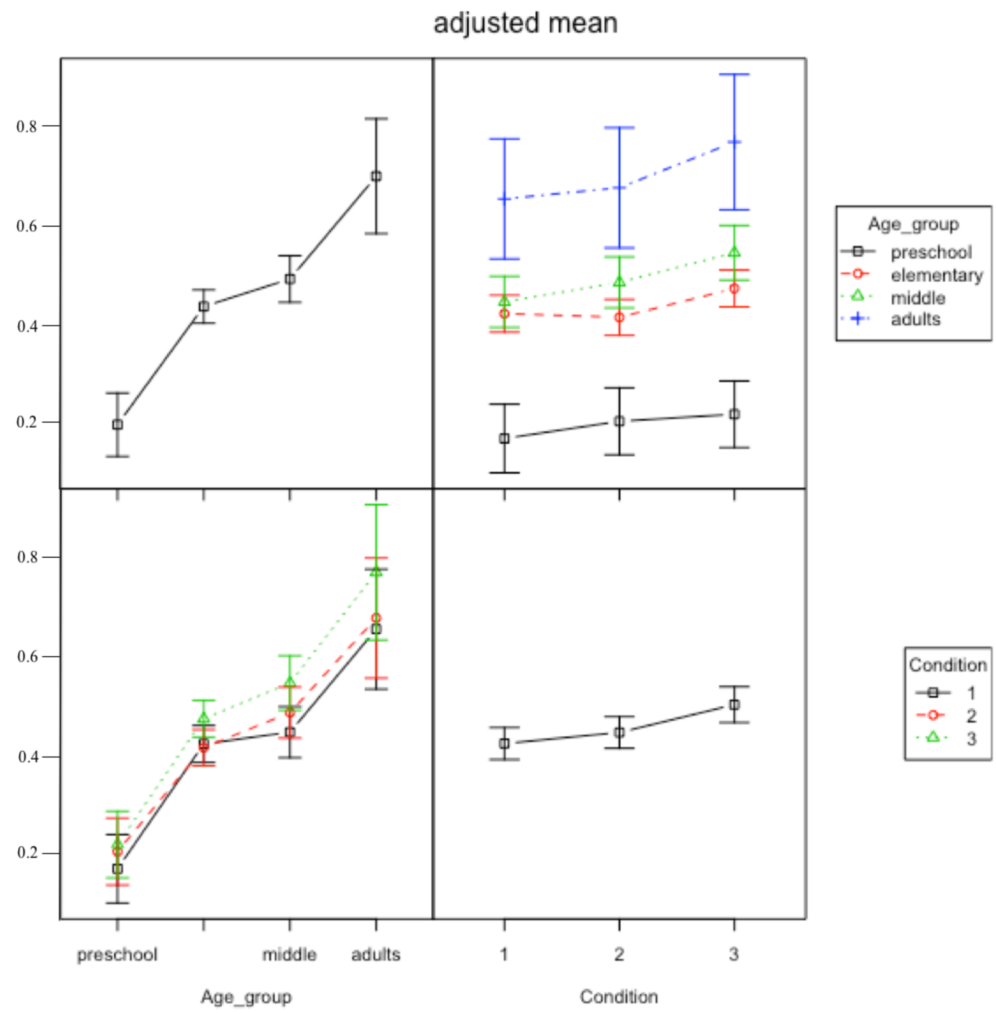

Figure 8. The left panels show the mean anticipation score in the four age groups (preschool, elementary, middle schoolers, adults) averaged (top left panel) or not (bottom left) over the levels of Condition. Condition 1 (G) is shown in black, condition 2 (GP) in red, condition 3 (GPS) in green. The right side of the figure shows the mean anticipation score by condition (bottom right) and by condition and age group (top right). As it can be seen, there are clear differences between age groups but not between conditions, though all participants are more likely to anticipate when they are presented with all the gender cues (i.e., in condition 3 as compared to 1 and 2).

Correlations between the rhythm tasks and the language and literacy ones

To investigate whether less precision in the WIT (i.e., farther responses from 0) corresponded to less efficient mechanisms of prediction in language (i.e., longer RTs in the language tasks) and reading, Spearman correlations were run between all the experimental tasks, and between each of them and the pseudoword reading test (function “cor.test”). For the WIT, only the responses preceding the beat (i.e., the negative RT values) were considered, as those are thought to reflect anticipatory processes and are consistently found in adults and musicians (Aschersleben, 2002).

Results showed a moderate, negative, significant correlation between mean synchronization error in the WIT in the unstressed condition and mean RTs in the determiner processing task in condition 1 (G) ($r_{(s)} = -0.893$, $p = .012$; see Figure 9). These results suggest that children who show better anticipation skills in rhythm also make better linguistic predictions.

To further investigate the possibility that improved anticipation skills in processing could also correspond to faster speed of pseudoword decoding (which is fundamental for efficient reading; cf. Guasti et al., 2017), we also ran correlations between RTs in the language tasks and pseudoword reading speed. Interestingly, the response speed in the determiner processing task did correlate with pseudoword reading speed, both in general ($r_{(s)} = 0.412$, $p = .012$) and within gender conditions 1 (G) and 2 (GP) (condition 1: $r_{(s)} = 0.399$, $p = .016$; condition 2: $r_{(s)} = 0.401$, $p = .014$). No significant correlations were found between the speed in the clitic processing task and the synchronization error in the warning imperative task. The absence of a significance correlation between them may be due to the fact that clitic pronouns also require semantic-pragmatic operations to be achieved: the hearer needs to identify a possible antecedent in the discourse space (which was, in this case, implicit), and then check agreement.

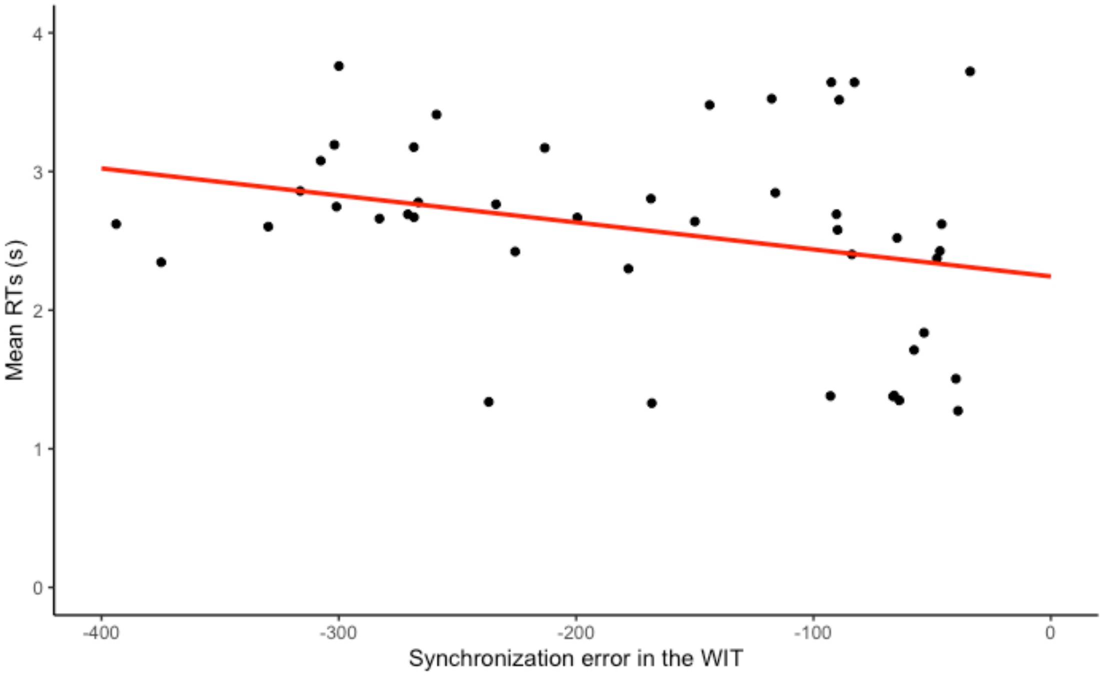

Figure 9. Correlation between the synchronization error in the WIT and the RTs in the determiner processing task in condition 1 (G).

2.2.3 Discussion

The primary goal of the present study was to investigate individual differences in the use of structure-based predictions for efficient processing of language and rhythm in typically-developing children, with the idea that varying degrees of prediction abilities in one domain would correspond to equivalent abilities in the other, possibly as a consequence of individual differences in neural entrainment. To study prediction abilities in rhythm and language, three behavioral tasks were used: rhythm anticipation abilities were investigated in a warning-imperative task, while language abilities were tested in a determiner and in a clitic processing task.

In the rhythmic task, we expected participants' performance to improve with age and to be generally benefited by the presence of physical accents (in the stressed condition R2). Results showed that asynchronies did not became smaller and predictions did not become more accurate in older groups: preschoolers were already quite precise in their taps and their response accuracy did not significantly differ from that of adults. The only exception was constituted by the middle school group, who performed significantly worse in the unstressed condition as compared to all the other groups. However, since this group has a very limited sample size, the differences found suggest an influence of individual – rather than group – variability. Though younger and older participants perform similarly, the analysis of within-participant variability suggests that preschoolers are more variable in their taps. This result, though only partially confirmed by our data given the numerosity problem discussed above, is in line with what is found in the literature (cf. McAuley, Jones, Holub, Johnston, & Miller, 2006). Children may build weaker metrical hierarchical representations: this might make it more difficult for them to form structure-based predictions about incoming tones. We expected the stressed condition to make it easier for children to be in time with the rhythm: unexpectedly, this result was found, again, in the middle schoolers only. However, since there is no main effect of condition, and since this is the group that shows the worst performance, this finding could indicate that the presence of physical accents is only beneficial in the case of participants who have particular difficulties with sensorimotor synchronization behaviors.

In language, we expected to see a different use of gender information and an advantage when the all cues were available, especially in the younger groups. However, in the determiner processing task this was only true in middle schoolers, who were faster when the semantic cue to gender was available. That is to say, middle schoolers were able to make faster anticipations based on determiners in the condition in which nouns also conveyed a biological gender information. On the contrary, adults – who were expected to show no differences at this stage of development – were fastest in the grammatical condition. It is possible that, once mechanisms of grammatical agreement are efficient, the presence of additional features that need to be processed might slow down the generation of agreement relations, especially when semantic access involves the previous processing of more sophisticated distinctions between sub-categories (as in 'queen' vs. 'princess', who can both have crowns and be distinguished only on the basis of age differences).

In the clitic processing task, preschoolers reached a conclusion as to which picture illustrated the target noun more slowly than elementary and middle schoolers did, who in turn were slower than adults. Though a difference in condition was not found in total RTs, the analysis of the ratio of anticipatory responses highlighted a significant difference between the condition in which more cues were available to infer the gender of the noun (GPS) and the condition in which only the lexical gender was available (G). Altogether, these analyses show that older participants are faster and more efficient in morphosyntactic processing, and that in general, the availability of all the gender cues allows for better morphosyntactic predictions.

Importantly, correlations suggested that better anticipation skills in rhythm corresponded to better anticipation skills in language. In fact, mean response speed in one of the language tasks was inversely correlated with the mean negative asynchrony in the tapping task. Interestingly, this correlation was found between the conditions that were thought to be the hardest in each of the tasks, i.e., the grammatical gender condition (G) and the unstressed rhythmic pattern. In other words, correlations appeared between the two tasks when no other external cue than what was offered by the basic foundations of each hierarchical structure was available: in those situations participants could efficiently perform the task only if they were able to analyze and reconstruct the rhythmic and linguistic hierarchical structures. The better predictions participants made based on their mental reconstruction of the meter in the rhythmic task, the faster they were in anticipating nouns based on the sole grammatical gender feature of its preceding determiner. Notably, anticipation speed in the determiner processing task in this condition (and not in GPS, for example) was also correlated with pseudoword decoding speed, which is important not only for literacy acquisition but also for learning new words. These significant correlations provide support for the theories stressing the importance of anticipation skills in reading and suggesting that children with dyslexia have impaired anticipation skills (cf. Guasti et al., 2017; Persici, Stucchi, & Arosio, 2019b). These topics are discussed in Chapter 3.

2.2.4 References

Arosio, F., Pagliarini, E., Perugini, M., Barbieri, L., & Guasti, M. T. (2016). Morphosyntax and logical abilities in Italian poor readers: The problem of SLI under-identification. *First Language*, *36*(3), 295–315. https://doi.org/10.1177/0142723716639501

Aschersleben, G. (2002). Temporal Control of Movements in Sensorimotor Synchronization. *Brain and Cognition*, *48*(1), 66–79. https://doi.org/10.1006/BRCG.2001.1304

Barber, H., Salillas, E., & Carreiras, M. (2004). Gender or genders agreement? In *The On-line Study of Sentence Comprehension: Eyetracking, ERPs and Beyond* (pp. 309–327). New York: Psychology Press. https://doi.org/10.4324/9780203509050

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using **lme4**. *Journal of Statistical Software*, *67*(1), 1–48. https://doi.org/10.18637/jss.v067.i01

Bolton, T. L. (1894). Rhythm. *American Journal of Psychology*, *6*, 145–238.

Borovsky, A., Elman, J. L., & Fernald, A. (2012). Knowing a lot for one's age: Vocabulary skill and not age is associated with anticipatory incremental sentence interpretation in children and adults. *Journal of Experimental Child Psychology*, *112*(4), 417–436. https://doi.org/10.1016/j.jecp.2012.01.005

Bortolini, U., Arfé, B., Caselli, C. M., Degasperi, L., Deevy, P., & Leonard, L. B. (2006). *Clinical markers for specific language impairment in Italian: the contribution of clitics and non-word repetition*. *International Journal of Language & Communication Disorders* (Vol. 41). John Wiley & Sons, Ltd (10.1111). https://doi.org/10.1080/13682820600570831

Caffarra, S., & Barber, H. A. (2015). Does the ending matter? The role of gender-to-ending consistency in sentence reading. *Brain Research*, *1605*(1), 83–92. https://doi.org/10.1016/j.brainres.2015.02.018

Caprin, C., & Guasti, M. T. (2009). The acquisition of morphosyntax in Italian: A cross-sectional study. *Applied Psycholinguistics*, *30*(1), 23–52. https://doi.org/10.1017/S0142716408090024

Chern, A., Tillmann, B., Vaughan, C., & Gordon, R. L. (2018). New evidence of a rhythmic priming effect that enhances grammaticality judgments in children. *Journal of Experimental Child Psychology*, *173*, 371–379. https://doi.org/10.1016/j.jecp.2018.04.007

Dahan, D., Swingley, D., Tanenhaus, M. K., & Magnuson, J. S. (2000). Linguistic Gender and Spoken-Word Recognition in French. *Journal of Memory and Language*, *42*(4), 465–480. https://doi.org/10.1006/jmla.1999.2688

De Rosario-Martinez, H. (2015). phia: Post-Hoc Interaction Analysis. R package version 0.2-1. Retrieved from https://cran.r-project.org/package=phia

Degé, F., & Schwarzer, G. (2011). The effect of a music program on phonological awareness in preschoolers. *Frontiers in Psychology*, *2*, 124. https://doi.org/10.3389/fpsyg.2011.00124

Ding, N., Melloni, L., Zhang, H., Tian, X., & Poeppel, D. (2015). Cortical tracking of hierarchical linguistic structures in connected speech. *Nature Neuroscience*, *19*(1), 158–164. https://doi.org/10.1038/nn.4186

Dispaldro, M., Ruggiero, A., & Scali, F. (2015). Real-time comprehension of gender and number in four- to seven-year-old children: A study of the relationship between Italian clitic pronouns and visual picture referents. *Journal of Child Language*, *42*(4), 917–931. https://doi.org/10.1017/S0305000914000427

Fox, J., & Weisberg, S. (2019). *An R Companion to Applied Regression* (3rd ed.). Thousand Oaks CA: Sage.

Fraisse, P., & Repp, B. H. (2012). Anticipation of rhythmic stimuli: Speed of establishment and precision of synchronization (1966). *Psychomusicology: Music, Mind, and Brain*, *22*(1), 84–93. https://doi.org/10.1037/a0028758

Friston, K. (2005). A theory of cortical responses. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *360*(1456), 815–836. https://doi.org/10.1098/rstb.2005.1622

Garnham, A., Oakhill, J., & Reynolds, D. (2002). Are inferences from stereotyped role names to characters' gender made elaboratively? *Memory and Cognition*, *30*(3), 439–446. https://doi.org/10.3758/BF03194944

Grondin, N., & White, L. (1996). *Functional Categories in Child L2 Acquisition of French* (Vol. 5). Lawrence Erlbaum Associates, Inc. Retrieved from https://about.jstor.org/terms

Grüter, T., Rohde, H., & Schafer, A. J. (2014). The role of discourse-level expectations in non-native speakers' referential choices. In *Proceedings of the 38th Annual Boston University Conference on Language Development (BUCLD).* Cascadilla Press.

Guasti, M. T. (1993). Verb Syntax in Italian Child Grammar: Finite and Nonfinite Verbs. *Language Acquisition*, *3*(1), 1–40. https://doi.org/10.1207/s15327817la0301_1

Guasti, M. T., Pagliarini, E., & Stucchi, N. (2017). Language, reading and motor control:

Get rhythm! *Biolinguistics*, *11*(1), 1–12.

Gunter, T. C., Friederici, A. D., & Schriefers, H. (2000). Syntactic gender and semantic expectancy: ERPs reveal early autonomy and late interaction. *Journal of Cognitive Neuroscience*, *12*(4), 556–568. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/10936910

Holmes, V. M., & Segui, J. (2004). Sublexical and lexical influences on gender assignment in French. *Journal of Psycholinguistic Research*, *33*(6), 425–457. https://doi.org/10.1007/s10936-004-2665-7

Jones, M. R. (2019). *Time will tell: A theory of Dynamic Attending*. New York: Oxford University Press.

Jones, M. R., & Boltz, M. (1989). Dynamic Attending and Responses to Time. *Psychological Review*, *96*(3), 459–491. https://doi.org/10.1037/0033-295X.96.3.459

Koelsch, S., Vuust, P., & Friston, K. (2019). Predictive Processes and the Peculiar Case of Music. *Trends in Cognitive Sciences*, *23*(1), 63–77. https://doi.org/10.1016/j.tics.2018.10.006

Kotz, S. A., Schwartze, M., & Schmidt-Kassow, M. (2009). Non-motor basal ganglia functions: A review and proposal for a model of sensory predictability in auditory language perception. *Cortex*, *45*(8), 982–990. https://doi.org/10.1016/j.cortex.2009.02.010

Ladányi, E., Persici, V., Fiveash, A., Tillmann, B., & Gordon, R. L. (n.d.). Is atypical rhythm a risk factor for speech and language disorders? *Submitted*.

Large, E. W., & Jones, M. R. (1999). The dynamics of attending: How people track time-varying events. *Psychological Review*. https://doi.org/10.1037/0033-295X.106.1.119

Léger, E., Prévost, P., Tuller, L., Haiden, M., Martineau, J., & Aguillon-Hernandez, N. (2015). The development of object clitics in French: A comparative study between production and real-time interpretation via eye-tracking while listening. In C. Hamann & E. Ruigendijk (Eds.), *Language acquisition and development: Proceedings of GALA 2013* (pp. 232–258). Newcastle: Cambridge Scholar Publishers.

Lenth, R. V. (2016). Least-Squares Means: The R Package lsmeans. *Journal of Statistical Software*, *69*, 1–33. https://doi.org/doi:10.18637/jss.v069.i01

Lew-Williams, C., & Fernald, A. (2007). Young children learning spanish make rapid use of grammatical gender in spoken word recognition. *Psychological Science*, *18*(3), 193–198. https://doi.org/10.1111/j.1467-9280.2007.01871.x

Marconi, L., Ott, M., Pesenti, E., Ratti, D., & Tavella, M. (1994). *Lessico elementare. Dati* *statistici sull'italiano scritto e letto dai bambini delle elementari.* Zanichelli.

McAuley, J. D., Jones, M. R., Holub, S., Johnston, H. M., & Miller, N. S. (2006). The time of our lives: Life span development of timing and event tracking. *Journal of Experimental Psychology: General*, *135*(3), 348–367. https://doi.org/10.1037/0096-3445.135.3.348

Miceli, G., Silveri, M. C., Romani, C., & Caramazza, A. (1989). Variation in the pattern of omissions and substitutions of grammatical morphemes in the spontaneous speech of so-called agrammatic patients. *Brain and Language*, *36*(3), 447–492. https://doi.org/10.1016/0093-934X(89)90079-5

Miyake, Y., Onishi, Y., & Pöppel, E. (2004). Two types of anticipation in synchronization tapping. *Acta Neurobiologiae Experimentalis*, *64*(3), 415–426. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/15283483

Müller, N., Crysmann, B., & Kaiser, G. A. (1996). Interactions between the Acquisition of French Object Drop and the Development of the. *Language Acquisition*, *5*(1), 35–63. Retrieved from https://www.jstor.org/stable/pdf/20011432.pdf?refreqid=excelsior%3Ab5d4dcf625b8c74faff387163949bffe

Müller, N., & Hulk, A. (2001). Crosslinguistic influence in bilingual language acquisition: Italian and French as recipient languages. *Bilingualism: Language and Cognition*, *4*(01), 1–21. https://doi.org/10.1017/S1366728901000116

Musacchia, G., Sams, M., Skoe, E., & Kraus, N. (2007). Musicians have enhanced subcortical auditory and audiovisual processing of speech and music. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(40), 15894–15898. https://doi.org/10.1073/pnas.0701498104

Oakhill, J., Garnham, A., & Reynolds, D. (2005). Immediate activation of stereotypical gender information. *Memory and Cognition*, *33*(6), 972–983. https://doi.org/10.3758/BF03193206

Pagliarini, E. (2015). *Predictive Timing in Developmental Dyslexia: A New Hypothesis Anticipatory skills across language and motor domains*. Università degli Studi di Milano - Bicocca.

Pagliarini, E., Maffioli, G., Molteni, B., & Stucchi, N. (2016). Predictive timing in Developmental Dyslexia. Poster presented at IWORDD International Workshop in Reading and Developmental Dyslexia.

Persici, V., Stucchi, N., & Arosio, F. (2019a). Predicting the future in rhythm and language: The anticipation abilities of a group of Italian-speaking children. In P. Guijarro-Fuentes & C. Suárez-Gómez (Eds.), *Proceedings of GALA 2017: Language Acquisition and Development* (pp. 451–468). Newcastle upon Tyne: Cambridge Scholar Publishers.

Persici, V., Stucchi, N., & Arosio, F. (2019b). Rhythmic and morphosyntactic predictions: The anticipation abilities of Italian children with Developmental Dyslexia. In M. Brown & B. Dailey (Eds.), *BUCLD 43: Proceedings of the 43rd annual Boston University Conference on Language Development*. Somerville, MA: Cascadilla Press.

Pirvulescu, M., & Strik, N. (2014). The acquisition of object clitic features in French: A comprehension study. *Lingua*, *144*, 58–71. https://doi.org/10.1016/j.lingua.2013.12.006

R Development Core Team. (2016). R: A Language and Environment for Statistical Computing. Retrieved from https://www.researchgate.net/publication/312455832_R_A_Language_and_Environment_for_Statistical_Computing

Rossi, E., Kroll, J. F., & Dussias, P. E. (2014). Clitic pronouns reveal the time course of processing gender and number in a second language. *Neuropsychologia*, *62*(1), 11–25. https://doi.org/10.1016/j.neuropsychologia.2014.07.002

Sartori, G., Job, R., & Tressoldi, P. E. (2007). *DDE-2: Batteria per la valutazione della dislessia e della disortografia evolutiva-2*. Firenze, Italia: O.S. Giunti.

Schmitz, K., & Müller, N. (2008). Strong and clitic pronouns in monolingual and bilingual acquisition of French and Italian. *Bilingualism*, *11*(1), 19–41. https://doi.org/10.1017/S1366728907003197

Varlokosta, S., Belletti, A., Costa, J., Friedmann, N., Gavarró, A., Grohmann, K. K., … Yatsushiro, K. (2016). A cross-linguistic study of the acquisition of clitic and pronoun production. *Language Acquisition*, *23*(1), 1–26. https://doi.org/10.1080/10489223.2015.1028628

Walter, W. G., Cooper, R., Aldridge, W. C., McCallum, W. C., & Winter, L. (1964). Contingent negative variation: an electric sign of sensori-motor association and expectancy in the human brain. *Nature Publishing Group*, *203*, 380–384.

Wickham, H. (2016). *ggplot2: Elegant Graphics for Data Analysis*. New York: Springer-Verlag.

Chapter 3

Rhythmic and morphosyntactic predictions in children with Developmental Dyslexia

3.1 Introduction

As discussed in Chapter 1, dyslexia is a developmental disorder associated with impaired reading and spelling abilities, not following from neurological impairments or other deficits. Given its relatively high incidence (Lindgren, De Renzi, & Richman, 1985), its impact on academic and economic life, as well as on emotional well-being (Mammarella et al., 2016), and the fact that deficits do not seem to be attenuated by the passing of time unless intervention takes place, accurate identification of this disorder is important for the remediation of deficits, especially if interventions start early in life (Lyytinen, Ronimus, Alanko, Poikkeus, & Taanila, 2007; Snowling, 2013).

Increasingly more research has suggested the use of musical training as a remediation tool for the phonological and morphosyntactic deficits shown in dyslexia. The idea that music, and in particular rhythm, could be beneficial to these deficits is based on the findings that children with dyslexia show improved language and reading-related skills after rhythmic training (Bonacina, Cancer, Lanzi, Lorusso, & Antonietti, 2015; Flaugnacco et al., 2015; Habib et al., 2016; Overy, 2003; Thomson, Leong, & Goswami, 2013), despite having impaired sensorimotor synchronization (Colling, Noble, & Goswami, 2017; Dellatolas, Watier, Le Normand, Lubart, & Chevrie-Muller, 2009; Overy, Nicolson, Fawcett, & Clarke, 2003; Thomson & Goswami, 2008; Wolff, Michel, Ovrut, & Drake, 1990) and rhythmic perception (Flaugnacco et al., 2014; Goswami, Huss, Mead, Fosker, & Verney, 2013; Huss, Verney, Fosker, Mead, & Goswami, 2011; Lee, Sie, Chen, & Cheng, 2015; Muneaux, Ziegler, Truc, Thomson, & Goswami, 2004; Thomson & Goswami, 2008).

The benefits of rhythmic training on language and reading-related skills have been interpreted as possibly stemming from stimulation of neural entrainment mechanisms. Neural entrainment, i.e., the phase-resetting of neural populations firing in correspondence to the onset of the sounds that are being attended, is thought to reflect coupling between distant brain regions (Bartolo, Prado, & Merchant, 2014), to enhance attention to important parts of the signal (Large & Jones, 1999), and to support phonological (Leong & Goswami,

2014) and syntactic processing (Ding et al., 2017) during language acquisition and development; however, individuals with dyslexia show atypical entrainment to both speech, especially at the syllable rate (~ 2 Hz; Leong & Goswami, 2014; Molinaro et al., 2016; Power, Colling, Mead, Barnes, & Goswami, 2016), and rhythm (Cutini, Szucs, Mead, Huss, & Goswami, 2016; Frey, François, Chobert, Besson, & Ziegler, 2019). Weaker and less stable entrainment throughout development may lead to the phonological deficits that are found in children with dyslexia (especially in recognition of speech envelope cues; Goswami et al., 2016; Huss et al., 2011; Leong, Hämäläinen, Soltész, & Goswami, 2011; Thomson, Fryer, Maltby, & Goswami, 2006a; cf. Temporal Sampling Framework by Goswami (2011), see Chapter 1 for more information).

For the same reasons, atypical entrainment may also lead to subtle morphosyntactic processing deficits. As shown in Cantiani, Lorusso, Perego, Molteni, and Guasti (2015), children who have a diagnosis of developmental dyslexia (but not of DLD) show impaired production of inflectional and derivational morphology with pseudowords (in line with previous literature finding reduced sensitivity to morphosyntactic information, e.g., see Rispens & Been, 2007) and atypical neural responses to morphosyntactic violations as compared to typically-developing peers. Atypical neural encoding of temporal information might impact not only phonological development but also affect morphosyntactic skills, possibly as a result of impaired prediction mechanisms. In fact, efficient entrainment is thought to support timing and content predictions (see Chapter 1); if entrainment is impaired, individuals may find it especially hard to predict linguistic content (Koelsch, Vuust, & Friston, 2018).

This difficulty would extend to reading. Anticipation is important for efficient reading: the incremental presentation of morphemes and words, and access to their orthographic and lexical representations, restricts the pool of possible alternatives and allows readers to skip parts of the text (either letters or portions of words or phrases; Rayner, 1998), thus making reading more fluent and less costly computationally. Children with DD do not seem to be able to anticipate incoming input, while reading: as shown by research using eye-tracking, they show slower eye movements and longer fixations (Rayner, 1998), especially in the case of languages with less fixed grapheme-phoneme associations (Landerl, Wimmer, & Frith, 1997). This different pattern of eye movements between TD and DD individuals may not only indicate greater difficulty accessing grapheme-phoneme associations (Ziegler & Goswami, 2005), but also a less efficient mechanism of anticipation.

Impaired predictions may also contribute to explain why individuals with dyslexia show rhythmic sensorimotor deficits (e.g., Wolff et al., 1990). Tapping in time with the beat requires the analysis of the rhythmic structure that is being presented, the anticipation of the successive stimuli, and the preparation of the movement required to be in time (Miyake, Onishi, & Pöppel, 2004); if predictions about the timing of the next stimulus and about the timing of the action to be prepared are inaccurate, tapping will be produced with asynchronies. In line with this idea (first formulated in Pagliarini (2016), cf. "Predictive Timing Framework"), it has been shown that children with dyslexia produce larger and less stable asynchronies in tapping tasks (Wolff et al., 1990).

Taken together, these studies suggest that children with dyslexia might have a timing deficit and less efficient prediction mechanisms; these may affect not only reading, but also morphosyntactic and rhythmic skills. These hypotheses are addressed in the present study.

3.2 The present study

In the present study we investigated the anticipation abilities of children with DD and compared them to those of a group of age-matched typically developing (TD) peers, based on the idea that problems in reading and in rhythmic and morphosyntactic processing might stem from a core deficit in prediction-making mechanisms. Specifically, we tested whether children with DD exhibited less efficient structure-based predictions in both language and rhythm, and whether abilities in the two domains correlated. Structure-based predictions, i.e., predictions that are made based on the analysis of a structure that contains combinatory features and on the automatic and compulsory activation of integration processes, were tested in a tapping task for rhythm, and in two morphosyntactic processing tasks for language. As in the previous study, the choice of these tasks was motivated by the idea that both tapping and morphosyntactic processing require anticipation of incoming input, though in different ways.

Tapping requires the analysis of the rhythmic structure, the anticipation of when the next stimulus will occur, and the preparation for an action to be in time with the rhythmic stimulus (Fraisse & Repp, 2012; Guasti, Pagliarini, & Stucchi, 2017; Miyake et al., 2004). Predicting incoming nouns based on the features of preceding elements such as articles or clitic pronouns is *also* based on the analysis of the structure presented and on the automatic expectation of input that matches preceding elements. As mentioned in Chapter 2, speakers of Romance languages show examples of these automatic morphosyntactic expectations when they are presented with gender-marked articles and clitics with a right-dislocated sentence antecedent (Dahan, Swingley, Tanenhaus, & Magnuson, 2000; Léger et al., 2015; Lew-Williams & Fernald, 2007), which cue the arrival of an agreeing nominal constituent. If predictive processes are impaired in dyslexia, as hypothesized, children with DD should show worse performance in both rhythm and morphosyntactic processing, and their abilities should correlate across domains.

As in the previous study, in the rhythmic task we further expected participants to produce more accurate taps in the presence of auditory cues stressing the beat, especially in the case of children with dyslexia. In fact, we hypothesized that the rhythmic deficits that are found in dyslexia may be due to impaired analysis and use of the hierarchical structure being processed, and that the presence of a perceivable beat could help them build an internal representation of meter. We also expected them to get increasingly more accurate throughout the task, not only because of possible practice effects, but also based on the studies showing improved language skills after exposure to rhythmic sequences (Chern, Tillmann, Vaughan, & Gordon, 2018; Ladányi, Lukács, & Gervain, submitted; Przybylski et al., 2013), possibly because of stimulation of entrainment mechanisms.

To test their morphosyntactic skills we used the same article and clitic processing tasks used in the previous studies. As already mentioned, we used both, because, although determiners and clitics are similar in phonological form in Italian, the latter are acquired later and with more difficulty in typical development (Dispaldro, Ruggiero, & Scali, 2015; Guasti, 1993) and children with dyslexia find their production problematic (Arosio, Branchini, Barbieri, & Guasti, 2014). Moreover, clitics are considered more stable and reliable clinical markers for DLD (Arosio, Pagliarini, Perugini, Barbieri, & Guasti, 2016): clitic omissions and their substitutions with a full nominal constituent in the canonical post verbal position in production are frequent, and constitute a good clinical marker for both preschoolers and school-aged children (Arosio et al., 2014; Bortolini et al., 2006; Paradis, Crago, & Genesee, 2003). Determiners are also omitted frequently in DLD (Bortolini, Caselli, & Leonard, 1997; Bottari, Cipriani, Chilosi, & Pfanner, 2001). Less is known about their comprehension (both in typical development and in dyslexia) and whether they are efficiently used in comprehension to anticipate incoming nouns. Moreover, as already mentioned in the previous chapter, it is also not known whether gender-marked determiner and clitics with a right-dislocated sentence antecedent elicit expectations differently or with different strength, and whether the type of cues available to infer gender information (grammatical, phonological, semantic) affects morphosyntactic predictions. To address these questions, we tested children with DD and age-matched TD peers in determiner and clitic processing tasks and manipulated the number of cues to gender that were available to them (see Table 1). Based on previous findings, we hypothesized that children with dyslexia would show worse performance in both determiner and clitic processing tasks, especially when no other cue than the grammatical information to gender was available.

Table 1
Examples of noun pairs in each gender cue condition

Condition	**Type of gender cue available**	**Examples of prototypical nouns associated with the two pictures simultaneously presented on the screen**
1	Grammatical (G)	chiave (f) 'key' vs. fiore (m) 'flower'
2	Grammatical, phonological (GP)	foglia (f) 'leaf' vs. fungo (m) 'mushroom'
3	Grammatical, phonological, semantic (GPS)	fatina (f) 'fairy' vs. soldato (m) 'soldier'

3.2.1 Methods

Participants

Thirty-seven children with a diagnosis of developmental dyslexia participated in the study. Participants were aged between 8 and 12 years, had received a diagnosis of developmental dyslexia (DD) by certified clinicians on the basis of standard inclusion and exclusion criteria (ICD-10; World Health Organization, 2004), and were recruited from public schools and clinical centers in the Milan metropolitan area. To make sure that participants had reading deficits, we investigated their reading abilities in a standardized word and pseudoword reading test (DDE-2; Sartori, Job, & Tressoldi, 2007). Those participants who did not show a mean accuracy between the two tests below 1.5 SD from the normative data, or who were bilingual, were excluded from the study. The remaining 24 monolingual children with DD (mean age: 10.2, SD = 1.1, 13 males) were matched with 24 monolingual typically developing (TD) children of the same age (mean age: 10.1, SD = 1.1, 12 males; see Table 2). T-tests on the reading accuracy and speed of the two groups confirmed significantly different scores in the TD and DD groups (word accuracy: *t*(46) = 6.959, *p* < .001; pseudoword accuracy: *t*(46) = 12.261, *p* < .001; word speed: *t*(46) = 3.682, *p* < .001; pseudoword speed: *t*(46) = 4.030, *p* < .001). All participants had age-appropriate nonverbal IQ, normal or corrected-to-normal vision, and no diagnosed or reported speech problems or hearing deficits. The study was approved by the ethics committee of the University of Milano – Bicocca (protocol number: 199_2018bis).

Table 2

Participants' characteristics and reading scores

	Children with developmental dyslexia	*Typically developing children*
N	24	24
Mean age (years)	10.2 (1.1)	10.1 (1.1)
Word reading (z-scores):		
Accuracy	-4.78 (3.23)	-0.09 (0.85)
Speed	-3.55 (5.62)	-0.79 (0.53)
Pseudoword reading (z-scores):		
Accuracy	-3.14 (1.25)	-0.34 (0.60)
Speed	-2.93 (4.36)	-0.68 (0.52)

Note. Z-scores were calculated in reference to the normative data provided in Sartori et al. (2007). Lower performance than standard is indicated by negative values in both accuracy and RTs data. Standard deviations from the mean are given in parentheses.

Materials

Warning imperative task. Participants' rhythmic abilities were tested in a warning-imperative task (WIT; Pagliarini, Maffioli, Molteni, & Stucchi, 2016; Walter, Cooper, Aldridge, McCallum, & Winter, 1964), adapted from Pagliarini (2016). As in the previous study, in this experiment participants listened to rhythmically regular sequences of pure tones with 440 Hz frequency, 8 millisecond (ms) rise and fall times, 200 ms steady-state duration, and inter-onset-intervals (IOI) of 750 ms, for a resulting tempo of 80 beats per minute (bpm). Tones were arranged in sequences of eight; each sequence had a duration of 6000 ms and was repeated ten times. *Warning sounds* (created by adding an 880 Hz beep to the basic sounds) were placed at random points throughout the sequence to alert participants to tap in time with the following tone (the *imperative*). Tone sequences (thus consisting of six basic tones, one warning tone, and one imperative tone) appeared either in an unstressed condition (condition 1, having all beeps with the same intensity) or in a stressed condition (condition 2, with intensity reductions on every other tone, to create the perception of a beat on the first one of each pair; see Figure 1 and Chapter 2 for more details). We included both conditions because, though we expected participants to form metrical interpretations of the signal regardless of whether or not physical accents were present (Bolton, 1894), we hypothesized that the presence of physical accents would help our participants, and especially our DD group, perform the task. Each participant was presented with a total of 160 tones (80 per condition).

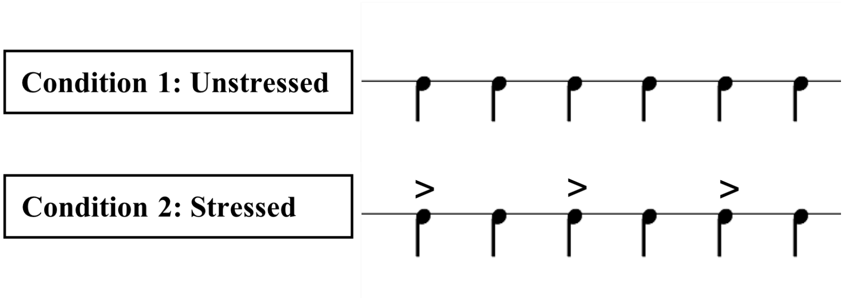

Figure 1. Rhythmic conditions in the warning imperative task. As in the previous study, the accented pattern was conveyed through an intensity reduction on the second tone of each pair.

Determiner processing task. In the determiner processing task participants were presented with two pictures on a computer screen while they listened to a sentence telling them about a character touching one of the two objects represented in the pictures (see Figure 2). As in the previous study, one picture depicted the referent of a noun of masculine gender, the other one of feminine gender. In each sentence, the noun describing the picture was preceded by a gender-marked determiner (in agreement with the noun) and a phonologically opaque adjective. The prototypical nouns associated with the pictures were drawn from Marconi, Ott, Pesenti, Ratti, and Tavella (1994) and were matched in number, syllable length, frequency, and animacy category between target and competitor pictures. As in the previous study, sentences contained nouns that: (i) had no other cue than the grammatical lexical information of gender (condition 1: G), (ii) were also phonologically marked in word ending[1] (condition 2: GP), or (iii) were phonologically marked and their referents had a biological gender, in that they referred to a human character (e.g., *mago* ‘wizard, ending in

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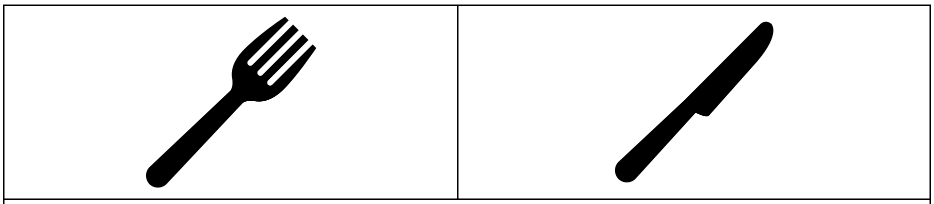
[1] Gender can be signaled by phonological marking in Italian, because nouns ending in -a are most often feminine, while nouns ending in -o are most often masculine

-o and having a masculine grammatical gender, besides denoting a masculine human entity). Each condition included six pairs of nouns, for a total of 18 items, all with the same onset time in the sentence and presented in pseudorandomized order.



🔊	Pinky	tocca	il	grande	coltello
	Pinky	touch-3PRS.SG.	the.SG.M	big	knife.SG.M.

‘Pinky will quickly touch the big knife’

Figure 2. In the determiner processing tasks participants were presented with two pictures, one associated with a prototypical noun of feminine gender (e.g., *forchetta* “fork”, on the left side), the other associated with a prototypical noun of masculine gender (e.g., *coltello* “knife”). Upon the presentation of the pictures, participants were played a sentence containing gender-marked determiners (here, masculine) cueing the arrival of an agreeing noun (*coltello* “knife”, masculine).

As in the previous study, the ability of the participants to recognize the noun referents associated with the pictures that were presented in both the determiner and the clitic tasks was controlled in a denomination task (administered before the determiner processing task). During this denomination task, children were shown pictures and asked to name them. All participants scored *within* 2 SD from the mean of the group (TD group, mean: 52.12, SD = 0.78; DD group, mean: 51.59, SD = 2.59) and within 1.5 SD from the mean of all the children who participated in the study (mean: 51.90, SD = 1.79). Therefore, the data of all participants were usable for analysis.

The experimental items were preceded by nine practice trials that were included to make sure participants understood the task (see the Appendix). Accuracy and response times (RTs) in the determiner processing task were recorded and analyzed. RTs were further compared across conditions and groups.

Clitic processing task. The clitic processing task was the same as the one used in Persici, Stucchi, and Arosio (2019) and described in Chapter 2. As in the determiner processing task, participants were presented with two pictures and with one sentence auditorily. Target and competitor pictures were matched and assigned a gender cue condition; sentences were created following Léger, Prévost, and Tuller (2015). In each, a third-person singular clitic pronoun was followed by an agreeing right-dislocated postverbal Determiner Phrase (DP), as in (1). The following gender-marked noun was preceded by a verb and an adverb, so as to provide participants with more time to converge on the target picture.

1.	Pinky	la	tocca	velocemente,	la	forchetta
	Pinky	CL.SG.M	touch-3PRS.SG.	quickly,	the.SG.F	fork.SG.F
	‘Pinky will quickly touch the fork’					

Participants were shown a total of 18 items with the same onset time, six for each condition, appearing in pseudorandomized order. The experimental items were preceded by five practice trials to make sure participants understood the task (see the Appendix). We measured accuracy (to make sure participants were able to perform the task) and analyzed and compared RTs across conditions and groups.

Procedure

Warning imperative task. As in the previous study, half of the participants were first tested in this task, the other half was first tested in one of the language anticipation tasks. During the warning imperative task, participants carried out this task in a quiet room, seated in front of a computer screen, and wearing headphones. Before the test started, the experimenter asked participants to attend the rhythmic sequences presented auditorily, and to click the mouse in time with the beat following a warning sound (i.e., the imperative, see Figure 3). The task was created and presented using customized scripts and the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997; Kleiner et al., 2007) in Matlab (The Mathworks, Inc., 2017). As in previous task, we calculated the time lag interspersed between the participant’s response and the beat (or synchronization error) in each trial.

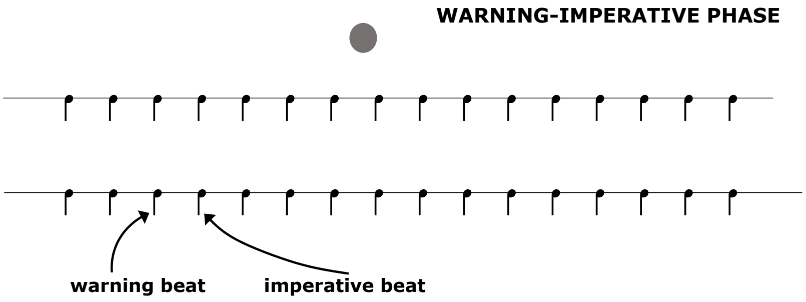


Figure 3. Warning-imperative task. Participants were required to tap in time with the beat following the warning sound (i.e., in time with the imperative beat). Tones were played with an IOI of 750 ms. Adapted from Pagliarini et al., 2016.

Determiner and clitic processing tasks. Participants carried out the two language tasks in two separate sessions over the span of a month. Before each test started, children were asked to carefully look at the pictures that would appear on the computer screen, to listen to the sentences played through the headphones, and to choose, as quickly as possible, the picture representing the noun referent of the sentence. Participants were asked to indicate their response by pressing either L (for the picture on the right side) or S (for the one on the left side) on the computer keyboard. Again, customized scripts and the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997; Kleiner et al., 2007) in Matlab (The Mathworks, Inc., 2017) were used to create and present the task, and to collect data. Accuracy and response times were analyzed and compared.

3.2.2 Data analysis and results

Warning imperative task

Individual Matlab output txt files were merged and re-organized in Matlab and then imported in R (R Development Core Team, 2016) using customized scripts. Three participants were removed, because 60% of their responses were beyond the IOI of 750 ms and were therefore considered invalid. Responses above four standard deviations from zero were considered outliers and substituted with the median value of the previous and following two responses.

The remaining data were analyzed in a Linear Mixed-Effects Model (LMM) in R (lmer function in the "lme4" package, Bates et al., 2015). The model included Group (TD vs. DD), Condition (1 – unstressed vs. 2 – stressed), and Item (from 1 to 10) as fixed effects, Age as covariate, Subject as random effect, and Synchronization error as the dependent variable. Posthoc tests after significant main effects were run using the function "glht" in package "multcomp" (Hothorn, Bretz, & Westfall, 2008) and the Tukey correction.

Results showed a significant main effect of Group ($F(1, 775.75) = 36.463$, $p < .001$), with the DD group being significantly less precise (i.e., their taps were farther away from the beat at 0 ms) than the TD group ($z = -5.031$, $p < .001$, see Figure 4A). Tests also showed a significant main effect of rhythmic Condition ($F(1, 758.06) = 4.212$, $p = .040$), with the stressed rhythmic condition being the one in which participants were more accurate ($z = 2.05$, $p = .040$, see Figure 4B). Finally, there was a positive significant effect of Item ($F(9, 758.42) = 1.904$, $p = .048$): as it can be seen in Figure 4, participants became more and more precise throughout the session.

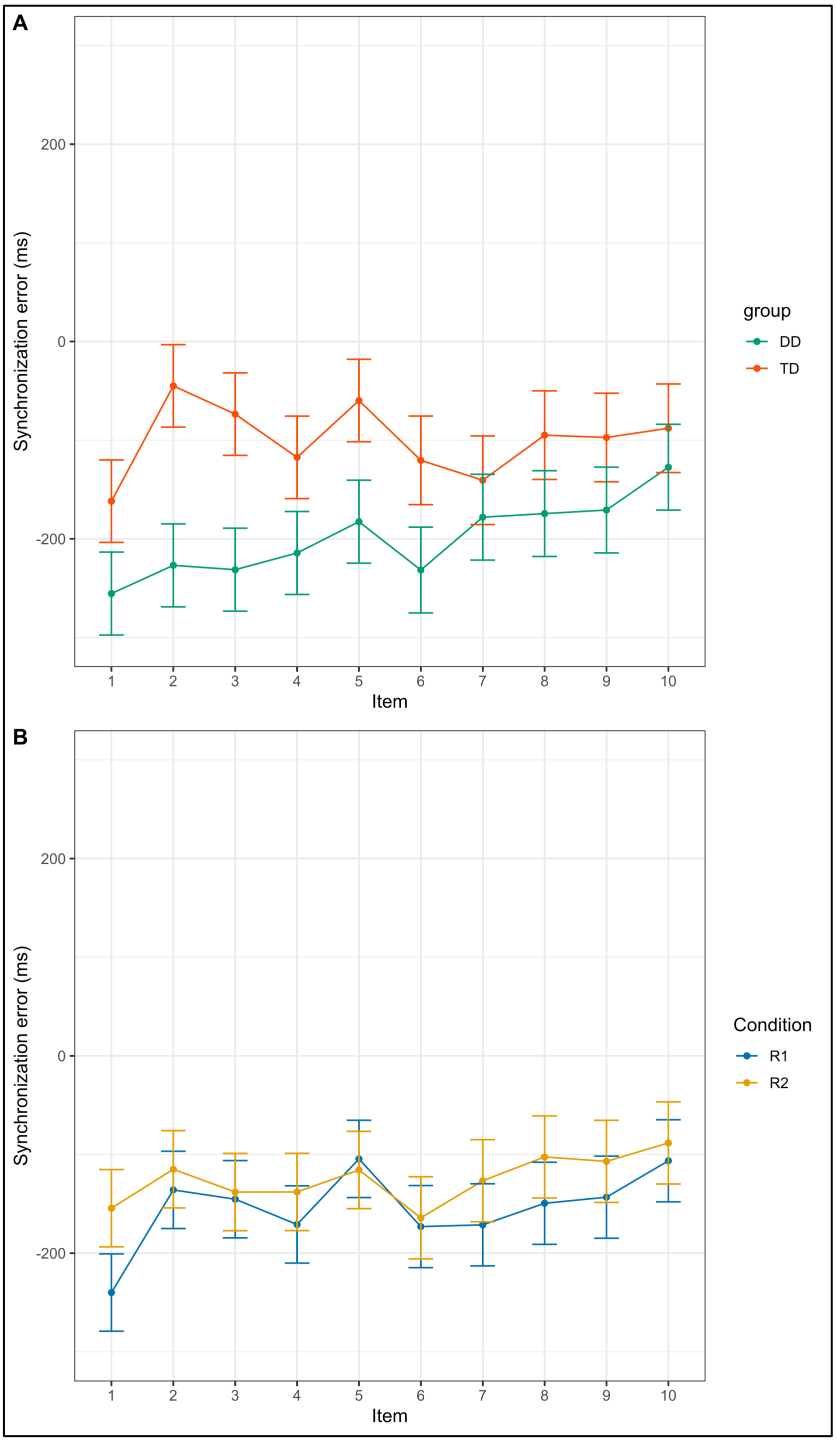


Figure 4. Participants' synchronization errors in the warning imperative task by item and by group (A) or rhythmic condition (B). The zero represents the onset of the tone: closer responses to 0 indicate smaller asynchronies and, thus, higher precision. Any response below or above 0 is given early or late, respectively, with respect to the beat. Model effects are plotted using the r package "effects" (Fox & Weisberg, 2019).

Determiner processing task

To minimize data handling errors, output txt files were imported in and prepared for R through loops using customized scripts. Item 10 was removed from the analysis because of a methodological problem. Accuracy in this task was at ceiling (98.6 %).

Response times (calculated as explained in Chapter 2) that had been given either too early (100 milliseconds after the onset of the determiner or earlier) or too late (three seconds later than the offset of the longest noun) were considered invalid and therefore substituted with NA. The remaining RTs were analyzed in a LMM in R (R Development Core Team, 2016; lmer function in the "lme4" package, Bates et al., 2015). The model included Condition and Group as fixed effects, Age as covariate, and Subject and Item as random effects. Results showed a non-significant effect of Group (p = .394) and a marginally significant effect of Condition (F(2, 13.92) = 3.343, p = .065). Post-hoc tests with the Tukey correction were run to further investigate possible trends across conditions: tests showed only a marginally significant difference between the third (GPS) and the first (G) conditions (z-value = -2.193, p = .072; condition 1 vs. condition 2: z-value = 0.573, p = .834; condition 2 vs. condition 3: z value = 1.699, p = .206), with the condition providing all three cues to gender being the one in which participants tended to have slightly (but not significantly) faster responses (see Figure 5).

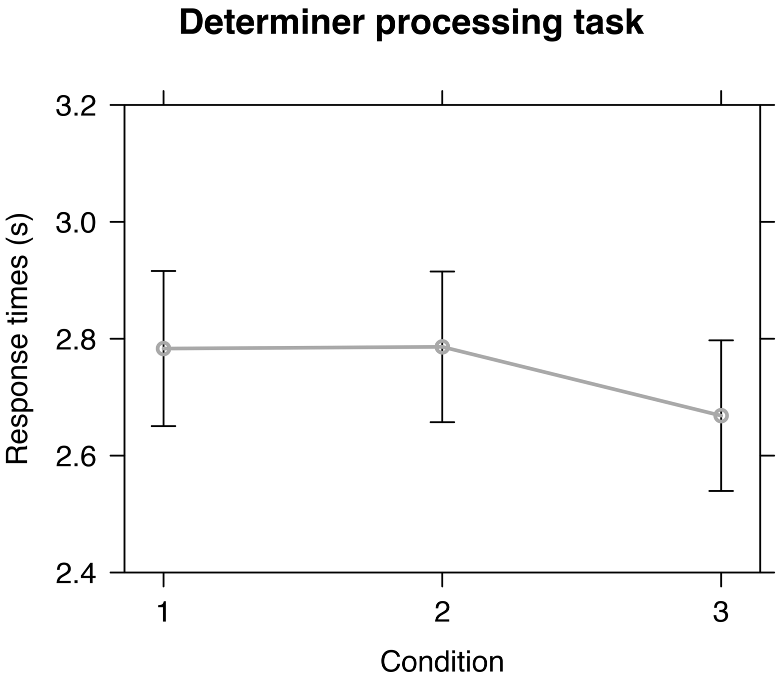


Figure 5. Response times (s) in the determiner processing task across the three conditions (1 G, 2 GP, and 3 GPS).

Clitic processing task

Matlab output txt files were imported in and prepared for R through loops using customized scripts. As in the determiner processing task, item 10 was removed from the analysis because of a methodological error. All children were able to perform this task, as shown by their very high accuracy rate (98.3%). Response times in the clitic processing task were calculated as in the determiner processing task; data cleaning procedures were carried out following the same criteria of the previous study (see Chapter 2).

The remaining RTs were analyzed in a LMM that included Condition and Group as fixed effects, Age as Covariate, and Subject and Item as random effects. We found significant effects of Condition ($F(2, 14.05) = 5.362, p = .019$), and of Group ($F(1, 43.08) = 4.916, p = .032$), and a significant interaction between Condition and Group ($F(2, 695.25) = 5.242, p = .005$). Post-hoc tests after the significant Condition × Group interaction were performed using the "testInteractions" function in the "phia" package (De Rosario-Martinez, 2015). Results showed significantly different performance between groups in conditions 1 ($\chi^2_{(2)} = 9.220, p = .002$) and 2 ($\chi^2_{(2)} = 4.594, p = .032$), but not in condition 3, where the two groups showed more comparable response speed ($\chi^2_{(2)} = 0.919, p = .338$). Post-hoc tests also showed that differences between conditions were statistically significant only in the DD group, and specifically in the comparison of conditions 1 and 3 ($\chi^2_{(2)} = 16.729, p < .001$), and conditions 2 and 3 ($\chi^2_{(2)} = 10.565, p = .001$), but not when comparing conditions 1 and 2 ($\chi^2_{(2)} = 0.994, p = .319$) (see Figure 6).

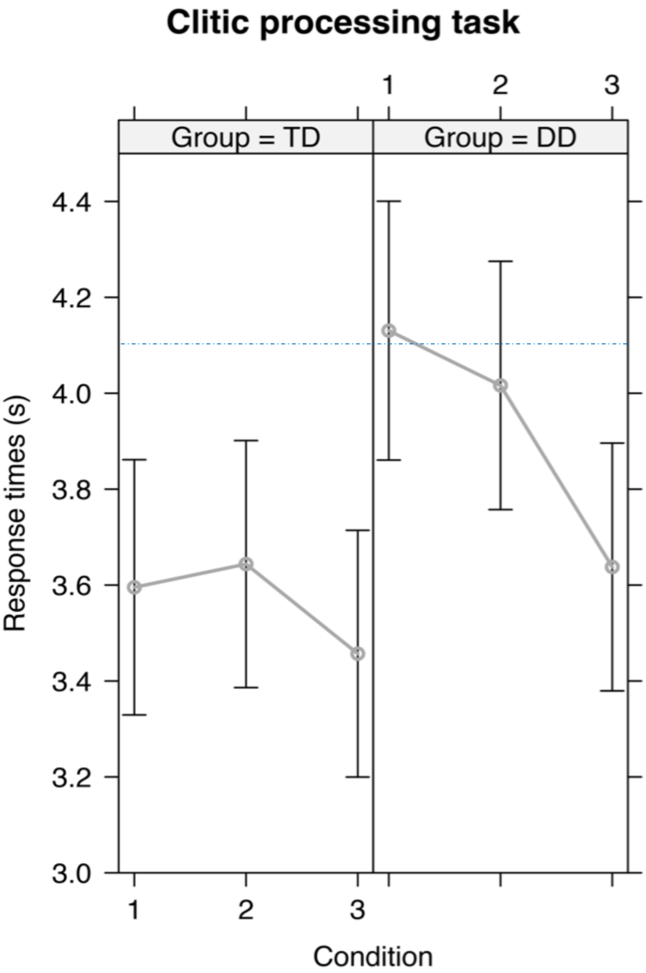


Figure 6. Response times (s) in the clitic processing task in the three conditions (1 G, 2 GP, and 3 GPS) by group. The blue dotted line represents the onset of the DP following the clitic pronoun.

To further investigate whether the number of gender cues available, and/or having dyslexia or not, had any influence on the degree with which participants correctly anticipated incoming nouns in this task, we assigned the responses given before the onset of the DP at 4100 ms a score of 1 and a score of 0 to all the others. The resulting ‘Anticipation ratio’ (of anticipated vs. not anticipated nouns) were analyzed in a Generalized Linear Mixed Model (GLMM) with Group and Condition as predictors, Age as covariate, and Subject and Item as random effects. Likelihood ratio tests showed significant effects of Group ($\chi^2_{(1)} = 5.003$, *p* = .025) and Condition ($\chi^2_{(2)} = 14.178$, *p* < .001), but no significant interaction (*p* = .097, see Figure 7). Posthoc tests (package “emmeans”; Lenth, 2018) showed significantly better ‘Anticipation ratio’ in the TD group (z-ratio = 2.256, *p* = .024) and in general in condition 3

(GPS) than in conditions 1 (G) (z-ratio = 4.043, $p < .001$) and 2 (GP) (z-ratio = 4.031, $p < .001$) (see Figure 7).

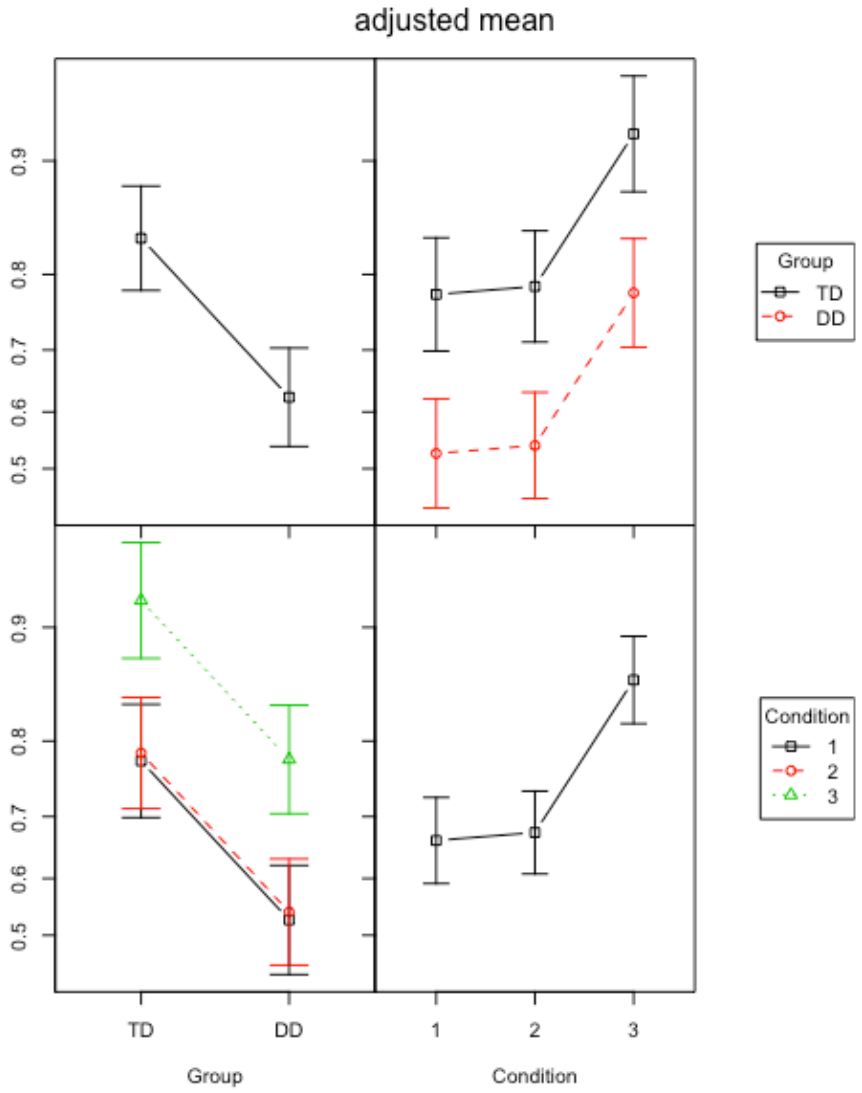


Figure 7. The left panels show the anticipation ratio in the two groups averaged (top left panel) or not (bottom left) over the levels of Condition. The right side of the figure shows the mean scores by condition (bottom right) and by condition and group (top right). The figure shows clear differences between groups and among conditions, with the TD performing better than the DD group, and with higher scores in condition 3 (GPS) than in the other two conditions. However, the two factors did not interact: the same pattern can be seen both in the two groups across conditions and in each condition across groups.

Correlations between the language and rhythm tasks

To investigate whether less precision in the warning imperative task (i.e., farther responses from 0) corresponded to less efficient mechanisms of prediction in language (i.e., longer RTs in the language tasks), Spearman correlations were run between the warning imperative task and the determiner and clitic processing tasks (function "cor.test") within each group. For the WIT, only the responses preceding the beat (i.e., the negative RT values) were considered. As mentioned in Chapter 2, negative asynchronies are the ones that are thought to reflect anticipatory processes and that are consistently found in adults and musicians (Aschersleben, 2002).

In the TD group, results showed moderate, significant, inverse correlations between mean synchronization error in the warning imperative task and mean RTs in the determiner processing task, and between the synchronization error in the stressed rhythmic condition and the RTs in the grammatical condition in the determiner processing task (condition 1, G), meaning that the closer to 0 the responses in the WIT were, the faster were the response times in the language task when only the lexical gender information was available (see Table 3 and Figure 8). Tests also showed a marginally significant correlation between the stressed rhythmic condition of the WIT and condition 2 (GP) of the determiner processing task (p = .052, see Table 3). Interestingly, the response times in the same condition of the determiner processing task also correlated with the speed of pseudoword decoding ($r_{(s)} = 0.581$, $p = .01$) in the typical kids, as in the previous study. No significant correlations were found between the WIT and the clitic processing task in this group (as in the previous study, see Chapter 2) or between any of the tasks in the DD group.

Table 3

Spearman correlations between the synchronization error in the rhythmic task and the RTs in the determiner processing task in the TD group.

		Determiner processing task			
		Mean RT	Condition 1 (G)	Condition 2 (GP)	Condition 3 (GPS)
Rhythmic task (WIT)	Mean synchronization error	-0.48 *	-0.28	-0.31	-0.23
	Condition 1 (unstressed)	-0.23	-0.29	-0.27	-0.07
	Condition 2 (stressed)	-0.53 *	-0.57 *	-0.47 .	-0.38

Note. p = .05 '.', p < .05 '*', p < .01 '**', p < .001 '***'.

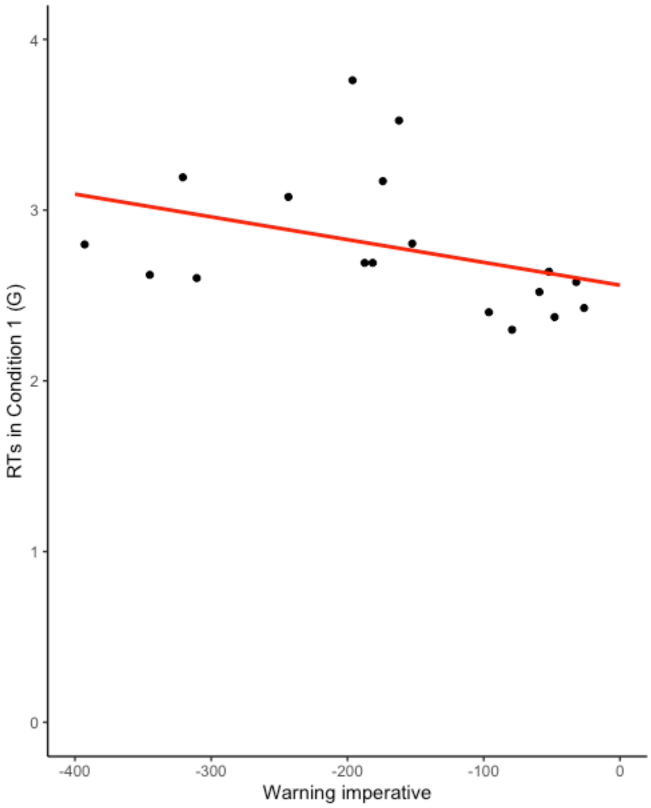


Figure 8. Correlation between the negative asynchrony in the warning imperative task and the response time in the grammatical condition in the determiner processing task.

3.2.3 Discussion

The goal of this study was to investigate whether anticipation abilities in language and music are impaired in children with developmental dyslexia. As hypothesized, reading difficulties in dyslexia may stem from an impairment in prediction-making mechanisms, which makes anticipating incoming input more difficult, and the overall process of reading less efficient.

Of interest in language and rhythmic processing, as well as in reading, are structure-based predictions, which are automatically and compulsorily given rise to upon the processing of the combinatory features of a structure. More specifically, here we investigated anticipation processes in rhythmic and morphosyntactic processing.

To investigate rhythmic processing we used a warning imperative (tapping) task with a stressed and an unstressed rhythmic condition. As already mentioned, rhythmic processing and production deficits in individuals with dyslexia are well documented in the literature (see section 1.1 in Chapter 1), though the underlying cause is still under debate. In our study, we found confirmation of a rhythmic deficit in children with DD. In fact, children with dyslexia were significantly less precise in synchronizing their taps to the beat than typically developing age-matched peers. As expected, we also found a general advantage in the stressed rhythmic condition. Though the absence of the beat is known not to compromise rhythmic processing or the automatic formation of a sense of meter (Bolton, 1894), the alternation of strong and weak tones may not only help participants build a stronger metric interpretation of the rhythmic structure, but also access its hierarchical structure more easily, and allow for more accurate predictions on the timing of future inputs. Importantly, we also found a general improvement over the course of the task, with more precise taps towards the end of the task than at the beginning. This improvement may not only be due to practice effects: exposure to rhythmic sequences and neural synchronization may also have contributed. As already discussed in Chapter 1, exposure to rhythmic sequences is thought to trigger mechanisms of neural entrainment that modulate temporal attention and facilitate perception, segmentation, and integration of future stimuli (Jones & Boltz, 1989; Large, Herrera, & Velasco, 2015). Similarly, accumulative exposure to the rhythmic sequences throughout our task may have led to improved neural entrainment and predictions. Interestingly, this improvement is found in general across participants, and not specifically in the TD group. This suggests that even children with dyslexia may benefit from exposure to rhythmic sequences, despite starting from a disadvantaged position in terms of neural entrainment (e.g., see Power, Mead, Barnes, & Goswami, 2013). This has even more important implications for clinical interventions, considering that improved predictions in one domain are found to transfer to other domains as well. In fact, positive rhythmic priming effects have not only been found in rhythm processing, but also in language (e.g., Chern, Tillmann, Vaughan, & Gordon, 2018; Ladányi, Lukács, & Gervain, in preparation).

To investigate structure-based anticipation processes in language, we used a determiner and a clitic processing task. Determiners and clitic pronouns are gender-marked elements that trigger the expectation of a following noun with the same gender features. However, little is known about the use of determiners and clitics in comprehension.

In the determiner processing task, we did not find differences between groups or conditions. This may suggest (i) that determiner comprehension is not impaired in dyslexia and (ii) that the type of gender information contained in the determiner does not affect processing efficiency in children. However, it should be noted that a limitation of this task was the little time granted to participants for the anticipation of the upcoming noun; therefore, absence of effects may also be due to a methodological problem.

On the other hand, in the clitic processing task, we found differences both between groups and conditions. More specifically, the DD group was significantly slower in choosing the appropriate target picture when the grammatical and phonological, or the grammatical information to gender only, were present, both as compared to the condition in which all cues were available, and as compared to TD group; the two groups performed similarly when the semantic gender information was available. These results suggest that, while semantic information to gender is processed efficiently and is used to infer the lexical gender of a noun by children with dyslexia, phonological information is processed less efficiently, and the access and use of lexical gender information alone might be problematic. Moreover, the DD group was also found to give anticipatory responses (that is, before the onset of the following DP) with a significantly lower rate than the TD group. Altogether, these results support the increasingly larger literature claiming the existence of an additional deficit in morphosyntactic processing in dyslexia (e.g., Cantiani et al., 2015).

Moreover, deficient (but not atypical) hierarchical processing in language correlates with the same process in rhythm and with rapidity of pseudoword decoding. In fact, the less efficiently the typically developing children anticipated what linguistic material would follow in the determiner processing task, the larger their negative asynchrony in the tapping task was: this suggests a certain difficulty with sensorimotor synchronization, as well as with anticipation processes. Critically, this result and the significant correlation found between response times in the determiner processing task and speed of pseudoword reading were found only in the condition in which the sole grammatical gender information is available. Given that this is the condition in which hierarchical processing is especially hard and structure-based anticipation mechanisms have to be especially efficient, these results support the idea of anticipation processes being critical for efficient rhythmic and morphosyntactic processing, as well as for efficient reading. Though children with dyslexia do not show clear correlations between their performance in the two tasks, the analyses presented above suggest deficient performance in both rhythmic and morphosyntactic processing, possibly as a result of impaired structure-based prediction abilities. Weaker anticipation processes may be one of the underlying causes of rhythmic and morphosyntactic deficits in dyslexia, possibly as a result of impaired neural entrainment to auditory stimuli.

Interestingly, intervention studies and research with adults show that musical training may partly remediate these deficits. As discussed in Chapter 1, musicians with dyslexia have both better auditory temporal processing (Bishop-Liebler, Welch, Huss, Thomson, & Goswami, 2014) and better amplitude information processing (Zuk et al., 2017) as compared to non-musicians with dyslexia. Rhythmic stimulation may enhance neural entrainment, and by consequence, speech and language processing. These hypotheses are addressed in Chapter 4.

3.2.4 References

Arosio, F., Branchini, C., Barbieri, L., & Guasti, M. T. (2014). Failure to produce direct object clitic pronouns as a clinical marker of SLI in school-aged Italian speaking children. *Clinical Linguistics and Phonetics*, *28*(9), 639–663. https://doi.org/10.3109/02699206.2013.877081

Arosio, F., Pagliarini, E., Perugini, M., Barbieri, L., & Guasti, M. T. (2016). Morphosyntax and logical abilities in Italian poor readers: The problem of SLI under-identification. *First Language*, *36*(3), 295–315. https://doi.org/10.1177/0142723716639501

Aschersleben, G. (2002). Temporal Control of Movements in Sensorimotor Synchronization. *Brain and Cognition*, *48*(1), 66–79. https://doi.org/10.1006/BRCG.2001.1304

Bartolo, R., Prado, L., & Merchant, H. (2014). Information processing in the primate basal ganglia during sensory-guided and internally driven rhythmic tapping. *Journal of Neuroscience*, *34*(11), 3910–3923. https://doi.org/10.1523/JNEUROSCI.2679-13.2014

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using **lme4**. *Journal of Statistical Software*, *67*(1), 1–48. https://doi.org/10.18637/jss.v067.i01

Bishop-Liebler, P., Welch, G., Huss, M., Thomson, J. M., & Goswami, U. (2014). Auditory temporal processing skills in musicians with dyslexia. *Dyslexia*, *20*(3), 261–279. https://doi.org/10.1002/dys.1479

Bolton, T. L. (1894). Rhythm. *American Journal of Psychology*, *6*, 145–238.

Bonacina, S., Cancer, A., Lanzi, P. L., Lorusso, M. L., & Antonietti, A. (2015). Improving reading skills in students with dyslexia: The efficacy of a sublexical training with rhythmic background. *Frontiers in Psychology*, *6*(OCT). https://doi.org/10.3389/fpsyg.2015.01510

Bortolini, U., Arfé, B., Caselli, C. M., Degasperi, L., Deevy, P., & Leonard, L. B. (2006). *Clinical markers for specific language impairment in Italian: the contribution of clitics and non-word repetition*. *International Journal of Language & Communication Disorders* (Vol. 41). John Wiley & Sons, Ltd (10.1111). https://doi.org/10.1080/13682820600570831

Bortolini, U., Caselli, M. C., & Leonard, L. B. (1997). Grammatical deficits in Italian-speaking children with specific language impairment. *Journal of Speech, Language, and Hearing Research*, *40*(4), 809–820. https://doi.org/10.1044/jslhr.4004.809

Bottari, P., Cipriani, P., Chilosi, A. M., & Pfanner, L. (2001). The Italian determiner system in normal acquisition, specific language impairment, and childhood aphasia. *Brain and Language*, *77*(3), 283–293. https://doi.org/10.1006/brln.2000.2402

Cantiani, C., Lorusso, M. L., Perego, P., Molteni, M., & Guasti, M. T. (2015). Developmental Dyslexia With and Without Language Impairment: ERPs Reveal Qualitative Differences in Morphosyntactic Processing. *Developmental Neuropsychology*, *40*(5), 291–312. https://doi.org/10.1080/87565641.2015.1072536

Chern, A., Tillmann, B., Vaughan, C., & Gordon, R. L. (2018). New evidence of a rhythmic priming effect that enhances grammaticality judgments in children. *Journal of Experimental Child Psychology*, *173*, 371–379. https://doi.org/10.1016/j.jecp.2018.04.007

Colling, L. J., Noble, H. L., & Goswami, U. (2017). Neural entrainment and sensorimotor synchronization to the beat in children with developmental dyslexia: An EEG study. *Frontiers in Neuroscience*, *11*(JUL). https://doi.org/10.3389/fnins.2017.00360

Cutini, S., Szucs, D., Mead, N., Huss, M., & Goswami, U. (2016). Atypical right hemisphere response to slow temporal modulations in children with developmental dyslexia. *NeuroImage*, *143*, 40–49. https://doi.org/10.1016/j.neuroimage.2016.08.012

Dahan, D., Swingley, D., Tanenhaus, M. K., & Magnuson, J. S. (2000). Linguistic Gender and Spoken-Word Recognition in French. *Journal of Memory and Language*, *42*(4), 465–480. https://doi.org/10.1006/jmla.1999.2688

De Rosario-Martinez, H. (2015). phia: Post-Hoc Interaction Analysis. R package version 0.2-1. Retrieved from https://cran.r-project.org/package=phia

Dellatolas, G., Watier, L., Le Normand, M. T., Lubart, T., & Chevrie-Muller, C. (2009).

Rhythm reproduction in kindergarten, reading performance at second grade, and developmental dyslexia theories. *Archives of Clinical Neuropsychology*, *24*(6), 555–563. https://doi.org/10.1093/arclin/acp044

Ding, N., Melloni, L., Yang, A., Wang, Y., Zhang, W., & Poeppel, D. (2017). Characterizing Neural Entrainment to Hierarchical Linguistic Units using Electroencephalography (EEG). *Frontiers in Human Neuroscience*, *11*, 481. https://doi.org/10.3389/fnhum.2017.00481

Dispaldro, M., Ruggiero, A., & Scali, F. (2015). Real-time comprehension of gender and number in four- to seven-year-old children: A study of the relationship between Italian clitic pronouns and visual picture referents. *Journal of Child Language*, *42*(4), 917–931. https://doi.org/10.1017/S0305000914000427

Flaugnacco, E., Lopez, L., Terribili, C., Montico, M., Zoia, S., & Schön, D. (2015). Music Training Increases Phonological Awareness and Reading Skills in Developmental Dyslexia: A Randomized Control Trial. *PLOS ONE*, *10*(9), e0138715. https://doi.org/10.1371/journal.pone.0138715

Flaugnacco, E., Lopez, L., Terribili, C., Zoia, S., Buda, S., Tilli, S., … Schön, D. (2014). Rhythm perception and production predict reading abilities in developmental dyslexia. *Frontiers in Human Neuroscience*, *8*, 392. https://doi.org/10.3389/fnhum.2014.00392

Fox, J., & Weisberg, S. (2019). *An R Companion to Applied Regression* (3rd ed.). Thousand Oaks CA: Sage.

Fraisse, P., & Repp, B. H. (2012). Anticipation of rhythmic stimuli: Speed of establishment and precision of synchronization (1966). *Psychomusicology: Music, Mind, and Brain*, *22*(1), 84–93. https://doi.org/10.1037/a0028758

Frey, A., François, C., Chobert, J., Besson, M., & Ziegler, J. C. (2019). Behavioral and electrophysiological investigation of speech perception deficits in silence, noise and envelope conditions in developmental dyslexia. *Neuropsychologia*, *130*, 3–12. https://doi.org/10.1016/J.NEUROPSYCHOLOGIA.2018.07.033

Goswami, U. (2011). A temporal sampling framework for developmental dyslexia. *Trends in Cognitive Sciences*, *15*(1), 3–10. https://doi.org/10.1016/J.TICS.2010.10.001

Goswami, U., Cumming, R., Chait, M., Huss, M., Mead, N., Wilson, A. M., … Fosker, T. (2016). Perception of filtered speech by children with developmental dyslexia and children with specific language impairments. *Frontiers in Psychology*, *7*(MAY). https://doi.org/10.3389/fpsyg.2016.00791

Goswami, U., Huss, M., Mead, N., Fosker, T., & Verney, J. P. (2013). Perception of patterns of musical beat distribution in phonological developmental dyslexia: Significant longitudinal relations with word reading and reading comprehension. *Cortex*, *49*(5), 1363–1376. https://doi.org/10.1016/J.CORTEX.2012.05.005

Guasti, M. T. (1993). Verb Syntax in Italian Child Grammar: Finite and Nonfinite Verbs. *Language Acquisition*, *3*(1), 1–40. https://doi.org/10.1207/s15327817la0301_1

Guasti, M. T., Pagliarini, E., & Stucchi, N. (2017). Language, reading and motor control: Get rhythm! *Biolinguistics*, *11*(1), 1–12.

Habib, M., Lardy, C., Desiles, T., Commeiras, C., Chobert, J., & Besson, M. (2016). Music and Dyslexia: A New Musical Training Method to Improve Reading and Related Disorders. *Frontiers in Psychology | Www.Frontiersin.Org*, *7*, 26. https://doi.org/10.3389/fpsyg.2016.00026

Hothorn, T., Bretz, F., & Westfall, P. (2008). Simultaneous Inference in General Parametric Models. *Biometrical Journal*, *50*(3), 346–363.

Huss, M., Verney, J. P., Fosker, T., Mead, N., & Goswami, U. (2011). Music, rhythm, rise time perception and developmental dyslexia: Perception of musical meter predicts reading and phonology. *Cortex*, *47*(6), 674–689. https://doi.org/10.1016/J.CORTEX.2010.07.010

Jones, M. R., & Boltz, M. (1989). Dynamic Attending and Responses to Time. *Psychological Review*, *96*(3), 459–491. https://doi.org/10.1037/0033-295X.96.3.459

Koelsch, S., Vuust, P., & Friston, K. (2018). Predictive Processes and the Peculiar Case of Music. *Trends in Cognitive Sciences*, *xx*, 1–15. https://doi.org/10.1016/j.tics.2018.10.006

Ladányi, E., Lukács, Á., & Gervain, J. (n.d.). Rhythmic priming in children with and without Specific Language Impairment. *In Preparation*.

Landerl, K., Wimmer, H., & Frith, U. (1997). The impact of orthographic consistency on dyslexia: A German-English comparison. *Cognition*, *63*(3), 315–334. https://doi.org/10.1016/S0010-0277(97)00005-X

Large, E. W., Herrera, J. A., & Velasco, M. J. (2015). Neural Networks for Beat Perception in Musical Rhythm. *Frontiers in Systems Neuroscience*, *9*(November), 1–14. https://doi.org/10.3389/fnsys.2015.00159

Large, E. W., & Jones, M. R. (1999). The dynamics of attending: How people track time-varying events. *Psychological Review*. https://doi.org/10.1037/0033-295X.106.1.119

Lee, H.-Y., Sie, Y.-S., Chen, S.-C., & Cheng, M.-C. (2015). The Music Perception

Performance of Children with and without Dyslexia in Taiwan. *Psychological Reports*, *116*(1), 13–22. https://doi.org/10.2466/15.28.PR0.116k15w8

Léger, E., Prévost, P., Tuller, L., Haiden, M., Martineau, J., & Aguillon-Hernandez, N. (2015). The development of object clitics in French: A comparative study between production and real-time interpretation via eye-tracking while listening. In C. Hamann & E. Ruigendijk (Eds.), *Language acquisition and development: Proceedings of GALA 2013* (pp. 232–258). Newcastle: Cambridge Scholar Publishers.

Lenth, R. V. (2018). emmeans: Estimated Marginal Means, aka Least-Squares Means. Retrieved from https://cran.r-project.org/package=emmeans

Leong, V., & Goswami, U. (2014). Impaired extraction of speech rhythm from temporal modulation patterns in speech in developmental dyslexia. *Frontiers in Human Neuroscience*, *8*, 96. https://doi.org/10.3389/fnhum.2014.00096

Leong, V., Hämäläinen, J., Soltész, F., & Goswami, U. (2011). Rise time perception and detection of syllable stress in adults with developmental dyslexia. https://doi.org/10.1016/j.jml.2010.09.003

Lew-Williams, C., & Fernald, A. (2007). Young children learning spanish make rapid use of grammatical gender in spoken word recognition. *Psychological Science*, *18*(3), 193–198. https://doi.org/10.1111/j.1467-9280.2007.01871.x

Lindgren, S. D., De Renzi, E., & Richman, L. C. (1985). Cross-national comparisons of developmental dyslexia in Italy and the United States. *Child Development*, *56*(6), 1404–1417. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/3878269

Lyytinen, H., Ronimus, M., Alanko, A., Poikkeus, A.-M., & Taanila, M. (2007). Early identification of dyslexia and the use of computer game-based practice to support reading acquisition. *Nordic Psychology*, *59*(2), 109–126. https://doi.org/10.1027/1901-2276.59.2.109

Mammarella, I. C., Ghisi, M., Bomba, M., Bottesi, G., Caviola, S., Broggi, F., & Nacinovich, R. (2016). Anxiety and depression in children with nonverbal learning disabilities, reading disabilities, or typical development. *Journal of Learning Disabilities*, *49*(2), 130–139. https://doi.org/https://doi.org/10.1177/0022219414529336

Marconi, L., Ott, M., Pesenti, E., Ratti, D., & Tavella, M. (1994). *Lessico elementare. Dati statistici sull'italiano scritto e letto dai bambini delle elementari.* Zanichelli.

Miyake, Y., Onishi, Y., & Pöppel, E. (2004). Two types of anticipation in synchronization tapping. *Acta Neurobiologiae Experimentalis*, *64*(3), 415–426. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/15283483

Molinaro, N., Lizarazu, M., Lallier, M., Bourguignon, M., & Carreiras, M. (2016). Out-of-synchrony speech entrainment in developmental dyslexia. *Human Brain Mapping*, *37*(8), 2767–2783. https://doi.org/10.1002/hbm.23206

Muneaux, M., Ziegler, J. C., Truc, C., Thomson, J., & Goswami, U. (2004). Deficits in beat perception and dyslexia: evidence from French. *Neuroreport*, *15*(8), 1255–1259. https://doi.org/10.1097/01.wnr.0000127459.31232.c4

Overy, K. (2003). Dyslexia and music: From timing deficits to musical intervention. *Annals of the New York Academy of Sciences*, *999*, 497–505. https://doi.org/10.1196/annals.1284.060

Overy, K., Nicolson, R. I., Fawcett, A. J., & Clarke, E. F. (2003). Dyslexia and music: Measuring musical timing skills. *Dyslexia*, *9*(1), 18–36. https://doi.org/10.1002/dys.233

Pagliarini, E. (2016). *Predictive Timing in Developmental Dyslexia: A New Hypothesis Anticipatory skills across language and motor domains*. Università degli Studi di Milano - Bicocca.

Pagliarini, E., Maffioli, G., Molteni, B., & Stucchi, N. (2016). Predictive timing in Developmental Dyslexia. Poster presented at IWORDD International Workshop in Reading and Developmental Dyslexia.

Paradis, J., Crago, M., & Genesee, F. (2003). Object clitics as a clinical marker of SLI in French: Evidence from French-English bilingual children. In *Proceedings of the Annual Boston University Conference on Language Development* (pp. 638–649). Somerville, MA: Cascadilla Press.

Persici, V., Stucchi, N., & Arosio, F. (2019). Predicting the future in rhythm and language: The anticipation abilities of a group of Italian-speaking children. In P. Guijarro-Fuentes & C. Suárez-Gómez (Eds.), *Proceedings of GALA 2017: Language Acquisition and Development* (pp. 451–468). Newcastle upon Tyne: Cambridge Scholar Publishers.

Power, A. J., Colling, L. J., Mead, N., Barnes, L., & Goswami, U. (2016). Neural encoding of the speech envelope by children with developmental dyslexia. *Brain and Language*, *160*. https://doi.org/10.1016/j.bandl.2016.06.006

Power, A. J., Mead, N., Barnes, L., & Goswami, U. (2013). Neural entrainment to rhythmic speech in children with developmental dyslexia. *Frontiers in Human Neuroscience*, *7*, 777. https://doi.org/10.3389/fnhum.2013.00777

Przybylski, L., Bedoin, N., Krifi-Papoz, S., Herbillon, V., Roch, D., Léculier, L., … Tillmann, B. (2013). Rhythmic auditory stimulation influences syntactic processing in children with developmental language disorders. *Neuropsychology*, *27*(1), 121–131. https://doi.org/10.1037/a0031277

R Development Core Team. (2016). R: A Language and Environment for Statistical Computing. Retrieved from https://www.researchgate.net/publication/312455832_R_A_Language_and_Environment_for_Statistical_Computing

Rayner, K. (1998). *Eye Movements in Reading and Information Processing: 20 Years of Research*. *Psychological Bulletin* (Vol. 124). Retrieved from https://search-proquest-com.proxy.library.vanderbilt.edu/docview/614338602/fulltextPDF/DAACFA0C9B9840A0PQ/1?accountid=14816

Rispens, J., & Been, P. (2007). Subject–verb agreement and phonological processing in developmental dyslexia and specific language impairment (SLI): a closer look. *International Journal of Language & Communication Disorders*, *42*(3), 293–305. https://doi.org/10.1080/13682820600988777

Sartori, G., Job, R., & Tressoldi, P. E. (2007). *DDE-2: Batteria per la valutazione della dislessia e della disortografia evolutiva-2*. Firenze, Italia: O.S. Giunti.

Snowling, M. J. (2013). Early identification and interventions for dyslexia: a contemporary view. *Journtal of Research in Special Educational Needs*, *13*(1), 7–14. https://doi.org/10.1111/j.1471-3802.2012.01262.x

Thomson, J. M., Fryer, B., Maltby, J., & Goswami, U. (2006). Auditory and motor rhythm awareness in adults with dyslexia. *Journal of Research in Reading*, *29*(3), 334–348. https://doi.org/10.1111/j.1467-9817.2006.00312.x

Thomson, J. M., & Goswami, U. (2008). Rhythmic processing in children with developmental dyslexia: Auditory and motor rhythms link to reading and spelling. *Journal of Physiology-Paris*, *102*, 120–129. https://doi.org/10.1016/j.jphysparis.2008.03.007

Thomson, J. M., Leong, V., & Goswami, U. (2013). Auditory processing interventions and developmental dyslexia: A comparison of phonemic and rhythmic approaches. *Reading and Writing*, *26*(2), 139–161. https://doi.org/10.1007/s11145-012-9359-6

Walter, W. G., Cooper, R., Aldridge, W. C., McCallum, W. C., & Winter, L. (1964). Contingent negative variation: an electric sign of sensori-motor association and expectancy in the human brain. *Nature Publishing Group*, *203*, 380–384.

Wolff, P. H., Michel, G. F., Ovrut, M., & Drake, C. (1990). Rate and Timing Precision of Motor Coordination in Developmental Dyslexia. *Developmental Psychology*, *26*(3), 349–359. https://doi.org/10.1037/0012-1649.26.3.349

World Health Organization. (2004). *International Statistical Classification of Diseases and Health Related Problems (ICD-10)* (Second Ed.). Genève: WHO Press.

Ziegler, J. C., & Goswami, U. (2005). Reading Acquisition, Developmental Dyslexia, and Skilled Reading Across Languages: A Psycholinguistic Grain Size Theory. *Psychological Bulletin*, *131*(1), 3–29. https://doi.org/10.1037/0033-2909.131.1.3

Zuk, J., Bishop-Liebler, P., Ozernov-Palchik, O., Moore, E., Overy, K., Welch, G., & Gaab, N. (2017). Revisiting the "Enigma" of Musicians With Dyslexia: Auditory Sequencing and Speech Abilities. *Journal of Experimental Psychology: General*, *146*(4), 495–511. https://doi.org/10.1037/xge0000281

Chapter 4

Rhythmic and morphosyntactic predictions in musician and non-musician typically-developing children

4.1 Introduction

Decades of research have shown that musicians have a number of advantages in language acquisition and processing: in fact, they not only find it easier to learn a second language (cf. Kraus & Chandrasekaran, 2010), but also show enhanced skills in their first language; examples are found in speech-in-noise perception, voice recognition, but also syllable processing, auditory working memory and attention, vocabulary development, speech segmentation, and reading skills (Brod & Opitz, 2012; Jakobson, Lewycky, Kilgour, & Stoesz, 2008; Kraus & Chandrasekaran, 2010; Lee, Lu, & Ko, 2007; Marie, Magne, & Besson, 2011; Musacchia, Sams, Skoe, & Kraus, 2007; Sares, Foster, Allen, & Hyde, 2018; Zuk et al., 2013). These advantages have been interpreted as the result of enhanced auditory and sensorimotor skills due to continuous music practice, and to transfer of these skills to the linguistic domain.

Evidence that long and continuous practice leads to enhanced skills in music is found in behavioral, electrophysiological, and neuroimaging studies. Musicians show better rhythm production abilities (both children and adults Drake, 1993), greater sensitivity in rhythmic processing (Habibi, Wirantana, & Starr, 2014; Vuust, Ostergaard, Pallesen, Bailey, & Roepstorff, 2009; Vuust et al., 2005), and structural differences in the brain areas directly involved in the execution of musical skills, i.e., in motor, auditory, and visual-spatial brain regions (Bangert et al., 2006; Gaser & Schlaug, 2003; Schneider, Scherg, & Dosch, 2002). Moreover, research has shown that musicians process rhythm just like native speakers process their first language (Vuust et al., 2005). In fact, it has been suggested that sounds are processed with greater involvement of the left hemisphere only when they are perceived as meaningful (Näätänen et al., 1997; Vuust et al., 2005); interestingly, differences in lateralization are not only found between native and non-native speakers when processing sounds in language (Näätänen et al., 1997), but also between musicians and non-musicians when processing rhythmic patterns: while rhythmic incongruities are right-lateralized in non-musicians, they appear to be left-lateralized in expert jazz musicians (Vuust et al., 2005).

Enhanced auditory and sensorimotor abilities developed through musical training might then transfer to the language domain, and possibly partly remediate language-related disorders. One interesting study providing evidence in favor of this hypothesis is Zuk et al. (2017). In this study the authors tested adult musicians and non-musicians, either with or without dyslexia, in a series of tasks to investigate their auditory sequencing and speech discrimination abilities. Interestingly, though musicians with DD did not perform as well as musicians with typical development (TD), the performance of the musicians with dyslexia was still significantly better than the performance of non-musician TDs: these results suggest a positive effect of musical training on language skills. There are several reasons to believe that music, and more specifically rhythm, can affect language skills. As discussed in the previous chapters, numerous evidence indicates that abilities in one domain are associated with abilities in the other (Anvari, Trainor, Woodside, & Levy, 2002; Degé, Kubicek, & Schwarzer, 2015; Douglas & Willatts, 1994; Flaugnacco et al., 2014; Forgeard, Winner, Norton, & Schlaug, 2008; Gordon, Shivers, et al., 2015; Grube, Kumar, Cooper, Turton, & Griffiths, 2012; Holliman, Wood, & Sheehy, 2010; Magne, Jordan, & Gordon, 2016; Moritz, Yampolsky, Papadelis, Thomson, & Wolf, 2013; Overy, 2003; Ozernov-Palchik, Wolf, & Patel, 2018; Politimou, Dalla Bella, Farrugia, & Franco, 2019; Strait, Hornickel, & Kraus, 2011); moreover, studies have shown that populations with disordered language or reading abilities exhibit deficits in rhythm production and perception (see our study in Chapter 2 and Corriveau & Goswami, 2009; Corriveau, Pasquini, & Goswami, 2007; Goswami et al., 2002; Wolff, Michel, Ovrut, & Drake, 1990).

Though differences in speech perception (Magne et al., 2016; Mankel & Bidelman, 2018) and syntactic processing abilities (Gordon, Jacobs, Schuele, & McAuley, 2015; Moritz et al., 2013; Politimou et al., 2019; Woodruff Carr, White-Schwoch, Tierney, Strait, & Kraus, 2014) have been found to be predicted by musical ability or aptitude *beyond* whether or not participants studied music, intervention studies have shown that even short- and mid-term musical training is beneficial for language and literacy abilities, both for typically-developing populations and for individuals with dyslexia (Degé & Schwarzer, 2011; François, Chobert, Besson, & Schön, 2013; Linnavalli, Putkinen, Lipsanen, Huotilainen, & Tervaniemi, 2018; Moritz, Yampolsky, Papadelis, Thomson, & Wolf, 2013; Patscheke, Degé, & Schwarzer, 2019; Rautenberg, 2015; Taub & Lazarus, 2012; Zhao & Kuhl, 2016; see Chapter 1). For instance, Overy (2003) showed that after only 15 weeks of musical training children with DD already showed improved performance in phonological and spelling tasks (important for reading); importantly, Moreno et al. (2009) showed that the language skills of a group of eight-year-old TD children were improved after nine months of musical training, but not after nine months of painting lessons (in the control group). Moreover, improvements seem to increase as a function of amount and intensity of musical training: Moritz et al. (2013) showed that the kindergarteners who received longer and daily music training over one academic year had significantly better phonological awareness than those who took part in shorter weekly music lessons. These findings confute the idea that linguistic benefits are due to training in general; there seems to be something specific to music that is particularly helpful for literacy and language development and processing, especially if training is intense and continuous. Though music *ability* has a genetic basis (Tan, McPherson, Peretz, Berkovic, & Wilson, 2014), musical training might influence mechanisms that are shared, or that facilitate, language. Further evidence for the importance of the exposure to rhythm, and to music in general, for language processing comes from priming studies, which have shown improved grammatical performance after hearing regular rhythmic primes, both in TD and in DLD children (Bedoin, Brisseau, Molinier, Roch, & Tillmann, 2016; Chern, Tillmann, Vaughan, & Gordon, 2018; Ladányi, Lukács, & Gervain, submitted; Przybylski et al., 2013). It should be noted that, in those tasks, only the exposure to *regular* rhythmic primes produced positive effects in grammar performance, not the exposure to any sound. Thus, musical rhythm and its regularity and predictability might be the key musical aspect that is most beneficial to language, possibly because exposure to it enhances the individuals' general prediction abilities.

Finally, if short-term exposure to rhythm is enough to create a facilitating effect on language, it is hypothesizable that long-term exposure and continuous practice of auditory and sensorimotor skills might yield more significant and long-lasting linguistic effects, especially if music instruction starts at an early age (and within 'a critical period'; Schlaug, 2001). Besides the findings reported above, research has shown that musicians' brains present structural differences that are related to the early start of and to long-term instrumental training (Schlaug, Lutz, Huang, Staigeri, & Steinmetz1, 1995), and that are thought to support advantages in functional connectivity (Schlaug, 2001; Zamorano, Cifre, Montoya, Riquelme, & Kleber, 2017). The structural and functional differences found in musicians who received early and continuous musical training throughout their life may lead to greater linguistic benefits; this hypothesis makes the comparison of 'early' musicians and non-musicians particularly interesting.

4.2 The present study

Prior studies have shown stronger harmonic syntactic predictions (e.g., Fogel, Rosenberg, Lehman, Kuperberg, & Patel, 2015; Koelsch, Schmidt, & Kansok, 2002), and more recently, stronger rhythmic predictions (Sun, Liu, Zhou, & Jiang, 2018) in musicians than in non-musicians. In fact, musicians show greater sensitivity to rhythmic syntactic violations than non-musicians (Sun et al., 2018), which suggests stronger syntactic predictions in rhythmic processing to start with. According to Patel and Morgan (2017), the enhanced harmonic and rhythmic prediction skills found in musicians may be the result of two processes: (i) the enhancement of auditory working memory due to musical training (and to the need to listen and reproduce long musical sequences), and (ii) the fact that predictions are strengthened by repetition in music perception. Better auditory working memory skills have been found to facilitate word associations and structure-based predictions involving access to hierarchical structures (Boudewyn, 2013; Just & Carpenter, 1992), possibly because greater memory skills make access and processing of complex hierarchical structures, as well as temporal and content predictions, easier (Arosio, Persici, & Pagliarini, in press). Secondly, the repetition of the same melodies or rhythmic patterns has been shown to draw the listeners' attention to other aspects of the stimuli, and more precisely, to higher levels of their structure (see Margulis, 2012).

The ability to predict incoming material based on the features of preceding elements of its structure may then transfer to language. This hypothesis would help explain why musicians have superior reading and language skills: musicians, who are used at making structure-based predictions in rhythm and therefore seemingly developed stronger prediction skills, might be better at predicting upcoming words. As already mentioned in previous chapters, predictions are important for language and for reading: anticipating incoming input makes language processing and reading more efficient and less resource-demanding (Kuperberg, 2013; see also Guasti, Pagliarini, & Stucchi, 2017; Persici, Stucchi, & Arosio, 2019). Moreover, given the structural differences in musicians' brains that are found in relation to age of initiation of musical training (Schlaug, 2001; Schlaug et al., 1995), it is possible to hypothesize that differences in prediction skills between musicians and non-musicians are largest if the musician group only includes participants who started training very early in their life.

To investigate whether enhanced prediction skills in both rhythm and language in musicians are already visible at childhood, we tested the anticipation skills of musician children aged between 4 and 12 years during tasks of rhythmic synchronization and morphosyntactic processing, and we compared their performance to a group of TD children without music experience. Our participants were drawn from music schools following the Suzuki method. This method, founded by a Japanese violinist named Shinichi Suzuki in the post-World War II period and initially called "Talent Education", is today widely taught and applied in many countries (Kendall, 1985). The method is based on two main concepts: the ideas that talent can be "taught", and that music can be learned in the same way as we learn our first language, if enough and adequate stimuli are provided in the surrounding environment. Importantly for our study, children are taught how to play before they are even able to read, around age three or four, by imitation and by giving great importance to listening and rhythm. Children who are trained following this method might show even greater linguistic enhancements, and are, in this sense, the perfect candidates for studying the effect of early exposure to rhythm on language skills.

In comparing musicians and non-musicians, we expected to find enhanced prediction skills in the musician group in both rhythm tasks (because of training) and language tasks (because of transfer effects). As explained in previous chapters of this work, efficient rhythmic synchronization and morphosyntactic processing rely on the ability to make accurate predictions regarding the timing or content of the underlying structure; therefore, musicians should show enhanced sensorimotor synchronization skills, but also enhanced predictions in morphosyntactic processing. Given the findings that report associations between musical training and reading component skills (e.g., Moritz et al., 2013) and between musical training and memory skills (e.g., Jakobson et al., 2008; Lee et al., 2007), we also compared musician and non-musician children in reading and short-term auditory memory tests.

Finally, we explored the possibility that the musician children's performance in these and in the anticipation tasks was affected by variables such as bilingualism, frequency of instrument play, and type of instrument played. Prior research has shown that both musicianship (e.g., Degé, Kubicek, & Schwarzer, 2011) and speaking more than one language (e.g., Bialystok, Craik, Klein, & Viswanathan, 2004) have positive effects on abilities such as cognitive control and executive function, which are important for language and music performance. However, it is still unclear whether these benefits are additive in bilingual musicians (cf. D'Souza, Moradzadeh, & Wiseheart, 2018; Moradzadeh, Blumenthal, & Wiseheart, 2015). We also tested the possible effect of the frequency with which participants played, because continuous practice of auditory and sensorimotor skills is important for the development of both rhythm and language skills, and more hours of exposure to and practice of music and rhythm at such a critical age are likely to give children a greater advantage in language as well (see Moritz et al., 2013 to see how more intensive musical training benefits phonological awareness). Finally, we explored the possibility that different instruments might yield different language and reading effects, as this variable has been shown to generate structural and functional brain differences within the musician group. In fact, previous research has shown that the musicians’ brains are not only different as compared to non-musicians, due to the exposure to and continuous practice of music, but also tend to adapt to the particular sensorimotor experiences associated with the instrument played: musicians playing different instruments show different neural responses to instrument sounds (Pantev, Roberts, Schulz, Engelien, & Ross, 2001) and exhibit hemispheric differences (Bangert & Schlaug, 2006).

This chapter will first present the results of the Suzuki group alone, to better study this sample and the possible influence of additional factors such as bilingualism on their language abilities. Then, the performance of the monolingual Suzuki children will be compared to that of monolingual TD children with no music experience. As mentioned above, we expected the Suzuki children to perform better in reading, short term memory, and anticipation tasks. As in the previous chapters, in the rhythmic task we further expected participants to be facilitated by the presence of physical accents in the rhythmic structure, and to make increasingly more accurate predictions throughout the task. In the morphosyntactic processing tasks we expected participants to anticipate the incoming noun based on the gender features of the preceding determiner or clitic pronoun, and we expected child participants to make faster predictions when all cues to gender were available. Finally, we expected the anticipation abilities in one domain to correlate with the anticipation abilities in the other domain, and therefore to see faster predictions in language for the children who had better sensorimotor synchronization skills (and vice versa).

4.2.1 Methods

Participants

Participants were recruited from two Suzuki schools, one in Milan, the other in Gallarate, near Milan, Italy. The children whose families agreed to take part in the study were 41 in Milan and 21 in Gallarate. Two subjects had to be excluded because of reported speech-language problems. The remaining 40 children in the Milan group ranged in age between 4 and 12 years and had a mean age of 8.5 years (SD = 2.2 years; 23 females). The remaining children from Gallarate were 20 in total and had a mean age of 7.5 years (SD = 2.7 years; range: 3 – 11 years, 11 females). As shown by t-tests, neither age ($t(32.65) = 1.5$, $p = .143$), nor socio-economic status (measured by using maternal education as proxy; $t(58) = 1.364$, $p = .178$) were significantly different between the participants of the two Suzuki schools (see Table 1).

Information on the participants and their families was collected through a parental questionnaire. Questions included the highest level of education of both parents (which we used to measure socio-economic status), the instrument played by the children, and the frequency with which they played music. Rates were given on a scale that went from 0 ("never") to 3 ("every day", with 1 and 2 being "a few hours a month" and "a few hours a week"). Additional questions required parents to indicate how many languages, how frequently (from "never" to "every day"), and how well their child spoke and understood any additional language besides Italian; scales for comprehension and production proficiency went from 1 ("barely") to 5 ("perfectly"). Based on the information provided by the parents, children were considered bilingual if they had a mean production and comprehension score of at least 4 in their L2 and if they spoke the L2 in family and/or elsewhere for at least a few hours a week. The resulting ratio of monolinguals and bilinguals is indicated in Table 1.

All participants had normal or corrected-to-normal vision and normal IQ. None of the participants included in the analyses had diagnosed or reported speech or language problems or hearing impairments. The study was approved by the ethics committee of the University of Milano – Bicocca (protocol number: 199_2018bis).

Table 1
Participants' characteristics

	Milan	*Gallarate*
N	40	20
Mean age in years (SD)	8.5 (2.2)	7 (2.6)
Monolinguals	29	18
Bilinguals/multilinguals	11	2
Instrument played		
Piano	14	0
Violin	15	7
Viola	0	1
Cello	8	5
Other[1]	2	2
None[2]	1	5
Frequency of instrument play		
Never	0	0
A few hours a month	0	1
A few hours a week	13	7
Every day	23	8
Mean maternal education level (from 1 to 3)[3]	2.9 (0.30)	2.8 (0.6)

Note. Only the participants with typical development are included.

[1] Cases in which participants played instruments less traditional and more recently introduced in the Suzuki method, or in which children played more than one instrument. In the Milan group, one participant played the flute, the other claimed to play both the cello and the piano with equal frequency. In the Gallarate group, two children played the guitar.

[2] Cases in which participants were still too young to play an instrument.

[3] Level 1 = middle school diploma; level 2 = high school diploma; level 3 = university degree.

Materials

Reading tests. The participants' reading abilities were tested in two standardized reading tests: the DDE-2 word and pseudoword reading tests by Sartori et al., (2007). Participants were presented with four lists of words in the word repetition task and with three lists of pseudowords in the pseudoword reading task. Lists contained mono- and plurisyllabic words and ranged in difficulty.

Short term memory task (forward digit span). Given the associations often found between musical training and enhanced memory skills in the literature, our Suzuki children were also tested in a short term memory task. To this end, we used a forward digit span task, a test often used as assessment of the phonological loop capacity in children (Baddeley, 2000), as it is easier than pseudoword repetition tasks, in which the sequence of items to be repeated is unfamiliar (Baddeley, 2003). In this task, children were presented with strings of digits organized in levels of increasing difficulty. Each level contained three strings of the same length; after each level, the length of the strings increased by one digit.

Anticipation tasks. ***Warning imperative (tapping) task.*** Participants were tested in a special tapping task with the aim to measure their rhythmic synchronization abilities. The task was the same as the one used for the studies presented in Chapters 2 and 3. In the rhythmic sequences, tones had a frequency of 440 Hz and an inter-onset-interval (IOI) of 750 milliseconds (ms) (for a resulting tempo of 80 bpm), and appeared either in a stressed or in an unstressed rhythmic condition; each participant was presented with 160 tones in total (80 per condition; see Figure 1 and Chapter 2 and 3 for more details). ***Determiner and clitic processing task.*** The participants' anticipation abilities in language were tested in the same determiner and clitic processing tasks used in the studies presented in Chapters 2 and 3. Participants were shown pictures representing entities associated with prototypical nouns with different grammatical gender, and listened to spoken sentences containing gender-marked determiners or clitic pronouns (with a right-dislocated sentence antecedent) followed by agreeing nouns. Based on the gender information of the preceding elements (feminine vs. masculine), we expected children to be able to anticipate the incoming nouns. As in other studies, gender information was either grammatical only (lexically encoded, condition 1: G), grammatical and phonologically marked in word ending (condition 2: GP), or grammatical, phonologically marked, and cued by the semantic information regarding the biological gender of the noun referent (see Table 2 and Chapter 2 for more details).

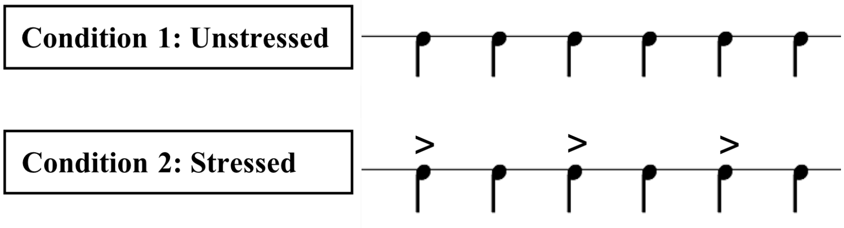


Figure 1. Rhythmic conditions in the warning imperative task. Note that the accented pattern was conveyed through an intensity reduction on the second tone of each pair, not through an intensity increase on the first tone.

Table 2

Examples of noun pairs in each gender cue condition

Condition	Type of gender cue available	Examples of prototypical nouns associated with the two pictures simultaneously presented on the screen
1	Grammatical (G)	chiave (f) 'key' vs. fiore (m) 'flower'
2	Grammatical, phonological (GP)	foglia (f) 'leaf' vs. fungo (m) 'mushroom'
3	Grammatical, phonological, semantic (GPS)	fatina (f) 'fairy' vs. soldato (m) 'soldier'

Procedure

Reading tests. Participants were tested individually in a quiet room at the Suzuki center. Each child was presented with a paper list of words or pseudowords which had to be read aloud as accurately and as fast as possible. The same process was repeated for all the remaining lists. Participants were recorded and tests were double scored by two researchers. Both accuracy (i.e., obtained by calculating the number of words correctly read) and speed were analyzed.

Short term memory task (forward digit span). In the digit span task each participant was asked to listen carefully to the strings of digits played through loudspeakers and to repeat the numbers in each string in the same order as they heard them. After three strings correctly repeated by the participant, the experimenter passed on to the next level (and therefore added one digit to the string to be remembered). The task ended when the participant incorrectly repeated two strings within the same level. Accuracy scores were calculated based on the number of strings correctly repeated and analyzed.

Anticipation tasks. ***Warning imperative (tapping) task.*** As in the other studies, half of the participants were first tested in this task, the other half was first tested in one of the language anticipation tasks. In the warning imperative task, after listening to regularly organized rhythmic sequences through headphones, participants were asked to give their synchronized response by clicking the mouse in time with the beat following a warning sound (i.e., with the imperative). As in the other studies, this was done to measure their rhythmic sensorimotor synchronization skills and their ability to temporally predict the arrival of the next beat. The task, presented using customized scripts and the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997; Kleiner et al., 2007) in Matlab (The Mathworks, Inc., 2017), was carried out individually by the participants in a quiet room at the Suzuki center in Milan. Their synchronization error (with the respect to the beat) was measured and compared across conditions. ***Determiner and clitic processing task.*** As in the studies presented in the previous chapters, these tasks were carried out individually in a quiet room at their Suzuki center on different days within a period of a month. The knowledge of the nouns and the familiarity and recognizability of the depicted referents used in the tasks were checked in a denomination task (carried out before the language tasks) in which children were asked to name a series of pictures. The visual stimuli were presented on a computer using customized scripts in Matlab, and the auditory stimuli were played through headphones. Children were asked to decide between the two pictures as soon as possible by pressing either L (for the picture on the right) or S (for the picture on the left) on the computer keyboard. Accuracy and response times (RTs) were analyzed.

Since it was not possible to schedule two sessions with all of the participants before the beginning of the summer holidays, a few children could not be tested in the clitic processing task: this is why this task includes fewer participants than the determiner processing task in section 4.2.2.

4.2.2 Data analysis and results

Results in the experimental tasks are presented first for Suzuki children only, and then in comparison to age-matched TDs.

4.2.2.1 Suzuki only (Milan and Gallarate schools)

Reading tests (accuracy)

Z-scores were calculated based on the normative data provided in Sartori et al. (2007). Results showed that only one participant in the Gallarate group met the criterium for exclusion (i.e., having a mean accuracy at or below 1.5 SD from the normative data, as in Chapters 2 and 3). That participant was excluded from all successive analyses for this and for the subsequent tasks.

As shown in Table 3, the rest of the musician children's scores were in line with – if not slightly above – the normative scores. A two sample t-test showed that participants coming from the two different Suzuki groups did not have significantly different word (*t*(13.6) = -0.42, *p* = .681) and pseudoword (*t*(14.5) = -1.287, *p* = .218) reading accuracy scores (see Table 1 for mean scores and SDs). To better study our Suzuki sample, we further checked the possible influence of variables that were likely to differentiate between musicians; specifically, we investigated the effects of number of languages spoken with high proficiency by the child, of frequency with which participants play music, and of instrument played.

Table 3

Reading and short term memory scores in the two Suzuki schools

	Milan	*Gallarate*
N	40	20
Mean age in years (SD)	8.5 (2.2)	7 (2.6)
Word reading (z-scores):		
Accuracy	0.26 (0.65)	0.36 (0.55)
Speed	0.27 (1.46)	0.67 (0.97)
Pseudoword reading (z-scores):		
Accuracy	0.23 (0.72)	0.55 (0.57)
Speed	0.34 (1.15)	0.66 (0.66)
Digit span scores	10.13 (2.26)[1]	7.95 (3.02)

Note. Z-scores in the reading tests were calculated in reference to the normative data provided in Sartori et al., 2007; positive values indicate better performance than standard in both accuracy and speed data, negative values indicate worse performance. Digit span scores are calculated based on the number of strings correctly repeated before participants reached their ceiling (two errors within the same level). Standard deviations are in parentheses.

[1] A score of 10 is equal to a total of 10 digit strings correctly repeated, and to a digit span level of 4 or 5.

Bilingualism. As mentioned above, children were considered bilingual if they had a high mean L2 proficiency score (based on the parental questionnaire) and if they spoke the L2 in family and/or elsewhere for at least a few hours a week (see Table 1). Age did not differ between the participants belonging to the two groups (*t*(10.28) = 0.111, *p* = .914). T-tests showed similar performance in monolingual and bilingual children, both in the word (monolingual mean: 0.263, bilingual mean: 0.344; *t*(14.06)=-0.35, *p* = .731) and in the pseudoword (monolingual mean: 0.255, bilingual mean: 0.487; *t*(14.51) = -0.936, *p* = .364) reading tests (see Figure 2). However, it should be noted that the bilingual children who had reading skills (i.e., who were in second grade or higher) in the Suzuki sample were only eight out of 34; the absence of significant differences may also depend on the limited sample size.

Frequency of instrumental practice. Out of the 34 children whose reading data were available, no child was reported to play his/her instrument ever or only a few hours a month; all parents claimed that their child played either a few hours a week or every day. Between these, there was neither a difference in age ($t(30.54) = -0.161$, $p = .873$), nor a difference in reading accuracy scores (a few hours a week: mean: 0.076; every day: mean: 0.444; $t(27.95) = -1.725$, $p = .095$). See Figure 2.

Instrument played. Of the children whose reading data were available, nine played the piano, 15 played the violin, and seven played the cello. Two participants played other instruments, and only one person played the viola. The ages of the participants in these instrument sub-groups were not significantly different, as shown in an ANOVA ($F(4, 29) = 0.454$, $p = .769$). Two separate Analysis of Variance (ANOVA) tests showed that word and pseudoword reading accuracy scores did not differ between participants playing different instruments (word: $F(4, 29) = 2.093$, $p = .107$; pseudoword: $F(4, 29) = 0.754$, $p = .563$; see Figure 2).

In summary, neither the number of languages spoken, nor the type of instrument or the frequency with which the children played significantly influenced the reading skills of the children in the Suzuki groups.

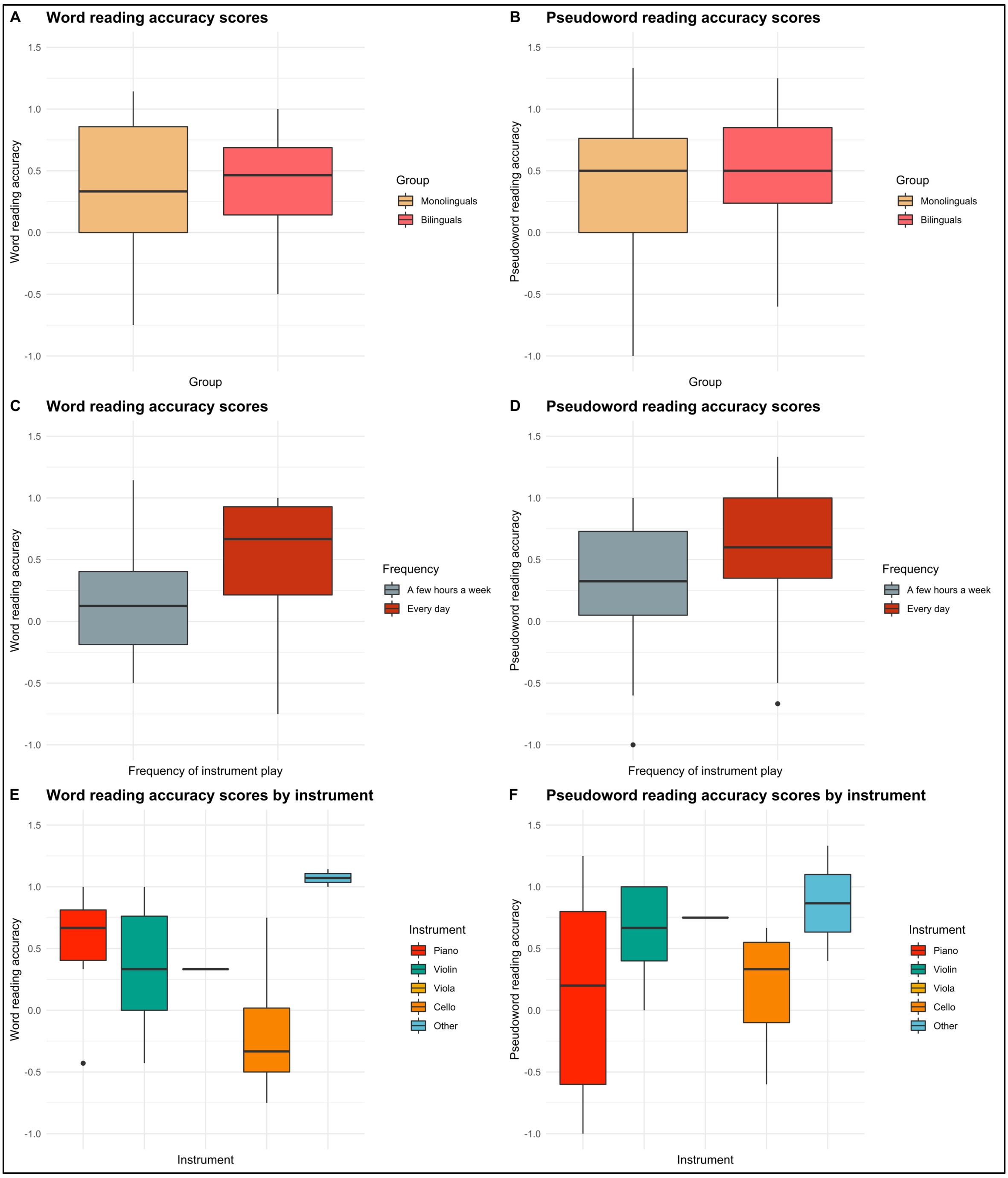


Figure 2. Word and pseudoword reading performance in monolinguals and bilinguals (A, B), in children playing with different frequency (C, D), and in children playing different instruments (E, F).

Short term memory

Short term memory scores, as measured in the digit span task, were available for all participants but one (see Table 3); thus, analyses were carried out on a total of 59 participants. A two sample t-test showed that the Milan Suzuki group had significantly better auditory memory skills than the Gallarate group (Milan, mean: 10.128, Gallarate, mean:

7.95; *t*(30.27) = 2.845, *p* = .007; see Table 3 for mean scores and SDs). This difference might be due to the fact that, although age did not differ significantly between groups (as mentioned in the *participants* section), the participants in the Gallarate group were slightly younger and less numerous. In any case, it should be noted that this difference between groups is not problematic for subsequent analyses, as the latter were run collapsing data across school groups, on all Suzuki participants.

Bilingualism. Our total Suzuki sample comprised 46 monolingual children and 13 bilingual children of similar age (monolinguals, mean age in months: 93.65; bilinguals, mean: 99.69; *t*(21.54) = -0.717, *p* = .481). To see whether being bilingual could have an influence on memory skills, we compared the digit span scores of the monolingual children with those of the bilinguals. Though bilinguals tended to have a higher mean score than monolinguals (monolinguals, mean: 9.15; bilinguals, mean: 10.23, see also Figure 3), this difference was not statistically significant (*t*(23.86) = 1.442, *p* = .162).

Frequency of instrumental practice. Out of 59 children, 31 played every day, 18 a few hours a week, one participant played only a few hours a month, and two did not play yet (because they were too young). Though participants who played more often had a higher mean digit span score ("A few hours a week": 10.06; "Every day": 10.03) than the ones who did not play (mean: 9.0) or played only a few hours a week (mean: 7.0), an ANOVA revealed that these differences were not statistically significant (*F*(3,48) = 0.710, *p* = .551, see Figure 3). Age was not significantly different across frequency groups either (*F*(3,48) = 1.209, *p* = .316). However, the possibility that playing more frequently enhances memory cannot be completely ruled out: the absence of differences may also depend on the participant sample size, which, again, might have been too small for differences to appear.

Instrument played. Out of 59 participants, 13 played the piano, 22 played the violin, one person played the viola, 13 played the cello, four played another instrument, and six played none, as they were still too young to play. An ANOVA on the digit span scores showed that auditory memory skills differed in mean between participants playing different instruments (*F*(5,53) = 6.277, *p* < .001, see Figure 3). However, it should be noted that age was also significantly different between children playing different instruments, as some of them could not play an instrument yet (*F*(5,53) = 4.930, *p* < .001). Furthermore, by removing from the dataset the participants who did not play any instrument, the same type of test ANOVA did no longer yield significant results (*F*(4, 48) = 1.049, *p* = .392), which suggests that there are significantly different memory skills between participants who play and those who do not play yet, but no effect of the specific type of instrument played.

To sum up, neither the reading abilities, nor the short term auditory memory skills of our Suzuki participants were affected by the number of languages spoken, the frequency with which the children played, or the type of instrument played. However, the absence of effects may be due to the very limited sample size and to not enough variance in the data for differences to appear. The possible influence of these factors warrants further investigation in future research.

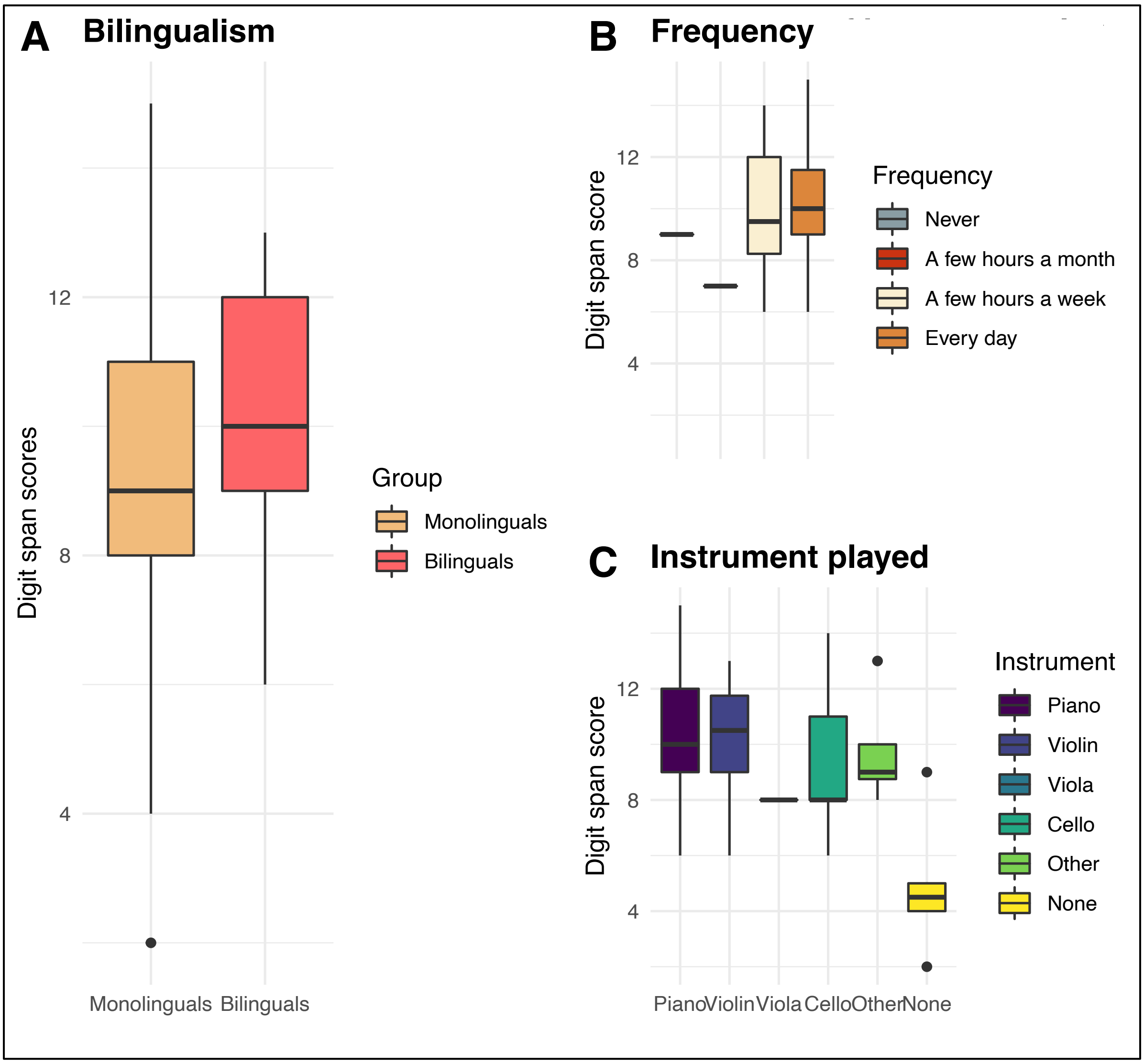


Figure 3. Auditory memory skills as measured in the digit span task in the monolingual and bilingual children (A), by frequency of instrumental practice (B), and by instrument played (C).

Anticipation skills – Suzuki only

To investigate the musician children's anticipation skills, we tested the Suzuki group in a rhythmic tapping task and in two morphosyntactic processing tasks. Only the Milan group (n = 40) had the chance to participate in these tasks; thus, the results presented below are drawn from this group only.

Warning imperative (tapping) task. As in the other studies, individual Matlab output txt files were merged and re-organized in Matlab and then imported in R (R Development Core Team, 2016) using customized scripts. Four participants were removed, because 60% of their responses were beyond the IOI of 750 ms and were therefore considered invalid; for this reason, the final sample included 36 participants. Furthermore, responses above four standard deviations from zero were considered outliers and substituted with the median value of the previous and following two responses.

The possible effects of age, condition, and item on synchronization error (the time lag interspersed between the participant's response and the beat) in this task were tested in a Linear Mixed-Effects Model (LMM) in R (lmer function in the "lme4" package, Bates et al., 2015). Given the wide age range in this Suzuki sample, we divided our participants into two age groups: a younger group (4-8 years, n = 21), and an older group (9-12, n = 15). Thus, the final model included Condition (1 – unstressed vs. 2 – stressed), Item (from 1 to 10) and Age group (younger vs. older) as fixed effects, Subject as random effect, and Synchronization error as the dependent variable. As already mentioned, this task was designed primarily to test whether the rhythmic anticipation skills of musician children differed between age groups and/or across conditions. However, to exclude the possible influence of additional factors such as bilingualism, instrument played, and frequency of music play, we ran hierarchical regressions (function "update") to see whether any of these variables improved our model: results showed that this was not the case (bilingualism: *p* = .159; frequency: *p* = .579; instrument: *p* = .506). For these reasons, these variables were not included. Posthoc tests after significant main effects were run using the function "glht" in package "multcomp" (Hothorn, Bretz, & Westfall, 2008) and the Tukey correction.

Results did not show significant effects: neither age (*p* = .583), nor the exposure to a stressed rhythmic pattern (*p* = .135), or the number of items already processed (*p* = .291) affected sensorimotor synchronization precision. However, taps were quite precise on average, especially considering that these participants are children (mean asynchrony: -62 ms, SD: 125 ms); the absence of significant improvements in older groups or throughout the task may be due to a high level of precision from the beginning and therefore to less room for improvement. See Figure 4 to see the Suzuki children's performance throughout the warning imperative task.

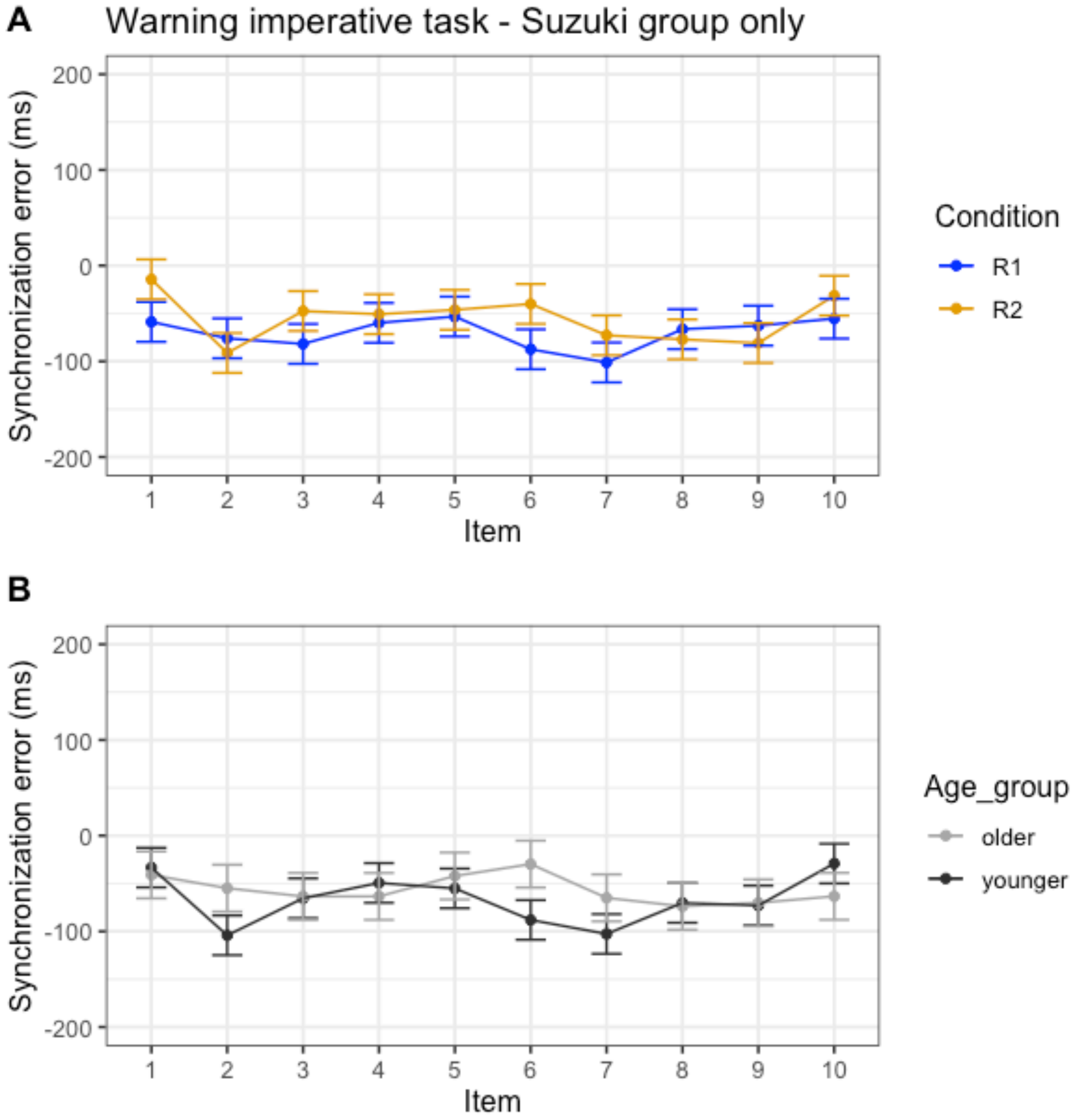


Figure 4. Participants' synchronization errors in the warning imperative task by item, and by rhythmic condition (A) or age group (B). The zero represents the onset of the imperative tone: the closer responses are to 0, the smaller the asynchrony. Any response below or above 0 is given early or late, respectively, with respect to the beat. Model effects were plotted using the r packages "effects" (Fox & Weisberg, 2019) and "ggplot2" (Wickham, 2016).

Determiner processing task. Data were cleaned and analyzed following the criteria reported in Chapters 2 and 3. Participants (n = 40) were again divided into two age groups:

a younger group (4-8 years, n = 24), and an older group (9-12, n = 16). One participant was excluded from the analyses, as she scored below 2 SD from the mean of the age group in the denomination task and, therefore, likely did not know some of the noun referents for the pictures. Results showed an overall accuracy at ceiling (98.7%), which indicates that all children were able to perform this task.

The participants' RTs were analyzed in an LMM that included Age Group (younger vs. older) and Condition (1 vs. 2 vs. 3) as fixed effects, and Subject and Item as random effects. As for the warning imperative task, additional factors such as bilingualism, frequency of instrumental practice, and instrument played were not included, as they did not improve our model, as shown by hierarchical regressions (bilingualism: $p = .845$; frequency: $p = .242$; instrument: $p = .106$). Analyses on the final model were carried out in R through the function lmer ("lme4" package, Bates et al., 2015). As explained in Chapters 2 and 3, this task did not grant participants enough time to respond before the onset of the noun; therefore, analyses will include any response given before the time-out limit.

Results did not show a significant effect of Condition ($p = .627$). However, there was a significant main effect of Age group ($F(1, 37.01)$, $p < .001$) and a significant Age group and Condition interaction ($F(2, 604.06) = 3.294$, $p = .037$). To test possible differences between conditions within group or between groups within condition, post-hoc tests were carried out using the "testInteractions" function in "phia" (De Rosario-Martinez, 2015). Results revealed significance differences between the younger and the older groups in each of the three conditions (G: $\chi^2_{(1)} = 11.599$, $p < .001$; GP: $\chi^2_{(1)} = 11.003$, $p < .001$; GPS: $\chi^2_{(1)} = 20.632$, $p < .001$; see Figure 5). These results suggest that the morphosyntactic anticipation skills of the children musicians may improve with age, but might also indicate that for these participants the three conditions were all of similar difficulty.

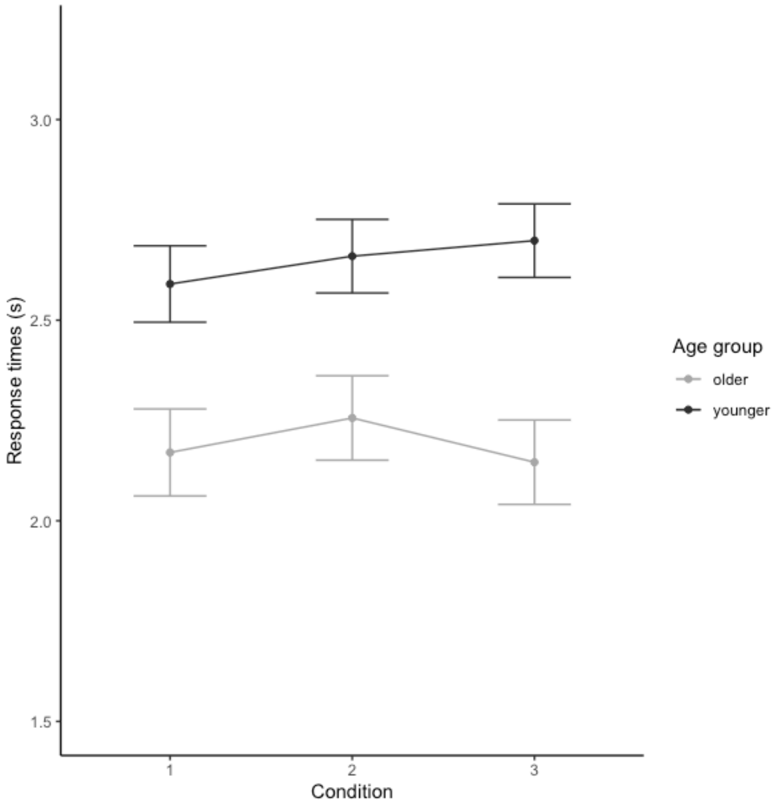


Figure 5. Response times (s) in the determiner processing task by condition (1 G, 2 GP, and 3 GPS). The grey line shows the performance of the younger Suzuki age group; the black line shows the performance of the older group.

Clitic processing task. For time constraints, only 14 Suzuki children (n = 9 in the younger group, n = 5 in the older group) performed this task. Their data were analyzed following the same criteria outlined in the determiner processing task section. Tests showed an accuracy of 97.5% in total, which indicates that the task could be carried out by children.

The effect of Age (younger vs. older) and Condition (1 vs. 2 vs. 3) on RTs in this task, instead, were investigated in a LMM that included Subject and Item as random effects. As for the determiner processing task, additional variables such as number of languages spoken with high proficiency, frequency of instrumental practice, and instrument played did not improve our model (as shown by hierarchical regressions; bilingualism: p = .845; frequency: p = .242; instrument: p = .106), and were therefore not included.

Results showed again a significant effect of Age group (F(1,11.98) = 4.919, p = .047), and nonsignificant Condition (p = .097) and Age group × Condition interaction effects (p = .669). As in the determiner processing task, morphosyntactic processing abilities seem not to be affected by the type of gender information, but to be improved in general in older participants than in younger ones (see Figure 6).

Since this task offered the participants more time between the gender-marked clitic pronoun and the gender-marked noun referent, we also conducted an analysis on the responses that were given before the onset of the DP. This was done to see if possible differences between age groups or conditions would become more evident if we differentiated between 'anticipatory' (i.e., coming before the onset of the DP) and 'non-anticipatory' responses. To do this, responses given before or within 100 ms after the onset of the DP were assigned a score of 1; all the others were given a score of 0. The resulting 'Anticipation ratio' for each participant was analyzed in a Generalized Linear Mixed Model (GLMM) with Age group and Condition as predictors, and Subject and Item as random effects. Likelihood ratio tests showed no significant effects (Age group: $\chi^2_{(2)} = 2.761$, $p = .097$; Condition: $\chi^2_{(2)} = 5.419$, $p = .067$). Post hoc tests (function "emmeans" in package "emmeans"; Lenth, 2018) showed only a marginally significant difference between conditions 1 (G) and 3 (GPS), with the third condition being the one in which participants were somewhat more likely to anticipate the correct nouns (z-value = -2.260, $p = .062$, see Figure 6). Though differences across conditions are not significant, there seems to be a trend for which the more gender cues are available, the greater the anticipation ratios are (see Figure 6). Taken together, these results suggest that having all three cues to gender make it somewhat easier for participants to anticipate the upcoming noun.

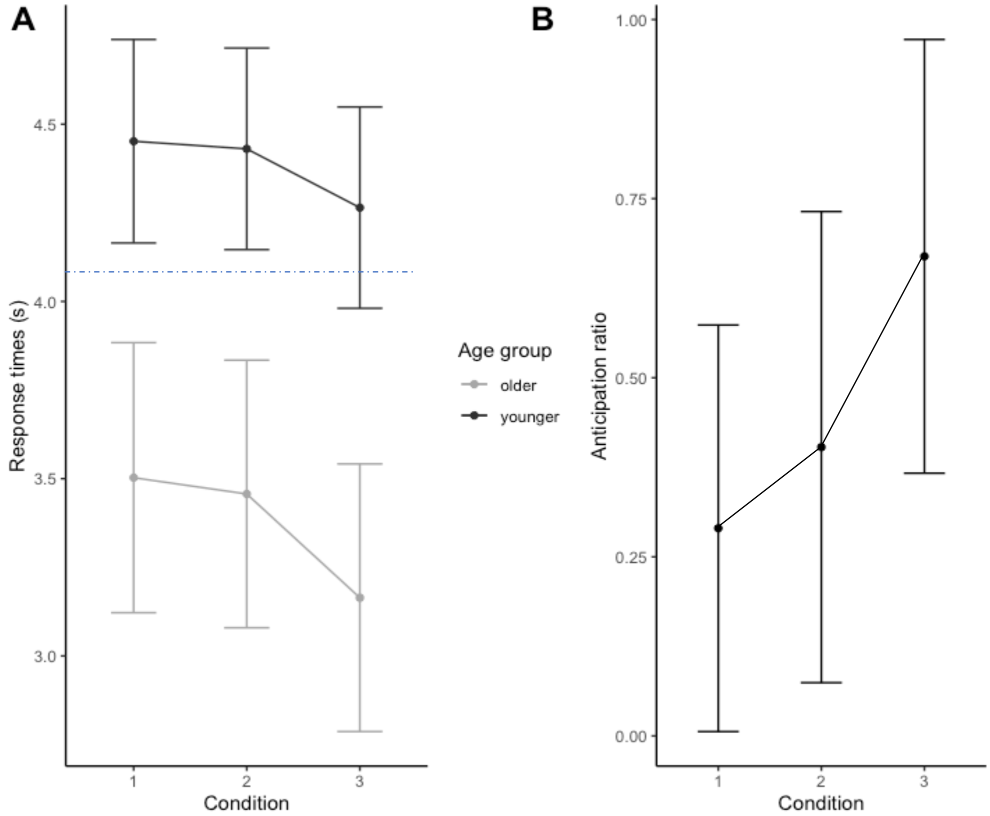


Figure 6. Figure 6A shows the Suzuki children's response times in the clitic processing task by condition and group (1 = G, 2 = GP, 3 = GPS). Lower values along the Y axis represent faster responses; the blue dotted line represents the onset of the DP. Figure 6B shows the ratio of anticipatory responses (i.e., those given before the onset of the DP) in the three conditions. Both figures show a trend for which participants anticipate more when all three cues are available.

4.2.2.2 Suzuki children vs. non-musician TD peers

In order to investigate whether children who receive early and continuous exposure to music have advantages in rhythmic and language and literacy tasks, we compared our Suzuki group with a group of monolingual TD children without musical experience. These children were part of a larger cohort that had participated in other studies and were from the Milan metropolitan area. To eliminate possible confounds due to bilingualism, we further removed from our dataset the Suzuki children that spoke more than one language. The final sample included 21 monolingual children musicians and 21 age-matched typically-developing children with no musical experience.

Reading tests

T-tests on the word and pseudoword reading accuracy z-scores of the children with reading abilities (n = 28) did not show significant differences between the Suzuki and the

TD groups (word reading: Suzuki mean: 0.213, TD mean: -0.018; $t(25.98) = 0.809$, $p = .426$; pseudoword reading: Suzuki mean: 0.144, TD mean: -0.189; $t(25.569) = 1.093$, $p = .284$), though the scores of the Suzuki group seemed slightly higher on average (see Figure 7). Interestingly, the two groups had significantly different reading speed: the Suzuki group was faster both in the word reading test (Suzuki mean: 0.320, TD mean: -0.498; $t(21.833) = 2.836$, $p = .01$) and in the pseudoword reading test (Suzuki mean: 0.265, TD mean: -0.581[1], $t(17.532) = 2.453$, $p = .025$) (see Figure 7). Note that these differences could not depend on the Suzuki participants being older, as the two groups were age-matched.

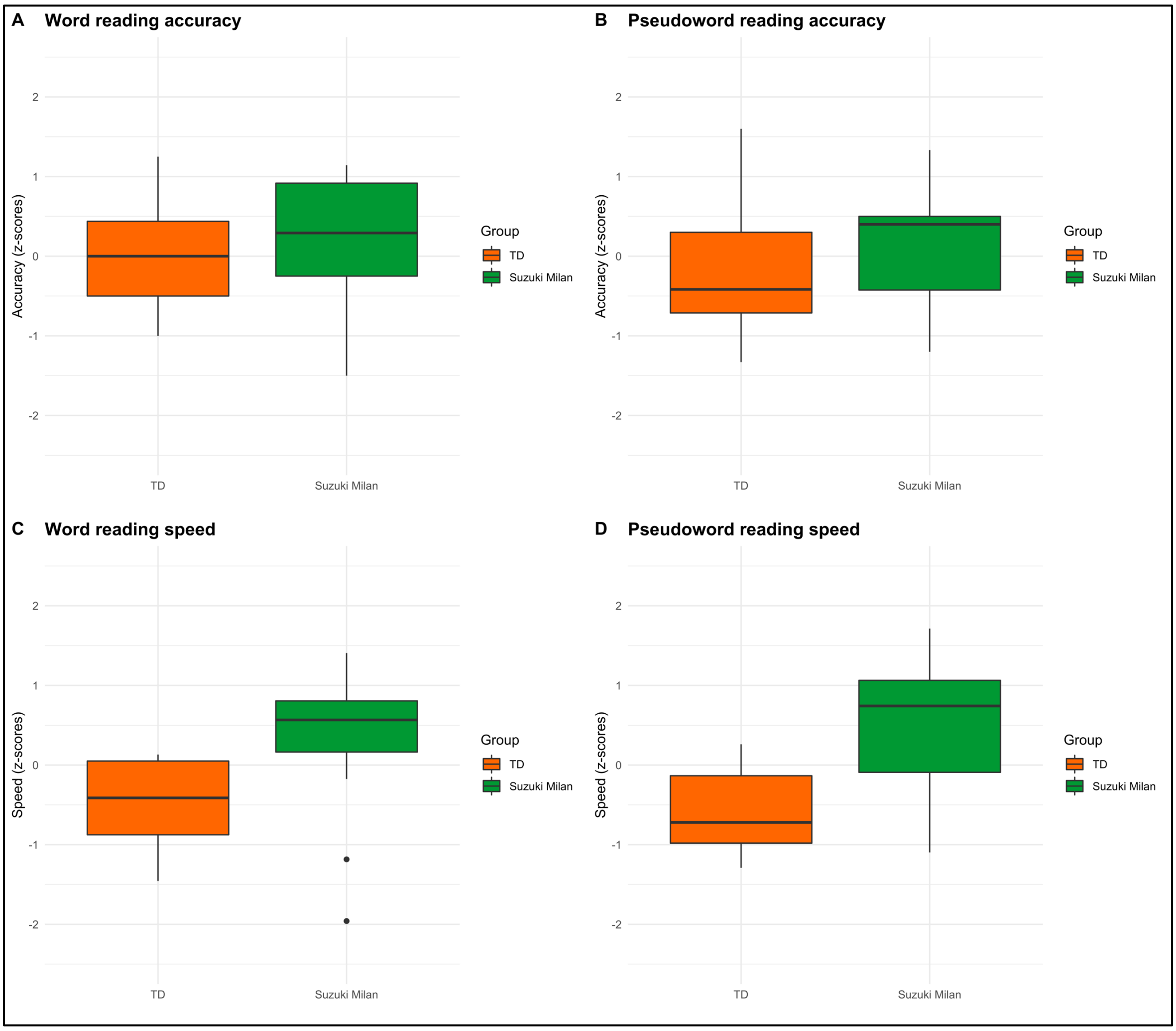


Figure 7. Word and pseudoword reading accuracy (A and B, respectively) and speed (C and D, respectively) in the Suzuki group (in green) and in the age-matched non-musician TD group (in orange).

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[1] As already mentioned, positive values indicate better performance, both in the accuracy and in the speed data.

Short term memory task (digit span)

The digit span scores of the children attending a Suzuki music school were compared with the digit span scores of the typically-developing children with no musical experience in a two sample t-test. In contrast with our hypothesis, the test showed similar scores in the two groups (see Figure 8, TD mean: 10.14, Suzuki mean: 10.45; *t*(29.5) = -0.644, *p* = .703).

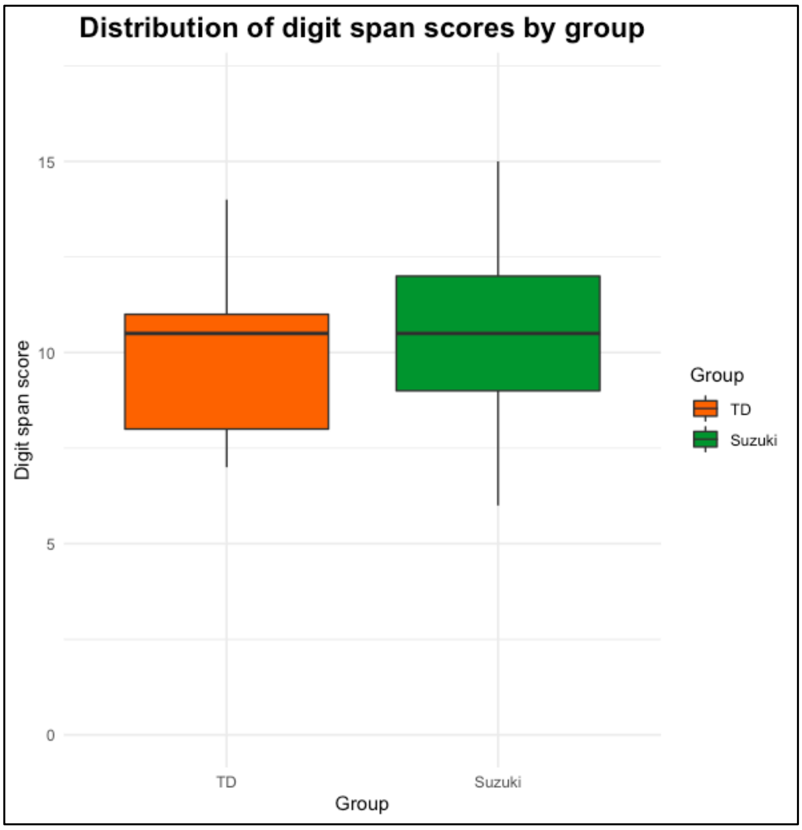

Figure 8. Short term auditory memory scores, as measured in the digit span task, by group.

Anticipation skills – musician vs. non-musician children

The performance of the Suzuki and TD children was also compared in a sensorimotor synchronization task and in two morphosyntactic processing tasks.

Warning imperative (tapping) task. As in the other studies, individual Matlab output txt files were merged and re-organized in Matlab and then imported in R using customized scripts. Two participants were removed, because 60% of their responses were beyond the IOI of 750 ms and were therefore considered invalid. Responses above four standard deviations from zero were considered outliers and substituted with the median value of the previous and following two responses.

The remaining data were analyzed in a LMM in R (lmer function in the "lme4" package, Bates et al., 2015). The model included Group (TD vs. Suzuki), Condition (1 – unstressed vs. 2 – stressed), and Item (from 1 to 10) as fixed effects, Age as covariate, Subject as random effect, and Synchronization error as the dependent variable. Posthoc tests after significant main effects were run using the function “glht” in package “multcomp” (Hothorn, Bretz, & Westfall, 2008) and the Tukey correction.

Results showed a significant main effect of Group ($F(1, 484.87) = 17.581$, $p < .001$), with the Suzuki group being significantly more precise (i.e., with closer taps to the beat at 0 ms) than the TD group ($z = 21.06$, $p < .001$, see Figure 9A). No significant effects of rhythmic Condition ($p = .238$), Item ($p = .730$) or interactions were found (see Figure 9B).

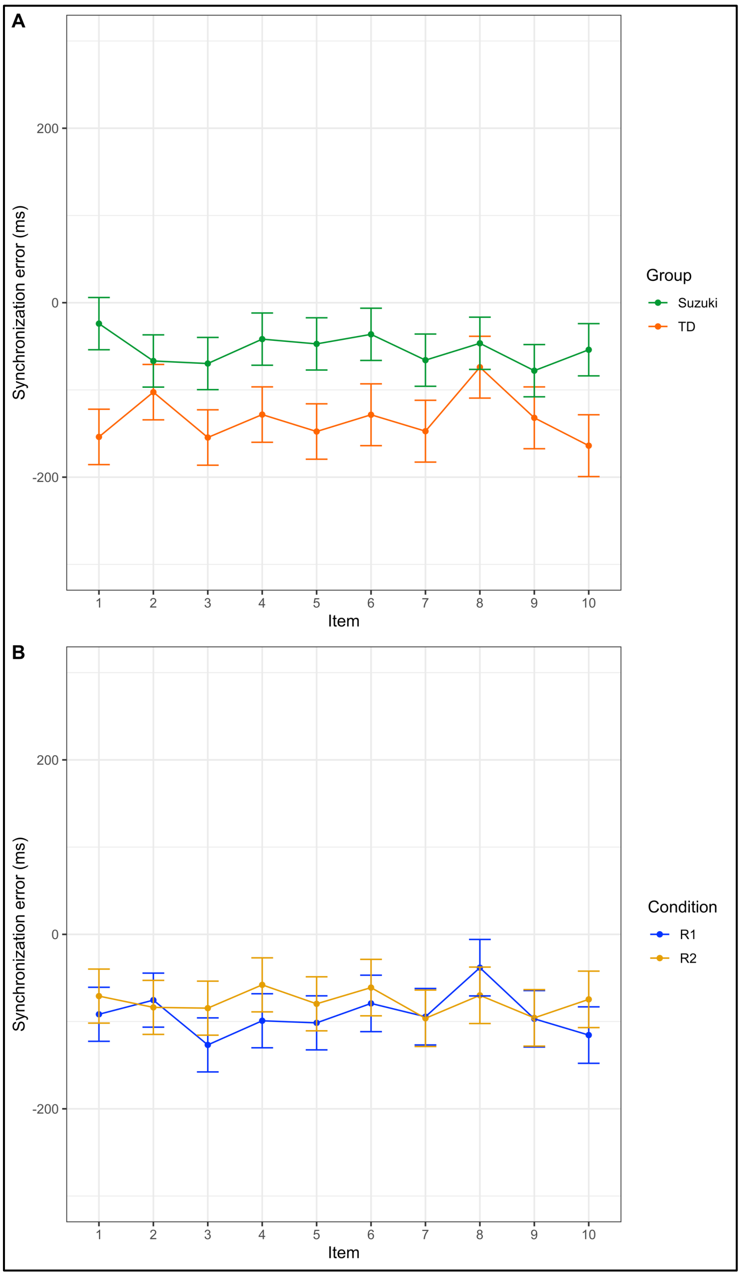

Figure 9. Participants' synchronization errors in the warning imperative task by item. Figure A (top) shows the performance of the Suzuki (in green) and of the TD (in orange) groups. Figure B (bottom) shows the general performance in the unstressed rhythmic condition (in blue) and in the stressed one (in yellow). The zero represents the onset of the tone: closer responses to 0 indicate smaller asynchronies and thus, higher precision. Any response below or above 0 is given early or late, respectively, with respect to the beat. Model effects are plotted using the r packages "effects" (Fox & Weisberg, 2019) and "ggplot2" (Wickham, 2016).

Determiner processing task. The same criteria described in Chapters 2 and 3 were used to compare the musician and non-musician children. Accuracy in this task was at ceiling (98.9%), meaning that all children could perform the task without problems. Their RTs in this task were analyzed in an LMM with Group (TD vs. Suzuki) and Condition (1 vs. 2 vs. 3) as fixed effects, Age as covariate, and Subject and Item as random effects. Results showed a significant main effect of Group ($F(1, 39.64) = 15.531, p < .001$), and a significant Group × Condition interaction ($F(2, 324.10) = 3.313, p = .038$). Post hoc tests (function "testInteractions" in package "phia") showed significant differences between groups in each of the three conditions, with the Suzuki group always being the faster one (TD vs. Suzuki, condition 1: $\chi^2_{(1)} = 19.963, p < .001$; condition 2: $\chi^2_{(1)} = 12.328, p < .001$; condition 3: $\chi^2_{(1)} = 7.404, p = .006$). These results indicate that the Suzuki children were not only faster in reading (as mentioned above), but also in morphosyntactic processing.

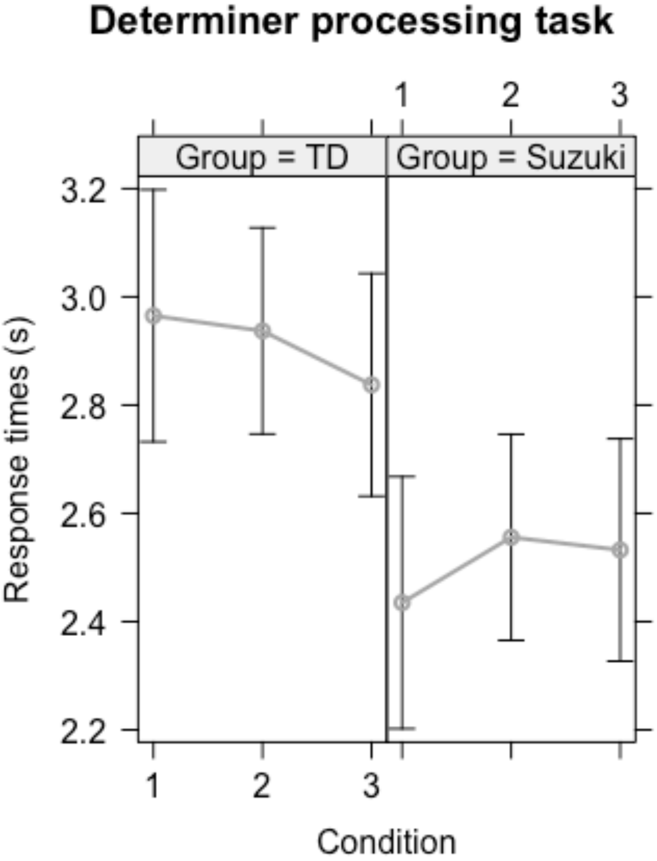

Figure 10. Response times (s) in the determiner processing task in the three conditions (1 G, 2 GP, and 3 GPS) by group (TD, on the left; Suzuki, on the right).

Clitic processing task – preliminary results. For time constraints the clitic processing task was administered only to six participants out of the 21 Suzuki children who were monolingual and matchable in age to the TD children.

Overall accuracy was very high (99.5%). The participants' RTs were analyzed in an LMM with Group (TD vs. Suzuki) and Condition (1 vs. 2 vs. 3) as fixed effects, Age as covariate, and Subject and Item as random effects. Results showed no significant effects (Condition: $p = .811$, Group: $p = .457$, Condition × Group: $p = .133$). However, it should be noted that this cohort only included six participants in each group; therefore, results should be interpreted with caution: the absence of differences in this task (as opposed to the determiner processing task) may be due to the very limited size of our sample. In fact, since clitic pronouns are part of a more complex hierarchical structure, and are more difficult to process and acquire as compared to determiners, it is unlikely that, if a difference between musicians and non-musicians were to be found, it would only be visible in the task testing the simpler hierarchical structure.

The limited number of participants who were tested in this task is also the reason why more refined analyses on the anticipatory responses were not possible.

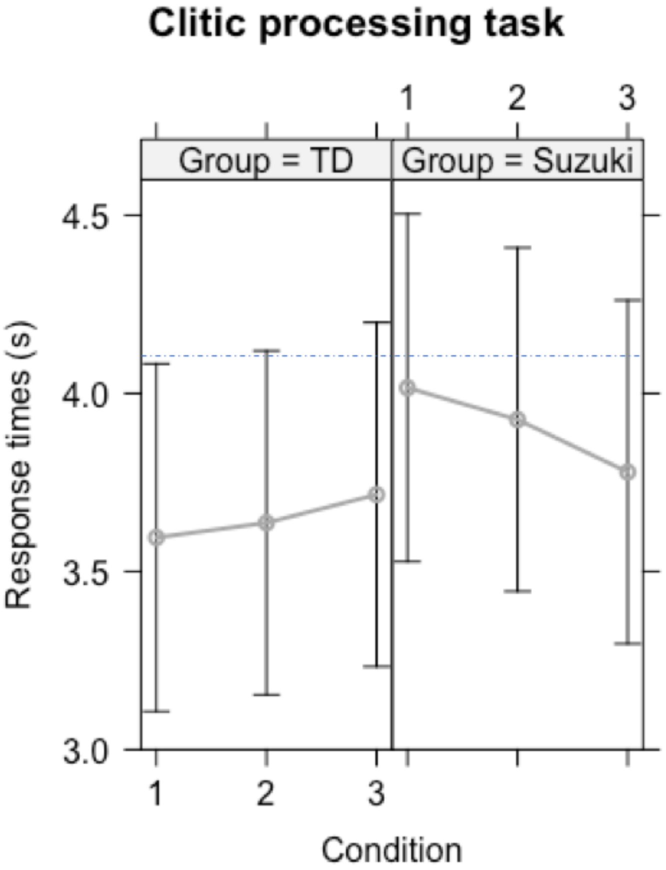

Figure 11. Response times (s) in the clitic processing task in the three conditions (1 G, 2 GP, and 3 GPS) and in the two groups (TD, on the left; Suzuki, on the right). The blue dotted line represents the onset of the DP following the clitic pronoun.

Correlations between the results of the rhythm tasks and the language and literacy scores. To investigate whether less precision in the warning imperative task (i.e., farther responses from 0) corresponded to less efficient mechanisms of prediction in language (i.e., longer response times in the language tasks), Spearman correlations were run between the warning imperative task and the determiner and clitic processing tasks (function "cor.test"). For the warning imperative task, only the responses preceding the beat (i.e., the negative RT values) were considered, as those are the ones thought to reflect anticipatory processes and that are consistently found in adults and musicians (Aschersleben, 2002). To further investigate the possibility that better anticipation skills corresponded to faster pseudoword decoding, we also ran Spearman correlations between the above-mentioned tasks and reading speed in the pseudoword test.

Results showed moderate, significant, inverse correlations between mean synchronization error in the warning imperative task and mean RTs in the determiner processing task ($r_{(s)} = -0.491$, $p = .029$; see Figure 12). When correlations were run between conditions, we also found moderate, significant, inverse correlations between each of the rhythmic conditions and conditions 1 (unstressed: $r_{(s)} = -0.350$, $p = .039$, stressed: $r_{(s)} = -0.467$, $p = .005$) and 2 (unstressed: $r_{(s)} = -0.394$, $p = .018$, stressed: $r_{(s)} = -0.370$, $p = .029$) of the determiner processing task. These results suggest that the more accurate children were in the tapping task, the faster they were in predicting incoming linguistic input: interestingly, this was true only in the two more difficult conditions of the determiner processing task: the ability to anticipate incoming linguistic input when a semantic information is also available does not seem to be related to the accuracy of sensorimotor synchronization in the WIT.

Interestingly, the response speed in the determiner processing task also correlated with pseudoword reading speed, both in general ($r_{(s)} = 0.554$, $p = .003$) and within gender cue condition (condition 1: $r_{(s)} = 0.56$, $p = .003$; condition 2: $r_{(s)} = 0.52$, $p = .005$; condition 3: 0.57, $p = .002$). No significant correlations were found between the clitic processing task and the warning imperative task (as in the previous studies), though the absence of results in this case may also depend on the very limited number of participants who were tested in the clitic processing task.

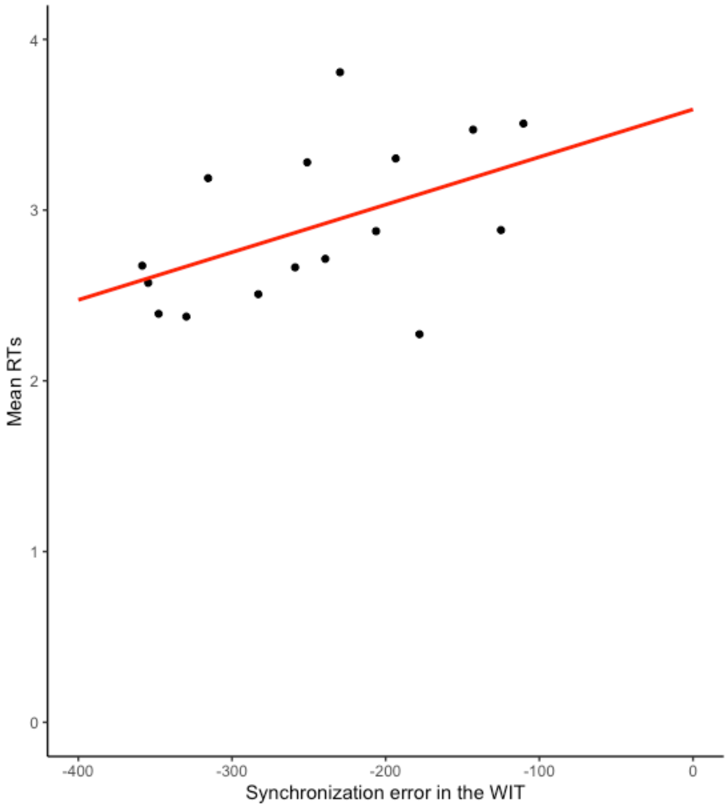

Figure 12. Correlation between the synchronization error in the warning imperative task and the RTs in the determiner processing task.

4.2.3 Discussion

In this study we investigated the rhythm, language, literacy, and short term memory skills of musician children and compared them with those of typically-developing non-musician children of the same age. Based on previous studies we expected better auditory short term memory and better reading abilities in musician children. In the same group we also expected better rhythm synchronization and morphosyntactic processing skills, as a result of better prediction skills (which in turn may reflect better neural entrainment to the stimuli). Finally, within the musician group we explored whether any of the skills tested were affected by other important variables such as bilingualism, instrument played, or frequency of instrumental practice.

As explained in the introduction of this chapter, we expected (i) bilinguals to perform better than monolinguals, based on the idea that enhanced cognitive control (found in bilinguals; Bialystok et al., 2004) could facilitate performance in our tasks; (ii) we expected participants who played every day to perform better than participants who played less frequently, given that intensive training has been linked to enhanced language skills (e.g., Moritz et al., 2013); finally, (iii) we explored whether any of the language and literacy skills tested in our work were influenced by the specific sensorimotor experience associated with the practice of a particular instrument, given that this has been shown to cause structural and functional brain differences in previous research (Bangert & Schlaug, 2006). Contrary to our expectations, the Suzuki group did not show any effects of bilingualism, frequency of instrument play, or of type of instrument played on any of our tasks. However, the sample size of the sub-groups compared might be linked to the absence of differences: participants in each sub-group might be too few for statistically significant differences to appear. Alternatively, these results might indicate that these effects are not cumulative (in line with D'Souza, Moradzadeh, & Wiseheart, 2018 and Moradzadeh, Blumenthal, & Wiseheart, 2015, for bilingualism).

As in our previous studies, we hypothesized that participants' performance in the rhythmic task would be improved in older children (for maturation of sensorimotor skills), in the accented condition (possibly because of facilitated metrical interpretation), and towards the end of the task (for practice and, possibly, entrainment effects). Contrary to our expectations, neither older age, nor more exposure, or the presence of physically accented tones in the rhythmic patterns benefited participants' performance in this task; however, improvements may be limited if participants start from a very good level, as in our case. As Figure 8 shows, Suzuki participants showed adult-like performance, as they tended to produce small negative asynchronies (i.e., their taps preceded the beat of ~60 ms on average, possibly, reflecting anticipation mechanisms; Aschersleben & Prinz, 1995). Moreover, as the comparison with age-matched peers showed, the performance of the Suzuki children in this task was significantly better than that of their non-musician peers, thus confirming previous research finding better rhythm production in musicians (e.g., Drake, 1993), and suggesting more accurate temporal predictions in the children who receive musical training.

As in the previous studies, in the morphosyntactic processing tasks we expected to see enhanced linguistic predictions in older groups and in the condition in which all cues to gender (grammatical, phonological, semantic) were available. We *did* find significantly faster responses in older Suzuki participants than in younger ones; however, no significant differences appeared between gender conditions, though the ratio of anticipatory responses suggest that anticipating the incoming noun was somewhat easier when all the three cues to gender were available. The absence of clear differences between gender conditions in this study, as opposed to the studies described in the previous chapters, suggest that the three conditions were of similar difficulty for the musician children, and that the presence or absence of additional cues did not significantly affect their ability to predict incoming input. Further support for their superior prediction abilities comes from the comparison with non-musician age-matched peers, who show slower responses in the determiner processing task.

Further, correlation tests between the rhythmic and the morphosyntactic processing tasks show inverse associations between asynchrony size in the tapping task and response speed in the determiner processing task, meaning that the children who make more accurate temporal predictions and sensorimotor responses are also the ones that are faster in anticipating incoming nouns based on the gender features of their preceding elements. Moreover, pseudoword speed decoding in the reading tests (a process that presumably requires the use of anticipation skills in order to be carried out efficiently) was not only significantly faster in musician children (in line with previous findings showing better reading skills in musicians than in non-musicians), but was also correlated with speed in the determiner processing task (as in the previous studies of this work).

Though inferences as to the prediction abilities of musician and non-musician children in language are limited by the small sample size in this study, our results suggest that musical training may be associated with enhanced predictive timing *and* predictive coding mechanisms. Abilities in tasks requiring anticipation may be benefited by prolonged exposure to rhythmic patterns from an early age, possibly because of more efficient entrainment at multiple levels of the structure that is being processed, and not necessarily to enhanced memory skills[2]. The hypothesis that superior prediction abilities may be related to neural entrainment are addressed in Chapters 5 and 6.

4.2.4 References

Anvari, S. H., Trainor, L. J., Woodside, J., & Levy, B. A. (2002). Relations among musical skills, phonological processing, and early reading ability in preschool children. *Journal of Experimental Child Psychology*, *83*(2), 111–130. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/12408958

Arosio, F., Persici, V., & Pagliarini, E. (in press). Processing of object clitics in Italian monolingual children.

Aschersleben, G. (2002). Temporal Control of Movements in Sensorimotor

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[2] In contrast with previous findings, our musician children did not show better performance than non-musicians in a digit span task.

Synchronization. *Brain and Cognition*, *48*(1), 66–79. https://doi.org/10.1006/BRCG.2001.1304

Aschersleben, G., & Prinz, W. (1995). Synchronizing actions with events: The role of sensory information. *Perception & Psychophysics*, *57*(3), 305–317. https://doi.org/10.3758/BF03213056

Baddeley, A. (2000). The episodic buffer: a new component of working memory? *Trends in Cognitive Sciences*, *4*(11), 417–423. https://doi.org/10.1016/S1364-6613(00)01538-2

Baddeley, A. (2003). Working memory and language: an overview. *Journal of Communication Disorders*, *36*(3), 189–208. https://doi.org/10.1016/S0021-9924(03)00019-4

Bangert, M., Peschel, T., Schlaug, G., Rotte, M., Drescher, D., Hinrichs, H., … Altenmüller, E. (2006). Shared networks for auditory and motor processing in professional pianists: evidence from fMRI conjunction. *NeuroImage*, *30*(3), 917–926. https://doi.org/10.1016/j.neuroimage.2005.10.044

Bangert, M., & Schlaug, G. (2006). Specialization of the specialized in features of external human brain morphology. *European Journal of Neuroscience*, *24*(6), 1832–1834. https://doi.org/10.1111/j.1460-9568.2006.05031.x

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using **lme4**. *Journal of Statistical Software*, *67*(1), 1–48. https://doi.org/10.18637/jss.v067.i01

Bedoin, N., Brisseau, L., Molinier, P., Roch, D., & Tillmann, B. (2016). Temporally regular musical primes facilitate subsequent syntax processing in children with Specific Language Impairment. *Frontiers in Neuroscience*, *10*(JUN), 1–11. https://doi.org/10.3389/fnins.2016.00245

Bialystok, E., Craik, F. I. M., Klein, R., & Viswanathan, M. (2004). Bilingualism, aging, and cognitive control: evidence from the Simon task. *Psychology and Aging*, *19*(2), 290–303. https://doi.org/10.1037/0882-7974.19.2.290

Boudewyn, M. A. (2013). Effects of working memory span on processing of lexical associations and congruence in spoken discourse. *Frontiers in Psychology*, *4*. https://doi.org/10.3389/fpsyg.2013.00060

Brod, G., & Opitz, B. (2012). Does it really matter? Separating the effects of musical training on syntax acquisition. *Frontiers in Psychology*, *3*(DEC). https://doi.org/10.3389/fpsyg.2012.00543

Chern, A., Tillmann, B., Vaughan, C., & Gordon, R. L. (2018). New evidence of a rhythmic priming effect that enhances grammaticality judgments in children. *Journal of Experimental Child Psychology*, *173*, 371–379. https://doi.org/10.1016/j.jecp.2018.04.007

Corriveau, K. H., & Goswami, U. (2009). Rhythmic motor entrainment in children with speech and language impairments: Tapping to the beat. *Cortex*, *45*(1), 119–130. https://doi.org/10.1016/j.cortex.2007.09.008

Corriveau, K. H., Pasquini, E., & Goswami, U. (2007). Basic Auditory Processing Skills and Specific Language Impairment: A New Look at an Old Hypothesis. *Journal of Speech, Language, and Hearing Research*, *50*, 647–666. https://doi.org/10.1044/1092-4388(2007/046

D'Souza, A. A., Moradzadeh, L., & Wiseheart, M. (2018). Musical training, bilingualism, and executive function: working memory and inhibitory control. *Cognitive Research: Principles and Implications*, *3*(1). https://doi.org/10.1186/s41235-018-0095-6

De Rosario-Martinez, H. (2015). phia: Post-Hoc Interaction Analysis. R package version 0.2-1. Retrieved from https://cran.r-project.org/package=phia

Degé, F., Kubicek, C., & Schwarzer, G. (2011). Music lessons and intelligence: A relation mediated by executive functions. *Music Perception*, *29*(2), 195–201. https://doi.org/10.1525/mp.2011.29.2.195

Degé, F., Kubicek, C., & Schwarzer, G. (2015). Associations between musical abilities and precursors of reading in preschool aged children. *Frontiers in Psychology*, *6*(August), 1–10. https://doi.org/10.3389/fpsyg.2015.01220

Degé, F., & Schwarzer, G. (2011). The effect of a music program on phonological awareness in preschoolers. *Frontiers in Psychology*, *2*, 124. https://doi.org/10.3389/fpsyg.2011.00124

Douglas, S., & Willatts, P. (1994). The relationship between musical ability and literacy skills. *Journal of Research in Reading*, *17*(2), 99–107. https://doi.org/10.1111/j.1467-9817.1994.tb00057.x

Drake, C. (1993). Reproduction of musical rhythms by children, adult musicians, and adult nonmusicians. *Perception & Psychophysics*, *53*(1), 25–33. Retrieved from https://link.springer.com/content/pdf/10.3758/BF03211712.pdf

Flaugnacco, E., Lopez, L., Terribili, C., Zoia, S., Buda, S., Tilli, S., … Schön, D. (2014). Rhythm perception and production predict reading abilities in developmental dyslexia. *Frontiers in Human Neuroscience*, *8*, 392. https://doi.org/10.3389/fnhum.2014.00392

Fogel, A. R., Rosenberg, J. C., Lehman, F. M., Kuperberg, G. R., & Patel, A. D. (2015).

Studying musical and linguistic prediction in comparable ways: The melodic cloze probability method. *Frontiers in Psychology*, *6*(NOV). https://doi.org/10.3389/fpsyg.2015.01718

Forgeard, M., Winner, E., Norton, A., & Schlaug, G. (2008). Practicing a Musical Instrument in Childhood is Associated with Enhanced Verbal Ability and Nonverbal Reasoning. *PLoS ONE*, *3*(10), e3566. https://doi.org/10.1371/journal.pone.0003566

Fox, J., & Weisberg, S. (2019). *An R Companion to Applied Regression* (3rd ed.). Thousand Oaks CA: Sage.

François, C., Chobert, J., Besson, M., & Schön, D. (2013). Music training for the development of speech segmentation. *Cerebral Cortex*, *23*(9), 2038–2043. https://doi.org/10.1093/cercor/bhs180

Gaser, C., & Schlaug, G. (2003). *Brain Structures Differ between Musicians and Non-Musicians*. Retrieved from https://www.jneurosci.org/content/jneuro/23/27/9240.full.pdf

Gordon, R. L., Jacobs, M. S., Schuele, C. M., & McAuley, J. D. (2015). Perspectives on the rhythm-grammar link and its implications for typical and atypical language development. *Annals of the New York Academy of Sciences*, *1337*(1), 16–25. https://doi.org/10.1111/nyas.12683

Gordon, R. L., Shivers, C. M., Wieland, E. A., Kotz, S. A., Yoder, P. J., & Devin Mcauley, J. (2015). Musical rhythm discrimination explains individual differences in grammar skills in children. *Developmental Science*, *18*(4), 635–644. https://doi.org/10.1111/desc.12230

Goswami, U., Thomson, J., Richardson, U., Stainthorp, R., Hughes, D., Rosen, S., & Scott, S. K. (2002). Amplitude envelope onsets and developmental dyslexia: A new hypothesis. *Proceedings of the National Academy of Sciences*, *99*(16), 10911–10916. https://doi.org/10.1073/pnas.122368599

Grube, M., Kumar, S., Cooper, F. E., Turton, S., & Griffiths, T. D. (2012). Auditory sequence analysis and phonological skill. *Proceedings of the Royal Society B: Biological Sciences*, *279*(1746), 4496–4504. https://doi.org/10.1098/rspb.2012.1817

Guasti, M. T., Pagliarini, E., & Stucchi, N. (2017). Language, reading and motor control: Get rhythm! *Biolinguistics*, *11*(1), 1–12.

Habibi, A., Wirantana, V., & Starr, A. (2014). Cortical activity during perception of musical rhythm: Comparing musicians and nonmusicians. *Psychomusicology: Music, Mind, and Brain*, *24*(2), 125–135. https://doi.org/10.1037/pmu0000046

Holliman, A. J., Wood, C., & Sheehy, K. (2010). The contribution of sensitivity to speech rhythm and non-speech rhythm to early reading development. *Educational Psychology*, *30*(3), 247–267. https://doi.org/10.1080/01443410903560922

Hothorn, T., Bretz, F., & Westfall, P. (2008). Simultaneous Inference in General Parametric Models. *Biometrical Journal*, *50*(3), 346–363.

Jakobson, L. S., Lewycky, S. T., Kilgour, A. R., & Stoesz, B. M. (2008). Memory for verbal and visual material in highly trained musicians. *Music Perception: An Interdisciplinary Journal*, *26*(1), 41–55. https://doi.org/10.1525/mp.2008.26.1.41

Just, M. A., & Carpenter, P. A. (1992). A capacity theory of comprehension: Individual differences in working memory. *Psychological Review*, *99*(1), 122–149. https://doi.org/10.1037/0033-295X.99.1.122

Kendall, J. (1985). *The Suzuki® Violin Method in American Music Education*. Alfred Publishing Co., Inc: USA. Retrieved from https://books.google.it/books?hl=it&lr=&id=kYvFjAyg9-cC&oi=fnd&pg=PA7&dq=suzuki+method+music&ots=lHm8hnfCdJ&sig=NfuhxEkNf4MAtrYhxKJiMdY5QRQ&redir_esc=y#v=onepage&q=suzuki method music&f=false

Koelsch, S., Schmidt, B. H., & Kansok, J. (2002). Effects of musical expertise on the early right anterior negativity: An event-related brain potential study. *Psychophysiology*, *39*(5), 657–663. https://doi.org/10.1017/S0048577202010508

Kraus, N., & Chandrasekaran, B. (2010, August). Music training for the development of auditory skills. *Nature Reviews Neuroscience*. https://doi.org/10.1038/nrn2882

Kuperberg, G. R. (2013). The proactive comprehender: What event-related potentials tell us about the dynamics of reading comprehension. In B. Miller, L. Cutting, & P. McCardle (Eds.), *Unraveling reading comprehension: Behavioral, neurobiological, and genetic components* (pp. 176–192). Baltimore, MD: Paul Brookes.

Ladányi, E., Lukács, Á., & Gervain, J. (submitted). Rhythmic priming in children with and without Specific Language Impairment.

Lee, Y. shiow, Lu, M. ju, & Ko, H. ping. (2007). Effects of skill training on working memory capacity. *Learning and Instruction*, *17*(3), 336–344. https://doi.org/10.1016/j.learninstruc.2007.02.010

Lenth, R. V. (2018). emmeans: Estimated Marginal Means, aka Least-Squares Means. Retrieved from https://cran.r-project.org/package=emmeans

Linnavalli, T., Putkinen, V., Lipsanen, J., Huotilainen, M., & Tervaniemi, M. (2018). Music playschool enhances children's linguistic skills. *Scientific Reports*, *8*(1), 8767. https://doi.org/10.1038/s41598-018-27126-5

Magne, C., Jordan, D. K., & Gordon, R. L. (2016). Speech rhythm sensitivity and musical aptitude: ERPs and individual differences. *Brain and Language*, *153–154*, 13–19. https://doi.org/10.1016/j.bandl.2016.01.001

Mankel, K., & Bidelman, G. M. (2018). Inherent auditory skills rather than formal music training shape the neural encoding of speech. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(51), 13129–13134. https://doi.org/10.1073/pnas.1811793115

Margulis, E. H. (2012, April). Musical repetition detection across multiple exposures. *Music Perception*. https://doi.org/10.1525/mp.2012.29.4.377

Marie, C., Magne, C., & Besson, M. (2011). Musicians and the metric structure of words. *Journal of Cognitive Neuroscience*, *23*(2), 294–305. https://doi.org/10.1162/jocn.2010.21413

Moradzadeh, L., Blumenthal, G., & Wiseheart, M. (2015). Musical Training, Bilingualism, and Executive Function: A Closer Look at Task Switching and Dual-Task Performance. *Cognitive Science*, *39*(5), 992–1020. https://doi.org/10.1111/cogs.12183

Moreno, S., Marques, C., Santos, A., Santos, M., Castro, S. L., & Besson, M. (2009). Musical Training Influences Linguistic Abilities in 8-Year-Old Children: More Evidence for Brain Plasticity. *Cerebral Cortex*, *19*(3), 712–723. https://doi.org/10.1093/cercor/bhn120

Moritz, C., Yampolsky, S., Papadelis, G., Thomson, J. M., & Wolf, M. (2013). Links between early rhythm skills, musical training, and phonological awareness. *Reading and Writing*, *26*(5), 739–769. https://doi.org/10.1007/s11145-012-9389-0

Musacchia, G., Sams, M., Skoe, E., & Kraus, N. (2007). Musicians have enhanced subcortical auditory and audiovisual processing of speech and music. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(40), 15894–15898. https://doi.org/10.1073/pnas.0701498104

Näätänen, R., Lehtokoski, A., Lennes, M., Cheour, M., Huotilainen, M., Iivonen, A., … Alho, K. (1997). Language-specific phoneme representations revealed by electric and magnetic brain responses. *Nature*, *385*(6615), 432–434. https://doi.org/10.1038/385432a0

Overy, K. (2003). Dyslexia and music: From timing deficits to musical intervention. *Annals of the New York Academy of Sciences*, *999*, 497–505.

https://doi.org/10.1196/annals.1284.060

Ozernov-Palchik, O., Wolf, M., & Patel, A. D. (2018). Relationships between early literacy and nonlinguistic rhythmic processes in kindergarteners. *Journal of Experimental Child Psychology*, *167*, 354–368. https://doi.org/10.1016/j.jecp.2017.11.009

Pantev, C., Roberts, L. E., Schulz, M., Engelien, A., & Ross, B. (2001). Timbre-specific enhancement of auditory cortical representations in musicians. *Neuroreport*, *12*(1), 169–174. https://doi.org/10.1097/00001756-200101220-00041

Patel, A. D., & Morgan, E. (2017). Exploring Cognitive Relations Between Prediction in Language and Music. *Cognitive Science*, *41*, 303–320. https://doi.org/10.1111/cogs.12411

Patscheke, H., Degé, F., & Schwarzer, G. (2019). The effects of training in rhythm and pitch on phonological awareness in four- to six-year-old children. *Psychology of Music*, *47*(3), 376–391. https://doi.org/10.1177/0305735618756763

Persici, V., Stucchi, N., & Arosio, F. (2019). Rhythmic and morphosyntactic predictions: The anticipation abilities of Italian children with Developmental Dyslexia. In M. Brown & B. Dailey (Eds.), *BUCLD 43: Proceedings of the 43rd annual Boston University Conference on Language Development*. Somerville, MA: Cascadilla Press.

Politimou, N., Dalla Bella, S., Farrugia, N., & Franco, F. (2019). Born to speak and sing: Musical predictors of language development in pre-schoolers. *Frontiers in Psychology*, *10*(APR). https://doi.org/10.3389/fpsyg.2019.00948

Przybylski, L., Bedoin, N., Krifi-Papoz, S., Herbillon, V., Roch, D., Léculier, L., … Tillmann, B. (2013). Rhythmic auditory stimulation influences syntactic processing in children with developmental language disorders. *Neuropsychology*, *27*(1), 121–131. https://doi.org/10.1037/a0031277

R Development Core Team. (2016). R: A Language and Environment for Statistical Computing. Retrieved from https://www.researchgate.net/publication/312455832_R_A_Language_and_Environment_for_Statistical_Computing

Rautenberg, I. (2015). The effects of musical training on the decoding skills of German-speaking primary school children. *Journal of Research in Reading*, *38*(1), 1–17. https://doi.org/10.1111/jrir.12010

Sares, A. G., Foster, N. E. V., Allen, K., & Hyde, K. L. (2018). Pitch and time processing in speech and tones: The effects of musical training and attention. *Journal of Speech, Language, and Hearing Research*, *61*(3), 496–509.

https://doi.org/10.1044/2017_JSLHR-S-17-0207

Sartori, G., Job, R., & Tressoldi, P. E. (2007). *DDE-2: Batteria per la valutazione della dislessia e della disortografia evolutiva-2*. Firenze, Italia: O.S. Giunti.

Schlaug, G. (2001). The Brain of Musicians A Model for Functional and Structural Adaptation. *Annals of the New York Academy of Sciences*, *930*, 281–299. https://doi.org/10.1111/j.1749-6632.2001.tb05739.x

Schlaug, G., Lutz, J., Huang, Y., Staigeri, J. F., & Steinmetz1, H. (1995). Increased corpus callosum size in musicians. *Neuropsychologia*, *33*(8), 1047–1055. Retrieved from http://www.brainmusic.org/EducationalActivitiesFolder/Schlaug_CCmus1995.pdf

Schneider, P., Scherg, M., & Dosch, H. G. (2002). Morphology of Heschl's gyrus reflects enhanced activation in the auditory cortex of musicians. *Nature Neuroscience*, *5*(7), 688–694. https://doi.org/10.1038/nn871

Strait, D. L., Hornickel, J., & Kraus, N. (2011). Subcortical processing of speech regularities underlies reading and music aptitude in children. *Behavioral and Brain Functions*, *7*(1), 44. https://doi.org/10.1186/1744-9081-7-44

Sun, L., Liu, F., Zhou, L., & Jiang, C. (2018). Musical training modulates the early but not the late stage of rhythmic syntactic processing. *Psychophysiology*, *55*(2), 1–10. https://doi.org/10.1111/psyp.12983

Tan, Y. T., McPherson, G. E., Peretz, I., Berkovic, S. F., & Wilson, S. J. (2014). The genetic basis of music ability. *Frontiers in Psychology*. Frontiers Research Foundation. https://doi.org/10.3389/fpsyg.2014.00658

Taub, G. E., & Lazarus, P. J. (2012). The effects of training in timing and rhythm on reading achievement. *Contemporary Issues in Education Research*, *5*(4), 343–350. https://doi.org/https://doi.org/10.19030/cier.v5i4.7598

Vuust, P., Ostergaard, L., Pallesen, K. J., Bailey, C., & Roepstorff, A. (2009). Predictive coding of music - Brain responses to rhythmic incongruity. *Cortex*. https://doi.org/10.1016/j.cortex.2008.05.014

Vuust, P., Pallesen, K. J., Bailey, C., van Zuijen, T. L., Gjedde, A., Roepstorff, A., & Østergaard, L. (2005). To musicians, the message is in the meter: Pre-attentive neuronal responses to incongruent rhythm are left-lateralized in musicians. *NeuroImage*, *24*(2), 560–564. https://doi.org/10.1016/J.NEUROIMAGE.2004.08.039

Wickham, H. (2016). *ggplot2: Elegant Graphics for Data Analysis*. New York: Springer-Verlag.

Wolff, P. H., Michel, G. F., Ovrut, M., & Drake, C. (1990). Rate and Timing Precision of

Motor Coordination in Developmental Dyslexia. *Developmental Psychology*, *26*(3), 349–359. https://doi.org/10.1037/0012-1649.26.3.349

Woodruff Carr, K., White-Schwoch, T., Tierney, A. T., Strait, D. L., & Kraus, N. (2014). Beat synchronization predicts neural speech encoding and reading readiness in preschoolers. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(40), 14559–14564. https://doi.org/10.1073/pnas.1406219111

Zamorano, A. M., Cifre, I., Montoya, P., Riquelme, I., & Kleber, B. (2017). Insula-based networks in professional musicians: Evidence for increased functional connectivity during resting state fMRI. *Human Brain Mapping*, *38*(10), 4834–4849. https://doi.org/10.1002/hbm.23682

Zhao, T. C., & Kuhl, P. K. (2016). Musical intervention enhances infants’ neural processing of temporal structure in music and speech. *Proceedings of the National Academy of Sciences of the United States of America*, *113*(19), 5212–5217. https://doi.org/10.1073/pnas.1603984113

Zuk, J., Bishop-Liebler, P., Ozernov-Palchik, O., Moore, E., Overy, K., Welch, G., & Gaab, N. (2017). Revisiting the “Enigma” of Musicians With Dyslexia: Auditory Sequencing and Speech Abilities. *Journal of Experimental Psychology: General*, *146*(4), 495–511. https://doi.org/10.1037/xge0000281

Zuk, J., Ozernov-Palchik, O., Kim, H., Lakshminarayanan, K., Gabrieli, J. D. E., Tallal, P., & Gaab, N. (2013). Enhanced syllable discrimination thresholds in musicians. *PLoS ONE*, *8*(12), 1–8. https://doi.org/10.1371/journal.pone.0080546

Chapter 5

Neural oscillatory markers of rhythm processing and individual differences in syntactic performance

5.1 Introduction

Individual differences in rhythm have been shown to correspond to individual differences in language in children (e.g., Gordon, Shivers, et al., 2015; see Chapter 1). Though most studies compared rhythm perception and early literacy development (e.g., Anvari, Trainor, Woodside, & Levy, 2002; Flaugnacco et al., 2014), recent evidence has shown that rhythm skills (in both perception and production) also predict language performance in children. In fact, children who better synchronize their movements to the beat (Woodruff Carr, White-Schwoch, Tierney, Strait, & Kraus, 2014) or who demonstrate better rhythmic perception skills (Gordon, Shivers, et al., 2015; Politimou, Dalla Bella, Farrugia, & Franco, 2019) have been found to have enhanced performance in tasks requiring syntactic skills (though not all evidence converges, cf. Ozernov-Palchik, Wolf, & Patel, 2018). Specifically, rhythm perception has been shown to correlate with performance on items organized in complex syntactic structures (Gordon, Jacobs, Schuele, & Mcauley, 2015). Though musical training may enhance mechanisms of neural entrainment (as discussed in Chapter 4), better performance in language cannot be interpreted as the mere result of transfer from musical skills, as associations between rhythmic and language skills have also been found in participants who did not received musical training (see Mankel & Bidelman, 2018). Moreover, as mentioned earlier, rhythmic priming paradigms have shown that even brief exposure to regular rhythmic primes positively affects subsequent grammar performance (Chern, Tillmann, Vaughan, & Gordon, 2018; Ladányi, Lukács, & Gervain, submitted; Przybylski et al., 2013). These associations between rhythm and grammar have been explained as the result of shared cognitive processes that are recruited when hierarchical structures are processed (Fitch, 2013; Fitch & Martins, 2014; Ladányi, Persici, Fiveash, Tillmann, & Gordon, submitted). In fact, both rhythm and grammar are hierarchically organized (see Figures 3 and 4 in Chapter 1) and their processing requires access to their hierarchical structures (Fitch, 2017).

It has been suggested that the processing of these structures is facilitated by the entrainment of neural oscillations to auditory stimuli. The phase-resetting of the oscillations produced by the firing of neurons is influenced by and synchronizes itself to external auditory stimuli (Luo, Wang, Poeppel, Simon, & Ding, 2006). This entrainment in rhythm and language takes place at multiple timescales, not only in relation to basic elements such as phones in language (Di Liberto, O'Sullivan, & Lalor, 2015) or durational intervals in musical rhythm (Nozaradan, Peretz, Missal, & Mouraux, 2011), but also to higher-level structures such as syntactic phrases (Ding, Melloni, et al., 2017) and meter (Fujioka, Ross, & Trainor, 2015). Based on this evidence, neural entrainment has been interpreted as a crucial mechanism not only for rhythm processing, but also for speech decoding, processing, and comprehension (Ahissar et al., 2001; Ding, Patel, et al., 2017; Ghitza, 2012; Luo & Poeppel, 2007). According to the Dynamic Attending Theory (DAT: Jones, 2019; Jones & Boltz, 1989; Large & Jones, 1999), auditory input processing would be facilitated by an increase in allocated attention to important time points of the stimulus. As it has been suggested for rhythm, this increase in attention and facilitation in language may depend on the internal entrainment of multiple nested oscillations (Jones, 2019).

Given these premises, testing neural entrainment to rhythm in children could give an insight into their language skills as well. This is important, because it could also allow for an earlier identification of grammar deficits (and possibly, of Developmental Language Disorder (DLD); see Chapter 6). Electroencephalography (EEG) allows testing of entrainment in a passive, implicit, rapid, and relatively inexpensive way. However, still little is known about the brain mechanisms underlying rhythm perception and grammar performance.

5.2 The present study

In the present study we aimed to identify neural oscillatory markers that may relate to individual differences in language performance in children using EEG. To do so, we tested children in an experimental paradigm adapted from Iversen, Repp, and Patel (2009). In that study the authors investigated adult processing of rhythmic structures that varied in the location of intensity accents marking the beat, using magnetoencephalography (MEG). The authors analyzed their participants' brain activity by looking at the magnetic counterpart of event-related potentials (ERP) and at oscillatory responses in the beta and gamma frequency bands. ERPs are brain responses calculated by averaging brain activity recorded in alignment with the tone onset; oscillatory activity can also be studied in relation to the stimulus onset (phase-locked or evoked activity), but has the advantage of giving a measure of the power change in brain activity as a result of the exposure to auditory stimuli. In fact, evoked data is calculated by preserving only those oscillations in the average ERP waveform that are phase-locked to the stimulus, and allows the analysis of brain activity within specific frequency bands. In Iversen et al. (2009)'s case, neural activity was analyzed within beta and gamma frequency bands. Beta oscillations (~ 15 to 30 Hz) are believed to be important for rhythmic processing (Fujioka, Trainor, Large, & Ross, 2012), as they are thought to index meter representation (Fujioka et al., 2015), to play a role in predictive processes – which are important for efficient rhythmic processing (Arnal & Giraud, 2012; Leventhal et al., 2012), and to reflect the coupling of brain activity originated in distant brain regions, such as the auditory and motor cortices (Bartolo, Prado, & Merchant, 2014). Gamma band activity (30 to 100 Hz) is thought to play a role in the formation of temporal expectancies (Zanto, Large, Fuchs, & Kelso, 2005) and has been associated with language skills involving phonological perception (Goswami, 2011; Power, Colling, Mead, Barnes, & Goswami, 2016) and, importantly for this study, hierarchical processing (Ding, Melloni, Zhang, Tian, & Poeppel, 2015).

In our study we adapted Iversen et al. (2009)'s paradigm by presenting children participants with two rhythmic structures differing for the placement of the intensity accents marking the beat. We expected these patterns to elicit different metrical interpretations and, thus, different fluctuations in both ERPs and beta and gamma evoked activity. Moreover, given the associations found between rhythm and language in other work (see Chapter 1 for more details) and the hypothesized shared mechanism for hierarchical processing between the two domains (Ladányi, Persici, et al., submitted), we expected individual differences in brain activity to relate to individual differences in grammar task performance, and more specifically, in the categories of Transformation and Complex Syntax. The term 'Transformation' refers to uni-clausal sentences with a non-canonical word order, and which require the participant to re-order the material in the sentence in order to understand it. An example of such sentences in English are wh-interrogatives, in which the direct-object is fronted, as in the sentence "What did the boy read?" (Sentence 3 in Figure 2 in Gordon, Jacobs, Schuele, & McAuley, 2015). The term 'Complex Syntax' refers to those sentences that contain multiple clauses and thus have complex structural dependency relations, as in the sentence "The boy read the book that his mother gave to him" (Sentence 2 in Figure 2 in

Gordon, Jacobs, Schuele, & McAuley, 2015). These types of sentences, which include subordinate, infinite, complement, and relative clauses, are acquired and used efficiently at a later age as compared to simpler structures in typical development (Vasilyeva, Waterfall, & Huttenlocher, 2008). Both Transformation and Complex Syntax require individuals to perform complex grammatical operations (though these are of greater complexity in the case of Complex Syntax). The ability to perform such operations is fundamental for efficient language processing and development.

Prior work with children has shown that rhythmic processing skills predict syntax performance, both in general (Gordon, Shivers, et al., 2015) and in the two above-mentioned specific sub-categories (Gordon, Jacobs, Schuele, & Mcauley, 2015). If rhythmic processing is subserved by neural entrainment, individual differences in such neural activity should also correspond to individual differences in hierarchical processing in language. For these reasons, in this study, we expected to find correspondence between individual differences in neural activity and individual differences in syntax, especially in the case of sentences that require more refined grammatical operations, i.e., in Complex Syntax.

5.2.1 Methods

Participants

The participants in this study are the ones reported in Gordon, Shivers, et al. (2015); here we report EEG results in relation to extant behavioral data from the same children. The sample included 25 children (12 females, 13 males), aged between 5;11 and 7;1 years (mean: 6;6 years, SD = 0.4). All were native speakers of American English and were reported to have normal hearing, and normal language, cognitive, and emotional development by their parents. Parents also provided information about their education and the child's musical activities. The highest level of education reached by the participants' mothers could go from 1, corresponding to no years in elementary school, to level 9, which corresponded to at least three or four years of graduate or professional school. In our sample, the mean maternal education score was 7.64 (SD = 0.83, range: 6-9), corresponding to three to four years of college or of technical school. In the questionnaire, parents also had to indicate whether their children had participated in musical lessons in school and/or outside of school, individually and/or in group; positive answers were assigned a score of 1, negative answers a score of 0.

Music experience was calculated by summing these scores. As reported in Gordon, Shivers, et al. (2015), musical experience scores ranged from 0 to 3 (mean: 1.08, SD = 0.81).

The study was approved by the Institutional Review Board of Vanderbilt University (Nashville, TN, United States of America). Before starting, the experimenter obtained the parents' written consent to the participation of their child and the child's separate assent. Families were compensated for participation with a small toy for the children and a $40 gift card.

Language ability. The expressive grammatical skills of the participants were tested using the Structured Photographic Expressive Language Test (SPELT-3; Dawson, Stout, & Eyer (2003), which has a high diagnostic accuracy for the identification of grammatical impairments in children (Perona, Plante, & Vance, 2005) and good construct validity (Greenslade, Plante, & Vance, 2009). In this task, participants are presented with various photographs and asked, through specific questions, to describe what they see. The questions are designed so as to elicit specific morpho-syntactic constructions, such as irregular plural nouns or past tense verbs. All participants scored within the normal range. Standard and raw scores were calculated and used in the analysis (see Table 1 for mean scores and SDs).

Non-verbal cognitive ability. Participants' non-verbal intelligence was measured using the Primary Test of Nonverbal Intelligence (PTONI; Ehrler & McGhee, 2008). PTONI's raw scores were calculated.

Table 1
Mean scores in the language and IQ tests for our participants.

N	25
SPELT standard score	114.16 (6.87)
Complex Syntax	0.81 (0.13)
Transformation	0.86 (0.14)
Nonverbal IQ raw	42.8 (10.72)
Nonverbal IQ standard	110.32 (22.75)

Note. The results of these behavioral tests were presented in Gordon, Jacobs, Schuele, and McAuley (2015).

Rhythm discrimination. The children's rhythm discrimination abilities were tested in two tests: the beat-based advantage assessment (BBA), and the rhythm section of the Primary Measures of Music Audiation (PMMA; Gordon, 1979). The BBA is a computer-based test adaptation of the test created by Grahn & Brett (2009), whereas PMMA was created by Gordon (1979). In both tests participants are presented with two rhythmic sequences and are required to say whether they are the 'same' or 'different' (see Gordon, Shivers, et al., 2015, for more details). Though both tests are measures of rhythmic perception skills, the two differ on a number of levels, including the number of trials (BBA has 28, PMMA has 40), and the characters used to introduce the task. More importantly, each has unique attributes: only PMMA is a validated and standardized test of music aptitude; on the other hand, BBA addresses beat perception specifically (important for this study), whereas PMMA includes stimuli with more varied metrical structures.

From these tests we obtained the Rhythm Composite Score, which is supposed to reflect individual differences in rhythmic discrimination. Differently from Gordon, Shivers, et al. (2015), the Rhythm Composite score was calculated by averaging z-scored BBA d' prime (rather than the BBA percent correct) and z-scored PMMA percent correct. This new measure was highly correlated with the previous Rhythm Composite measure ($r = .99$, $p < .001$).

Materials

Electroencephalography. Auditory stimuli were organized and presented following the paradigm presented in Iversen, Repp, & Patel (2009) (see Figure 1). Each sound had a frequency of 1000 Hz, a duration of 50 milliseconds (ms), and an inter-onset interval of 200 ms. Pairs of sounds were organized in accented sequences and were always followed by silence. In the first condition (PA1), sequences had a strong-weak-rest pattern: the accent, conveyed by doubling the intensity of the sound, was placed on the first tone; in the second condition (PA2), the accent was placed on the second tone, thus creating a weak-strong-rest pattern. Both types of sequences had each a duration of 600 ms. Each condition, which included forty-eight repetitions of the same tone sequence for a duration of 30 seconds, was presented nine times in random order, for a total of 864 items.

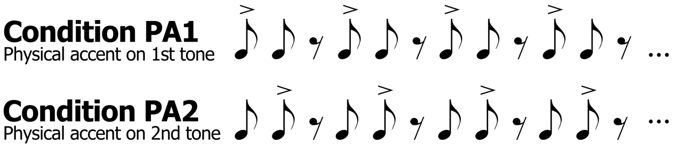

Figure 1. Rhythmic conditions in the experimental paradigm (figure from Yu et al. (in preparation), adapted from Iversen et al. (2009)). Participants heard tone sequences in two conditions (PA1: accented tone – tone – rest; PA2: tone – accented tone – rest).

Procedure

EEG Acquisition. Participants' EEG recordings were collected individually in a sound-dampened room at the EEG Lab at the Vanderbilt Kennedy Center in Nashville, Tennessee (USA). Brain activity was measured continuously by EEG using 124 Ag/AgCl electrodes embedded in soft sponges (EGI Geodesic Sensor Net). Lower eye channels were excluded. EEG signals were sampled at 500 Hz for temporal precision. The data of two participants were inadvertently sampled at 250 Hz and then later upsampled to 500 Hz. Data was acquired in Net Station 4.4 with amplifier NetAmps 200 and with a hardware filter of 0.1 to 200 Hz. Participants were instructed to sit as still as possible while we showed them a silent movie and played them some sounds. Stimuli were presented through speakers and were matched in loudness. EEG was recorded while participants listened passively to the auditory stimuli; no behavioral responses were required. To keep participants engaged but still during data acquisition, an age-appropriate video with muted sound was shown. The experiment had a duration of about ten minutes; the entire session lasted about 30 minutes.

Data Preprocessing. EEG data processing was performed using EEGLAB (Delorme & Makeig, 2004). Signals were smoothed using a 100-Hz low-pass filter and a 0.5-Hz high-pass filter to eliminate non-brain-related frequencies. Data were referenced to the average of the activity picked up from all channels. Line noise was cleaned using the pop_cleanline function. Bad electrodes characterized by consistently high noise levels were identified using the Artifact Subspace Reconstruction (ASR) approach (US 2016/0113587 A1, 2014) and interpolated using the spherical spline interpolation algorithm (Perrin, Pernier, Bertrand, & Echallier, 1989).

Artifacts in the data were identified using Individual Component Analysis (ICA); type of artifact was identified with the help of ICLabel (Pion-Tonachini, Kreutz-Delgado, & Makeig, 2019). Cardiac and ocular artifacts were removed. Next, data were divided into 1600-ms epochs with the interval of [-400, + 1200], time-locked to the onset of the first tone (tone-tone-rest, in both conditions). For event-related potential analysis, data were baseline-corrected with a baseline of [-100, 0] ms and averaged across trials for each stimulus condition.

5.2.2 Data Analysis

ERP analyses

After EEG preprocessing, individual Event-Related Potentials (ERPs) for each subject were exported to MATLAB R2017b (The Mathworks Inc., 2017) and analyzed using the Fieldtrip Toolbox (Oostenveld, Fries, Maris, & Schoffelen, 2011) at the time window [-100, +500]. Statistical significance was assessed using cluster-based permutation tests (Maris & Oostenveld, 2007). In these tests conditions are first compared at each time point, channel, and frequency using t-tests, and results are used to create clusters of samples that are similar to one another; then, the significance of each cluster ($p < .05$) between conditions is assessed by comparing each cluster to randomly-permutated clusters of values from both conditions using the Monte Carlo method (Maris & Oostenveld, 2007). To visualize possible differences between conditions, we subtracted the ERPs elicited by PA2 from those elicited by PA1.

Time-frequency analyses

Time-frequency analysis was conducted using Fieldtrip. Evoked (that is, phase-locked) activity for each condition was obtained by convolving the average ERP waveform with a Morlet wavelet with a width of five cycles. This was done with a frequency step of 2 Hz and a time step of 2 ms in the time window [-400, +850], with zero being the onset of the stimulus. Then, power values were baseline-corrected to the total power across all conditions to compensate for inter-individual variability in absolute power. Baseline values were calculated in relation to the relative power change from the average of the time-frequency data across conditions.

Individual differences and brain-behavior relationship

Individual differences in neural activity were calculated by summing up voltage of difference waves (for ERPs) and power values within each frequency band (for time-frequency data) for each participant in the time period of clusters with statistical significance. These measures are designed to reflect the magnitude of the difference in neural activity between conditions (cf. Lense et al., 2014). The relationship between the neural data and the grammar scores (both SPELT total and within Transformation and Complex Syntax) was analyzed in a set of Spearman correlations (function "cor.test") and hierarchical regressions (function "update") in R (R Development Core Team, 2016).

5.2.3 Results

ERP analysis

After running cluster-based permutation tests, results revealed a significant difference between the PA1 and PA2 conditions on both tones. On the first tone, participants showed a greater response in PA1 than in PA2 ($p = .015$, Figures 2 and 3A to see the first ('ERPcluster1') and second ('ERPcluster2') significant positive clusters). On the second tone, children showed a greater response in PA2 than in PA1 ($p < .001$, see Figures 2 and 3B to see the first ('ERPcluster1') and second ('ERPcluster2') significant negative clusters). Figure 2 shows the grand average ERP wave; Figure 3 shows the significant clusters in timestep over central and parietal regions of the scalp. Clusters are constituted by power values that go in the same direction of effect; positive clusters are obtained from positive t-values in the comparison of neural activity in each time point, channel, and frequency between conditions; negative clusters are obtained from negative t-values.

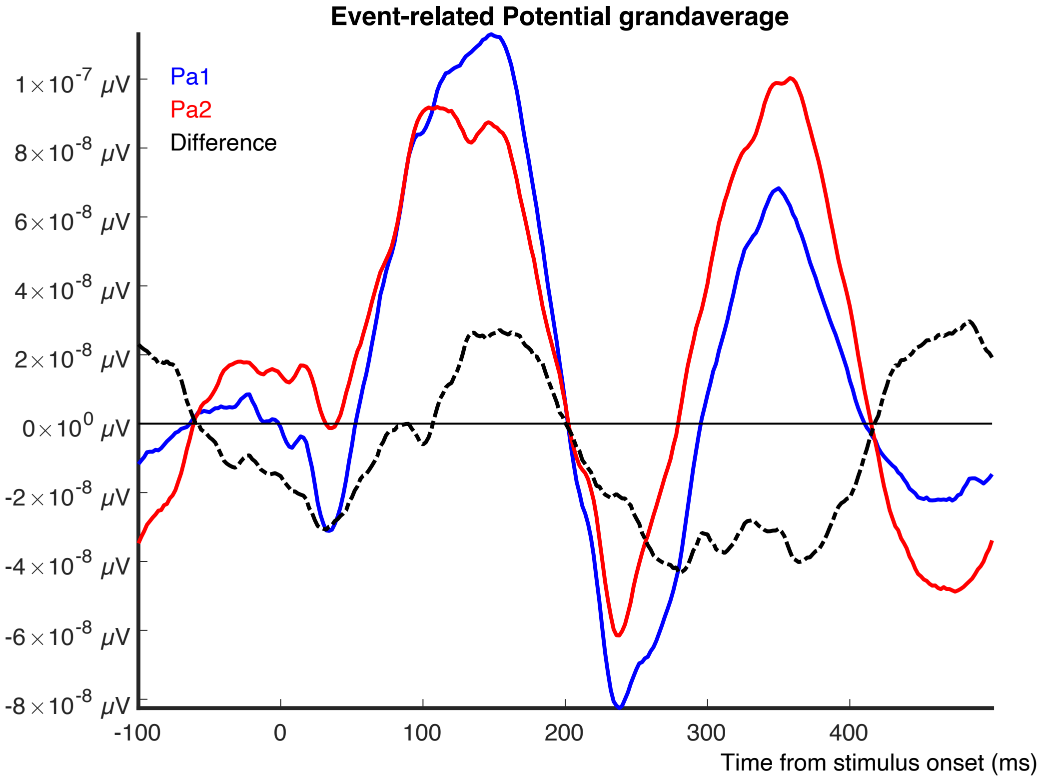

Figure 2. Grand average ERP (n = 25). The onsets of the first and second tone were at 0 and 200 ms, respectively, in both conditions. Condition PA1(strong-weak-rest) is in blue, condition PA2 (weak-strong-rest) is in red. The dashed black line shows the difference between the two conditions (PA1 - PA2). The horizontal black line shows power at 0 microvolts (μV). The plot shows a stronger response on the accented tone in each condition (i.e., on the first tone in PA1 and on the second tone in PA2).

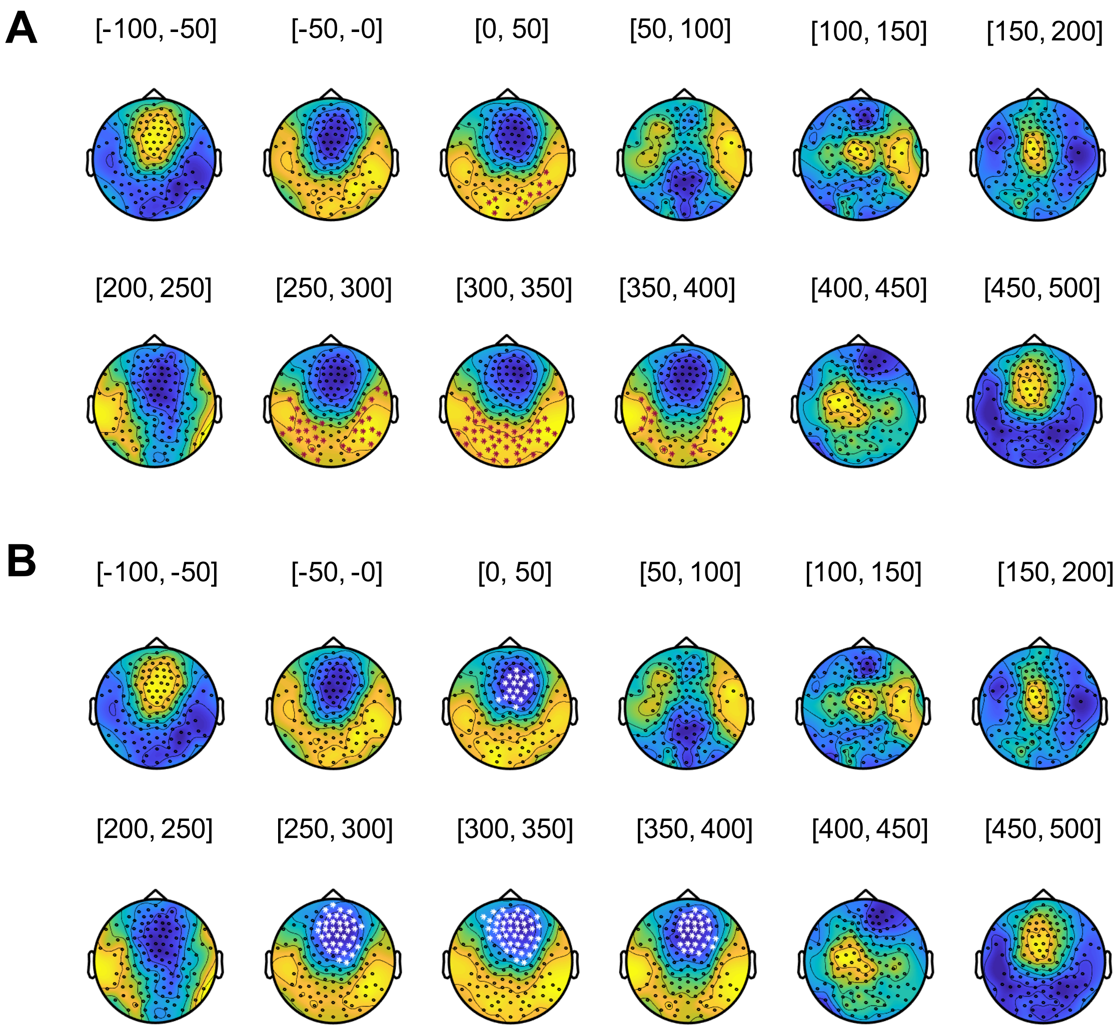

Figure 3. Significant ERP clusters in timestep (in ms). Topographies are shown for segments of 50 ms. The yellow and blue colors indicate positive and negative raw effects, respectively, which are the result of the subtraction of activity in PA2 from PA1 (in µV). Figure 3A shows significant positive clusters (significant channels are marked in red); latency of the clusters: ERPcluster1: 212 to 408 ms; ERPcluster2: -34 to 66 ms. Figure 3B shows significant negative clusters (significant channels are marked in white, in this case); latency of the clusters: ERPcluster1 222 - 428 ms; ERPcluster2: -44 to 45 ms.

Time-frequency analysis

Results showed a greater response in PA1 than in PA2 on the first tone in beta ($p <$ .001) but not in gamma, and a greater response in PA2 than in PA1 on the second tone in both frequency bands (beta: $p = .005$, gamma: $p = .004$, see Figure 4). The significant beta and gamma clusters are shown in timestep in Figures 5, 6, and 7.

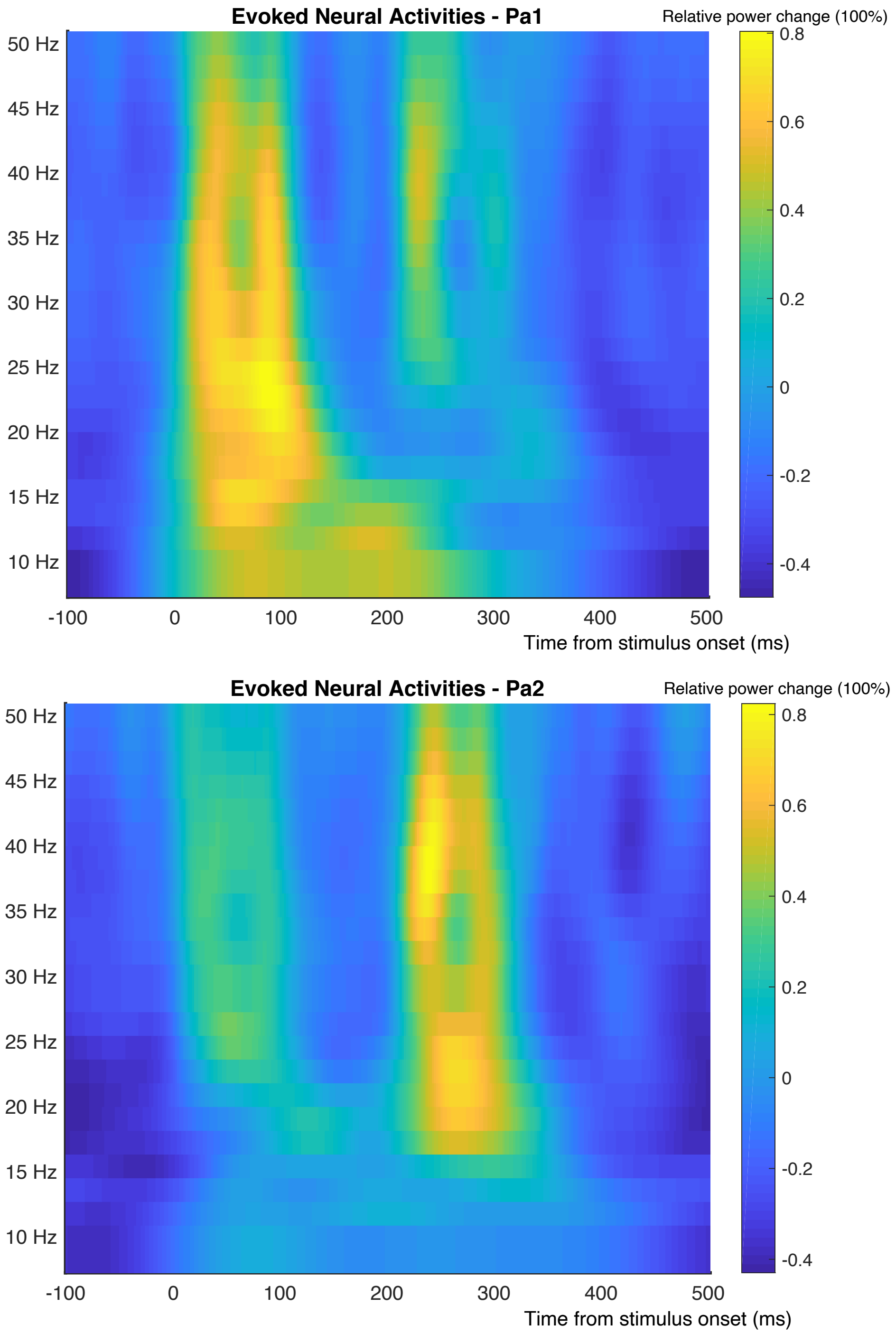

Figure 4. Evoked responses (10 - 50 Hz) of PA1 (top panel) and PA2 (bottom). In the color bar 1 stands for 100%. The onsets of the first and second tone were at 0 and 200 ms, respectively. The plots show stronger responses in the beta band (~15 to 30 Hz) and in the gamma band (> 30 Hz) in correspondence to the accented tone in each condition (i.e., on the first tone in PA1 and on the second tone in PA2).

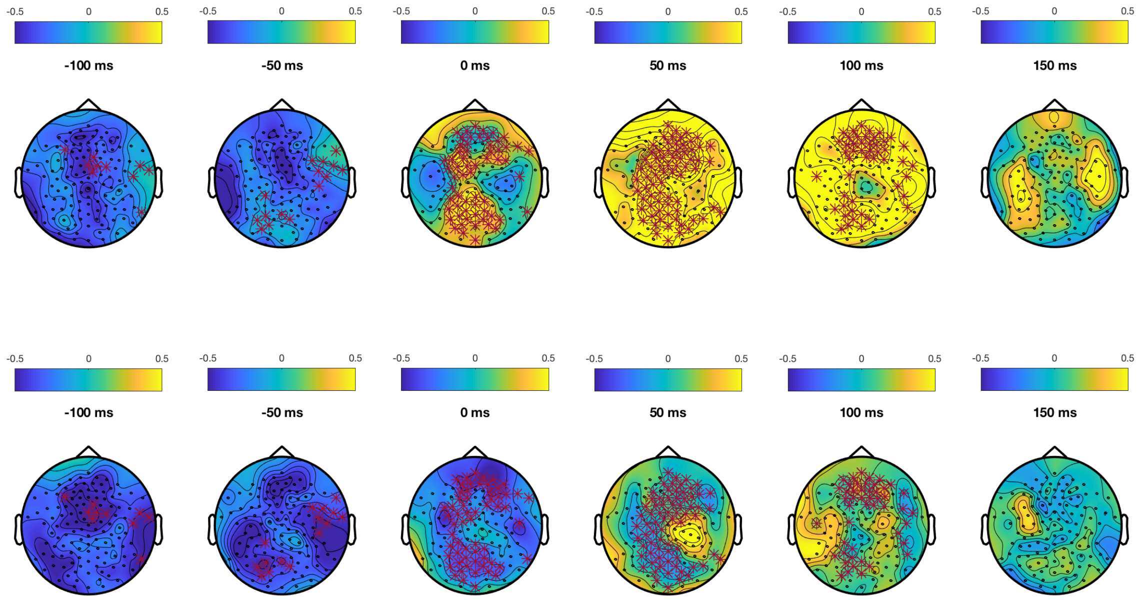

Figure 5. Beta positive cluster (latency: -100 to 140 ms) in timestep in condition PA1 (on the top row) and in condition PA2 (on the bottom row). Topographies are shown for segments of 50 ms. The color bars, going from dark blue to bright yellow, represent the percent change from baseline (i.e., normalized power): dark blue indicates a negative effect, bright yellow indicates a positive effect (in µV). Significant channels are marked with red asterisks.

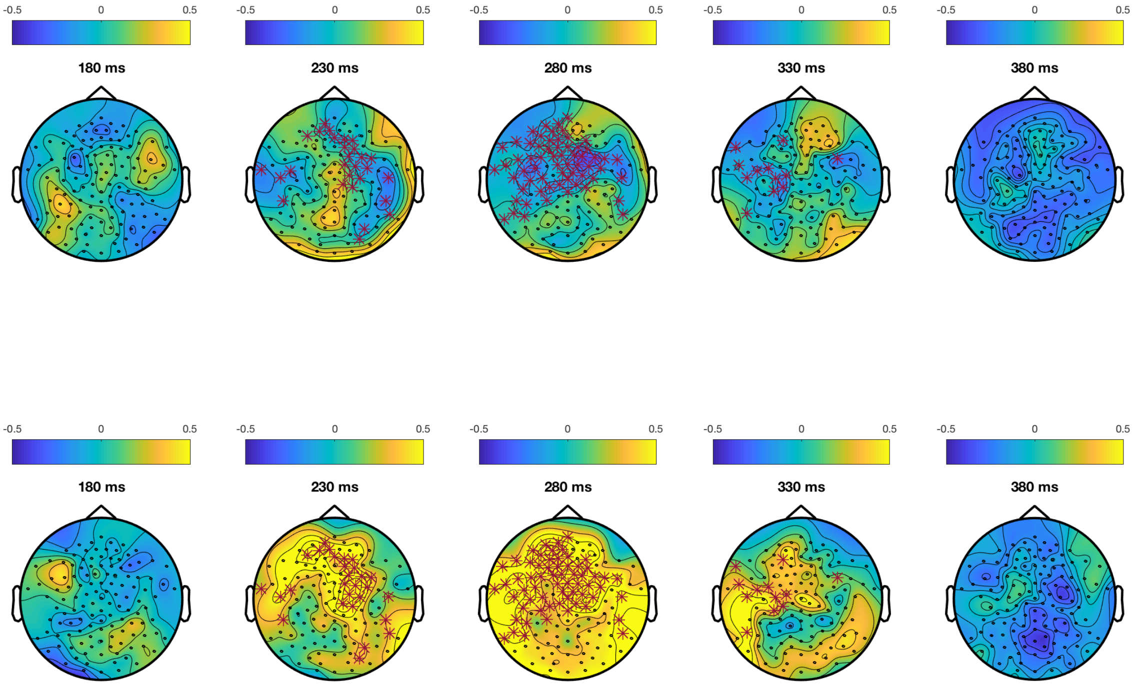

Figure 6. Beta negative cluster (latency: 186 to 346 ms) in timestep in condition PA1 (on the top row) and in condition PA2 (on the bottom row). Topographies are shown for segments of 50 ms. The color bars, going from dark blue to bright yellow, represent the percent change from baseline (i.e., normalized power): dark blue indicates a negative effect, bright yellow indicates a positive effect (in µV). Significant channels are marked with red asterisks.

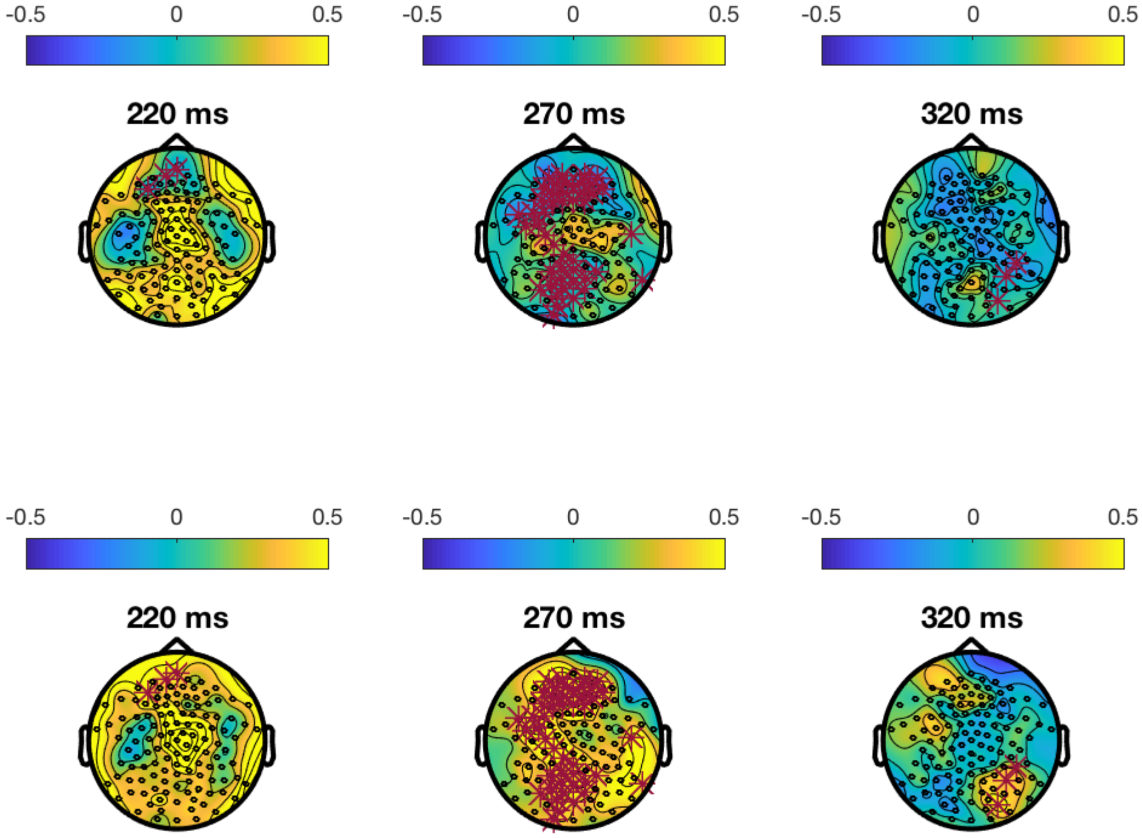

Figure 7. Gamma negative cluster (latency: 218 to 320 ms) in timestep in condition PA1 (on the top row) and in condition PA2 (on the bottom row). Topographies are shown for segments of 50 ms. The color bars, going from dark blue to bright yellow, represent the percent change from baseline (i.e., normalized power): dark blue indicates a negative effect, bright yellow indicates a positive effect (in µV). Significant channels are marked with red asterisks.

Brain-behavior relationship

Neural entrainment and expressive language ability: correlations. To investigate whether individual differences in performance in SPELT score, Transformation, and Complex Syntax corresponded to individual differences in neural response to rhythmic stimuli, we ran Spearman correlations between the total SPELT score or the scores in each of the SPELT subcategories of interest and significant ERP clusters, while controlling for both age and non-verbal intelligence. The same was then repeated for beta and gamma evoked activity.

Correlations between SPELT scores and ERP clusters showed non-significant correlations, regardless of whether total SPELT score (with the ERP positive cluster: p =

.563; negative: p = .519) or separate scores within the Transformation (ERP positive: p = .179; negative: p = .43) and Complex Syntax (ERP positive: p = .538; negative: p = .95) subcategories were considered.

However, the analysis of beta and gamma activity yielded different results: tests showed moderate and significant correlations between the positive beta cluster and SPELT total ($r_{(s)}$ = 0.33, p = .02), and also between positive beta and both Transformation ($r_{(s)}$ = 0.35, p = .013) and Complex Syntax ($r_{(s)}$ = 0.34, p = .015) scores. Moderate and significant correlations were also found between the same SPELT scores and negative gamma (SPELT total: $r_{(s)}$ = 0.42, p = .003; Transformation: $r_{(s)}$ = 0.37, p = .009; Complex Syntax: $r_{(s)}$ = 0.36, p = .012). No significant correlations were found between SPELT (whether total or in each subcategory) and negative beta (SPELT total: p = .168; Transformation: p = .233; Complex Syntax: p = .957).

Stepwise regression. As reported in Gordon, Jacobs, et al. (2015), and Gordon, Shivers, et al. (2015), the Rhythm Composite Score (calculated here as the mean of the z-scored BBA d’ and PMMA percent correct) explained unique variance in SPELT scores, whether total or within the Transformation and Complex Syntax subcategories. Here, we added the significant beta and gamma evoked clusters to see if more variance in the grammar scores of our participants could be explained by their neural responses to rhythm.

Results showed that adding positive beta to the base model (which included Rhythm as predictor and Age as covariate) increased significantly (p < .001) the amount of variance explained in the total SPELT score by 19.6% (the R^2 value changed from 0.537 to 0.733). On the contrary, negative beta and negative gamma did not explain unique variance in these scores (beta: p = .436, gamma: p = .876).

Within Transformation scores, results showed that positive beta explained significant (p < .001) and 20.3% unique variance (R^2 value change from 0.414 to 0.617). Adding negative beta to the base model also accounted for a significant (p = .008) increase of 11% in proportion of variance explained (R^2 value change from 0.414 to 0.425). Finally, adding negative gamma increased significantly (p = .009) the proportion of variance explained by 0.2 % (R^2 value change from 0.414 to 0.416).

The same results were found within Complex Syntax: results showed significant (p = .001) and unique variance (19.7%; the R^2 value changed from 0.323 to 0.520) explained by positive beta. Adding negative beta to the base model also increased significantly (p =

.019) the proportion of variance explained, though this time the unique variance explained by negative beta was 5% (R^2 value change from 0.323 to 0.370). Finally, a significant increase was found when negative gamma was added to the base model: proportion of variance explained in Complex Syntax increased significantly ($p = .038$) by 0.5% (R^2 value change from 0.323 to 0.324).

5.2.4 Discussion

The aim of the present study was to identify neural oscillatory markers that may relate to individual differences in language performance in children. Neural activity, analyzed both using ERPs and oscillatory evoked activity in the beta and gamma frequency bands, was recorded while children listened to rhythmic patterns that were designed to elicit different metrical interpretations; grammar performance was analyzed by looking at SPELT scores, both total and within the specific subcategories of Transformation and Complex Syntax (which require refined grammatical operations, especially the latter). We hypothesized that neural entrainment to rhythm may be linked to individual differences in language skills, especially in hierarchical processing, based on previous findings indicating that rhythm skills predict grammar performance (Gordon, Jacobs, et al., 2015; Gordon, Shivers, et al., 2015), and based on the idea that neural entrainment is crucial for hierarchical processing in both rhythm and language (Ahissar et al., 2001; Ding, Patel, et al., 2017; Ghitza, 2012; Ladányi, Persici, et al., submitted; Luo & Poeppel, 2007). Individual differences in neural entrainment may result in individual differences in hierarchical processing, both in rhythm and in grammar (possibly because of mechanisms of internal entrainment (Jones, 2019) and of increased attention (Large & Jones, 1999)).

Our study showed that the neural responses of the children tested entrained to the auditory stimuli, and confirmed previous research finding different neural responses to different metrical patterns (e.g., Iversen et al., 2009). In fact, our participants showed neural responses that fluctuated in both ERPs and evoked beta and gamma activity according to the metrical pattern that they were exposed to: enhanced neural responses were found in correspondence to the tone on which the physical accent was placed and which was thought to be perceived as the beat.

Moreover, in line with our predictions, not only rhythm perception skills, but also neural responses to this type of hierarchical structure were found to correlate and predict variance in six-year-olds' spoken complex syntactic abilities, especially in the cases where more refined grammatical abilities had to be used. Though more comprehensive tests, investigating both comprehension and production, should also be used in future research to analyze syntactic performance, our study contributes to the literature by showing that individual differences in syntactic performance are predicted by neural – above behavioral – measures of rhythm.

In particular, these results were found in relation to the evoked neural activity, and not to ERPs. This suggests that oscillatory activity gives more precise insight into the mechanisms underlying rhythm processing and grammar performance. More specifically, these results were found in relation to both beta (closely related to rhythmic processing (Fujioka et al., 2012) and beat perception (Cirelli, Spinelli, Nozaradan, & Trainor, 2016; Fujioka et al., 2015)) and gamma activity (which has been shown to track hierarchical linguistic structures: Ding et al., 2015). It should be noted that the beta band is thought to regulate the entrainment of the auditory and motor cortices, which are important for both language and rhythm, as sensorimotor coupling is thought to be part of the network subserving their processing, together with fine-grained auditory processing, and neural entrainment (Fiveash, Bedoin, & Tillmann, submitted; Ladányi, Persici, et al., submitted). More efficient entrainment between these brain regions may facilitate rhythm and language processing, possibly by enhancing predictions about sensory events (Kotz, Schwartze, & Schmidt-Kassow, 2009).

Relevantly for the previous chapters of this work, support for this idea comes from previous evidence showing that activity in both beta and gamma bands is associated with predictive processes (Arnal & Giraud, 2012; Leventhal et al., 2012; Zanto et al., 2005), as both are thought to reflect synchronization of neuronal populations during sensory processing of regular, predictive information (Arnal & Giraud, 2012). It is possible that individual differences in neural rhythms may correspond to individual differences in strength of predictive processes, and thus to different abilities of processing hierarchical structures.

In line with previous research (e.g., Woodruff Carr et al., 2014), the present findings suggest that precise neural encoding of temporal information may be a key mechanism for typical language development and acquisition. This idea would also help explain why children with DLD show deficits in rhythmic tasks (e.g., tapping: Corriveau & Goswami, 2009; rise time perception: Corriveau, Pasquini, & Goswami, 2007; prosody discrimination: Fisher, Plante, Vance, Gerken, & Glattke, 2007; Wells & Peppé, 2003). These hypotheses will be investigated in a study with a larger independent sample and with both TD and DLD children in Chapter 6.

5.2.5 References

Ahissar, E., Nagarajan, S., Ahissar, M., Protopapas, A., Mahncke, H., & Merzenich, M. M. (2001). Speech comprehension is correlated with temporal response patterns recorded from auditory cortex. *Proceedings of the National Academy of Sciences of the United States of America*, *98*(23), 13367–13372. https://doi.org/10.1073/pnas.201400998

Anvari, S. H., Trainor, L. J., Woodside, J., & Levy, B. A. (2002). Relations among musical skills, phonological processing, and early reading ability in preschool children. *Journal of Experimental Child Psychology*, *83*(2), 111–130. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/12408958

Arnal, L. H., & Giraud, A. L. (2012). Cortical oscillations and sensory predictions. *Trends in Cognitive Sciences*. https://doi.org/10.1016/j.tics.2012.05.003

Bartolo, R., Prado, L., & Merchant, H. (2014). Information processing in the primate basal ganglia during sensory-guided and internally driven rhythmic tapping. *Journal of Neuroscience*, *34*(11), 3910–3923. https://doi.org/10.1523/JNEUROSCI.2679-13.2014

Chern, A., Tillmann, B., Vaughan, C., & Gordon, R. L. (2018). New evidence of a rhythmic priming effect that enhances grammaticality judgments in children. *Journal of Experimental Child Psychology*, *173*, 371–379. https://doi.org/10.1016/j.jecp.2018.04.007

Cirelli, L. K., Spinelli, C., Nozaradan, S., & Trainor, L. J. (2016). Measuring neural entrainment to beat and meter in infants: Effects of music background. *Frontiers in Neuroscience*, *10*(MAY), 1–11. https://doi.org/10.3389/fnins.2016.00229

Corriveau, K. H., & Goswami, U. (2009). Rhythmic motor entrainment in children with speech and language impairments: Tapping to the beat. *Cortex*, *45*(1), 119–130. https://doi.org/10.1016/J.CORTEX.2007.09.008

Corriveau, K. H., Pasquini, E., & Goswami, U. (2007). Basic Auditory Processing Skills and Specific Language Impairment: A New Look at an Old Hypothesis. *Journal of Speech, Language, and Hearing Research*, *50*, 647–666. https://doi.org/10.1044/1092-4388(2007/046

Dawson, J., Stout, C., & Eyer, J. (2003). *Structured Photographic Expressive Language Test-3*. Dekalb, IL: Janelle Publications.

Delorme A, & Makeig S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*. https://doi.org/10.1016/j.jneumeth.2003.10.009

Di Liberto, G. M., O'Sullivan, J. A., & Lalor, E. C. (2015). Low-Frequency Cortical Entrainment to Speech Reflects Phoneme-Level Processing. *Current Biology : CB*, *25*(19), 2457–2465. https://doi.org/10.1016/j.cub.2015.08.030

Ding, N., Melloni, L., Yang, A., Wang, Y., Zhang, W., & Poeppel, D. (2017). Characterizing Neural Entrainment to Hierarchical Linguistic Units using Electroencephalography (EEG). *Frontiers in Human Neuroscience*, *11*, 481. https://doi.org/10.3389/fnhum.2017.00481

Ding, N., Melloni, L., Zhang, H., Tian, X., & Poeppel, D. (2015). Cortical tracking of hierarchical linguistic structures in connected speech. *Nature Neuroscience*, *19*(1), 158–164. https://doi.org/10.1038/nn.4186

Ding, N., Patel, A. D., Chen, L., Butler, H., Luo, C., & Poeppel, D. (2017). Temporal modulations in speech and music. *Neuroscience and Biobehavioral Reviews*, *81*, 181–187. https://doi.org/10.1016/j.neubiorev.2017.02.011

Ehrler, D. J., & McGhee, R. L. (2008). *PTONI: Primary Test of Nonverbal Intelligence*. (Pro-Ed, Ed.). Austin, TX.

Fisher, J., Plante, E., Vance, R., Gerken, L. A., & Glattke, T. J. (2007). Do children and adults with language impairment recognize prosodic cues? *Journal of Speech, Language, and Hearing Research*, *50*(3), 746–758. https://doi.org/10.1044/1092-4388(2007/052)

Fitch, W. T. (2013). Rhythmic cognition in humans and animals: distinguishing meter and pulse perception. *Frontiers in Systems Neuroscience*, *7*. https://doi.org/10.3389/fnsys.2013.00068

Fitch, W. T. (2017). Empirical approaches to the study of language evolution. https://doi.org/10.3758/s13423-017-1236-5

Fitch, W. T., & Martins, M. D. (2014). Hierarchical processing in music, language, and action: Lashley revisited. *Annals of the New York Academy of Sciences*, *1316*(1), 87–104. https://doi.org/10.1111/nyas.12406

Fiveash, A., Bedoin, N., & Tillmann, B. (submitted). Rhythmic processing of music and language: A review and implications for developmental disorders.

Flaugnacco, E., Lopez, L., Terribili, C., Zoia, S., Buda, S., Tilli, S., … Schön, D. (2014). Rhythm perception and production predict reading abilities in developmental dyslexia. *Frontiers in Human Neuroscience*, *8*, 392. https://doi.org/10.3389/fnhum.2014.00392

Fujioka, T., Ross, B., & Trainor, L. J. (2015). Beta-Band Oscillations Represent Auditory Beat and Its Metrical Hierarchy in Perception and Imagery. *The Journal of Neuroscience*, *11*(NOV), 15187–15198. https://doi.org/10.3389/fnins.2016.00389

Fujioka, T., Trainor, L. J., Large, E. W., & Ross, B. (2012). Internalized timing of isochronous sounds is represented in neuromagnetic β oscillations. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *32*(5), 1791–1802. https://doi.org/10.1523/JNEUROSCI.4107-11.2012

Ghitza, O. (2012). On the role of theta-driven syllabic parsing in decoding speech: intelligibility of speech with a manipulated modulation spectrum. *Frontiers in Psychology*, *3*, 238. https://doi.org/10.3389/fpsyg.2012.00238

Gordon, E. E. (1979). *Primary Measures of Music Audiation.* Chicago, IL: GIA Publications.

Gordon, R. L., Jacobs, M. S., Schuele, C. M., & Mcauley, J. D. (2015). Perspectives on the rhythm-grammar link and its implications for typical and atypical language development. *Annals of the New York Academy of Sciences*, *1337*(1), 16–25. https://doi.org/10.1111/nyas.12683

Gordon, R. L., Jacobs, M. S., Schuele, C. M., & McAuley, J. D. (2015). Perspectives on the rhythm-grammar link and its implications for typical and atypical language development. *Annals of the New York Academy of Sciences*, *1337*(1), 16–25. https://doi.org/10.1111/nyas.12683

Gordon, R. L., Shivers, C. M., Wieland, E. A., Kotz, S. A., Yoder, P. J., & Devin Mcauley, J. (2015). Musical rhythm discrimination explains individual differences in grammar skills in children. *Developmental Science*, *18*(4), 635–644. https://doi.org/10.1111/desc.12230

Goswami, U. (2011). A temporal sampling framework for developmental dyslexia. *Trends in Cognitive Sciences*, *15*(1), 3–10. https://doi.org/10.1016/J.TICS.2010.10.001

Grahn, J. A., & Brett, M. (2009). Impairment of beat-based rhythm discrimination in Parkinson's disease. *Cortex*, *45*, 54–61. https://doi.org/10.1016/j.cortex.2008.01.005

Greenslade, K. J., Plante, E., & Vance, R. (2009). The diagnostic accuracy and construct validity of the structured photographic expressive language test-preschool: Second edition. *Language, Speech, and Hearing Services in Schools*, *40*(2), 150–160.

https://doi.org/10.1044/0161-1461(2008/07-0049)

Iversen, J. R., Repp, B. H., & Patel, A. D. (2009). Top-down control of rhythm perception modulates early auditory responses. *Annals of the New York Academy of Sciences*, *1169*, 58–73. https://doi.org/10.1111/j.1749-6632.2009.04579.x

Jones, M. R. (2019). *Time will tell: A theory of Dynamic Attending*. New York: Oxford University Press.

Jones, M. R., & Boltz, M. (1989). Dynamic Attending and Responses to Time. *Psychological Review*, *96*(3), 459–491. https://doi.org/10.1037/0033-295X.96.3.459

Kothe, C. A. E., & Jung, T.-P. (2014). *US 2016/0113587 A1*. United States of America.

Kotz, S. A., Schwartze, M., & Schmidt-Kassow, M. (2009). Non-motor basal ganglia functions: A review and proposal for a model of sensory predictability in auditory language perception. *Cortex*, *45*(8), 982–990. https://doi.org/10.1016/j.cortex.2009.02.010

Ladányi, E., Lukács, Á., & Gervain, J. (submitted). Rhythmic priming in children with and without Specific Language Impairment.

Ladányi, E., Persici, V., Fiveash, A., Tillmann, B., & Gordon, R. L. (submitted). Is atypical rhythm a risk factor for speech and language disorders?

Large, E. W., & Jones, M. R. (1999). The dynamics of attending: How people track time-varying events. *Psychological Review*. https://doi.org/10.1037/0033-295X.106.1.119

Lense, M. D., Gordon, R. L., Key, A. P. F., & Dykens, E. M. (2014). Neural correlates of cross-modal affective priming by music in williams syndrome. *Social Cognitive and Affective Neuroscience*, *9*(4), 529–537. https://doi.org/10.1093/scan/nst017

Leventhal, D. K., Gage, G. J., Schmidt, R., Pettibone, J. R., Case, A. C., & Berke, J. D. (2012). Basal ganglia beta oscillations accompany cue utilization. *Neuron*, *73*(3), 523–536. https://doi.org/10.1016/j.neuron.2011.11.032

Luo, H., & Poeppel, D. (2007). Phase Patterns of Neuronal Responses Reliably Discriminate Speech in Human Auditory Cortex. *Neuron*, *54*(6), 1001–1010. https://doi.org/10.1016/j.neuron.2007.06.004

Luo, H., Wang, Y., Poeppel, D., Simon, J. Z., & Ding, N. (2006). Concurrent Encoding of Frequency and Amplitude Modulation in Human Auditory Cortex : MEG Evidence Concurrent Encoding of Frequency and Amplitude Modulation in Human Auditory Cortex : MEG Evidence. *Journal of Neurophysiology*, *96*(5), 2712–2723. https://doi.org/10.1152/jn.01256.2005

Mankel, K., & Bidelman, G. M. (2018). Inherent auditory skills rather than formal music training shape the neural encoding of speech. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(51), 13129–13134. https://doi.org/10.1073/pnas.1811793115

Maris, E., & Oostenveld, R. (2007). Nonparametric statistical testing of EEG- and MEG-data. *Journal of Neuroscience Methods*, *164*(1), 177–190. https://doi.org/10.1016/j.jneumeth.2007.03.024

Nozaradan, S., Peretz, I., Missal, M., & Mouraux, A. (2011). Tagging the neuronal entrainment to beat and meter. *Journal of Neuroscience*, *31*(28), 10234–10240. https://doi.org/10.1523/JNEUROSCI.0411-11.2011

Oostenveld, R., Fries, P., Maris, E., & Schoffelen, J. M. (2011). FieldTrip: Open source software for advanced analysis of MEG, EEG, and invasive electrophysiological data. *Computational Intelligence and Neuroscience*. https://doi.org/10.1155/2011/156869

Ozernov-Palchik, O., Wolf, M., & Patel, A. D. (2018). Relationships between early literacy and nonlinguistic rhythmic processes in kindergarteners. *Journal of Experimental Child Psychology*, *167*, 354–368. https://doi.org/10.1016/j.jecp.2017.11.009

Perona, K., Plante, E., & Vance, R. (2005). Diagnostic accuracy of the structured photographic expressive language test: third edition (SPELT-3). *Language, Speech, and Hearing Services in Schools*, *36*(2), 103–115.

Perrin, F., Pernier, J., Bertrand, O., & Echallier, J. F. (1989). Spherical splines for scalp potential and current density mapping. *Electroencephalography and Clinical Neurophysiology*. https://doi.org/10.1016/0013-4694(89)90180-6

Pion-Tonachini, L., Kreutz-Delgado, K., & Makeig, S. (2019). ICLabel: An automated electroencephalographic independent component classifier, dataset, and website. *NeuroImage*, *198*, 181–197. https://doi.org/10.1016/j.neuroimage.2019.05.026

Politimou, N., Dalla Bella, S., Farrugia, N., & Franco, F. (2019). Born to speak and sing: Musical predictors of language development in pre-schoolers. *Frontiers in Psychology*, *10*(APR). https://doi.org/10.3389/fpsyg.2019.00948

Power, A. J., Colling, L. J., Mead, N., Barnes, L., & Goswami, U. (2016). Neural encoding of the speech envelope by children with developmental dyslexia. *Brain and Language*, *160*. https://doi.org/10.1016/j.bandl.2016.06.006

Przybylski, L., Bedoin, N., Krifi-Papoz, S., Herbillon, V., Roch, D., Léculier, L., … Tillmann, B. (2013). Rhythmic auditory stimulation influences syntactic processing in children with developmental language disorders. *Neuropsychology*, *27*(1), 121–131. https://doi.org/10.1037/a0031277

R Development Core Team. (2016). R: A Language and Environment for Statistical Computing. Retrieved from https://www.researchgate.net/publication/312455832_R_A_Language_and_Environment_for_Statistical_Computing

The Mathworks Inc. (2017). MATLAB - MathWorks. *Www.Mathworks.Com/Products/Matlab*. https://doi.org/2016-11-26

Vasilyeva, M., Waterfall, H., & Huttenlocher, J. (2008). Emergence of syntax: Commonalities and differences across children. *Developmental Science*, *11*(1), 84–97. https://doi.org/10.1111/j.1467-7687.2007.00656.x

Wells, B., & Peppé, S. (2003). Intonation abilities of children with speech and language impairments. *Journal of Speech, Language, and Hearing Research*, *46*(1), 5–20. https://doi.org/10.1044/1092-4388(2003/001)

Woodruff Carr, K., White-Schwoch, T., Tierney, A. T., Strait, D. L., & Kraus, N. (2014). Beat synchronization predicts neural speech encoding and reading readiness in preschoolers. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(40), 14559–14564. https://doi.org/10.1073/pnas.1406219111

Yu, L., Persici, V., Boorom, O., Schuele, C. M., McAuley, J. D., Camarata, S., & Gordon, R. L. (in preparation). Musical rhythm processing in children with typical and atypical language development.

Zanto, T. P., Large, E. W., Fuchs, A., & Kelso, J. A. S. (2005). Gamma-band responses to perturbed auditory sequences: Evidence for synchronization of perceptual processes. *Music Perception*, *22*(3), 531–547. https://doi.org/10.1525/mp.2005.22.3.531

Chapter 6

Neural oscillatory markers of rhythm processing and individual differences in syntactic performance in children with TD and children with DLD

6.1 Introduction

As discussed in Chapter 1, Developmental Language Disorder (DLD; Bishop, 2017) is a disorder characterized by deficits in language comprehension and/or production which can persist in adult life (Bishop, 2017; Clegg, Hollis, Mawhood, & Rutter, 2005) and which do not follow from brain injury, acquired or degenerative neurological disease, hearing loss, intellectual disability, or autism spectrum disorder. Children with DLD have difficulty learning lexical (Kan & Windsor, 2010) and syntactic (Hsu & Bishop, 2014) information as compared to typically-developing (TD) children, and show deficits in verb morphology and complex syntax (Hulme & Snowling, 2009; Schuele & Tolbert, 2001a). This difficulty is thought to be caused by an inability to extract and encode verbal regularities (Krishnan, Watkins, & Bishop, 2016), a process that is subserved by the basal ganglia (Conway & Pisoni, 2008), a subcortical area that is also important for motor functions and rhythmic processing (Grahn & Brett, 2007, 2009; Kotz, Schwartze, & Schmidt-Kassow, 2009; Merchant, Grahn, Trainor, Rohrmeier, & Fitch, 2015).

In line with these findings, children with DLD also show impaired rhythm processing (Bedoin, Brisseau, Molinier, Roch, & Tillmann, 2016; Cumming, Wilson, Leong, Colling, & Goswami, 2015; Sallat & Jentschke, 2015) and synchronization (Corriveau & Goswami, 2009a; Cumming, Wilson, Leong, et al., 2015), though not all studies agree (cf. Vuolo, Goffman, & Zelaznik, 2017; Zelaznik et al., 2012). Moreover, temporal processing deficits extend to language: children with DLD have deficits in processing temporal information in speech, and more specifically, in processing amplitude envelope and rise time information (Corriveau, Pasquini, & Goswami, 2007; Goswami et al., 2016; Richards & Goswami, 2015), which are fundamental for the adequate acquisition and development of vocabulary, phonological awareness, reading, and speech stress processing (Corriveau et al., 2007; Cumming, Wilson, Leong, et al., 2015; Richards & Goswami, 2015). Importantly, syntactic skills can be enhanced by the previous presentation of regular rhythmic stimuli both in TD children (e.g., Chern, Tillmann, Vaughan, & Gordon, 2018) and in children with DLD (Bedoin et al., 2016; Ladányi, Lukács, et al., submitted; Przybylski et al., 2013). As mentioned in the previous chapters of this work, improved syntactic performance after rhythm exposure may be the result of an enhancement of neural entrainment to the stimuli (see Chapters 1 and 5 for more information).

The deficits found in rhythmic processing in language and music in DLD have been interpreted as stemming from impaired temporal perception (Goswami et al., 2016; Weinert, 1992), which in turn would be caused by atypical neural entrainment, as in dyslexia (Ladányi, Persici, Fiveash, Tillmann, & Gordon, submitted; see Chapter 1 for more information). Atypical entrainment, in turn, may reflect atypical coupling between distant regions of the brain, such as the auditory and motor areas (Bartolo, Prado, & Merchant, 2014). However, it is not known whether children with DLD, like children with dyslexia, show atypical entrainment, though previous electrophysiological and neuroimaging studies showing structural and functional differences between children with TD and DLD during language tasks (cf. Krishnan, Watkins, & Bishop, 2016) suggest that this might be the case. As a consequence, it is also not known whether individual differences in brain responses correspond to individual differences in syntactic abilities.

6.2 The present study

In the present study we aimed to identify neural oscillatory markers that may relate to individual differences in language performance in a bigger group of TD children than the one tested in the previous study and in an additional group of children with DLD. As in the previous study, children were presented with two rhythmic structures differing for the placement of the intensity accents marking the beat, while we recorded their neural responses using electroencephalography (EEG). We expected these patterns to elicit different metrical interpretations and, thus, different fluctuations in both Event-Related Potentials (ERPs) and beta and gamma evoked (phase-locked) activity. As explained in Chapter 5, ERPs are brain responses calculated by averaging brain activity recorded in alignment with the tone onset; oscillatory activity can also be studied in relation to the stimulus onset (phase-locked or evoked activity), but has the advantage of giving a measure of the power change in brain activity as a result of the exposure to auditory stimuli; evoked data is calculated by preserving only those oscillations in the average ERP waveform that are phase-locked to the stimulus, and allows for the analysis of brain activity within specific frequency bands.

As in the previous study, we looked at the beta (~ 15 to 30 Hz) and gamma (30 to 100 Hz) frequency bands. Beta has been associated with rhythmic processing (Fujioka, Trainor, Large, & Ross, 2012), and meter representation (Fujioka, Ross, & Trainor, 2015), and is thought to play a role in predictive processes, which are important for efficient rhythmic processing (Arnal & Giraud, 2012; Leventhal et al., 2012), as discussed in the previous chapters of this work; moreover, beta is thought to reflect the coupling of brain activity originated in distant brain regions, such as the auditory and motor cortices (Bartolo et al., 2014). Gamma has been associated with the formation of temporal expectancies (Zanto, Large, Fuchs, & Kelso, 2005) and with language skills involving phonological perception (Goswami, 2011; Power, Colling, Mead, Barnes, & Goswami, 2016) and, importantly for this study, hierarchical processing (Ding, Melloni, Zhang, Tian, & Poeppel, 2015). In this study we expected DLD children to show reduced sensitivity to metrical (hierarchical) patterns.

In accordance with previous studies, we further expected children with DLD to show not only worse grammatical abilities (Hulme & Snowling, 2009; Schuele & Tolbert, 2001b), but also deficits in rhythmic discrimination: it has been shown that children with DLD have impaired rhythmic perception (Corriveau et al., 2007; Cumming, Wilson, & Goswami, 2015) and production (Corriveau & Goswami, 2009b).

Based on the findings that rhythmic processing skills predict grammar performance, both in general (Gordon, Shivers, et al., 2015) and in the two specific sub-categories analyzed in Chapter 5 (Gordon, Jacobs, Schuele, & Mcauley, 2015) (see also our Chapter 5), and on the hypothesis that mechanisms for hierarchical processing are shared between the two domains (Ladányi, Persici, et al., submitted), we expected individual differences in syntactic performance, and more specifically, in the categories of Transformation and Complex Syntax, to relate to individual differences in brain activity. As explained in Chapter 5, 'Transformation' included uni-clausal sentences with a non-canonical word order, which required the participant to re-order the material in the sentence in order to understand it; 'Complex Syntax' included sentences containing multiple clauses (thus having complex structural dependency relations) such as subordinate, infinite, complement, and relative clauses; these sentences are acquired and used efficiently at a later age as compared to simpler structures even in typical development (Vasilyeva, Waterfall, & Huttenlocher, 2008). Both Transformation and Complex Syntax require individuals to perform complex grammatical operations (though these are of greater complexity in the case of Complex Syntax), that are fundamental for efficient language processing and development.

As in the previous study, we expected individual differences in neural activity to correspond to individual differences in hierarchical (syntactic) processing in language, especially in case of sentences that require more refined grammatical operations, i.e., in Complex Syntax.

6.2.1 Methods

Participants

Sixty-six children with typical development (32 boys) and 16 children with DLD (11 boys), all aged between 5 and 8 years, participated in the study (see Table 1 to see the participants' characteristics). All were native speakers of American English and were recruited from multiple schools and public libraries and museums in Middle Tennessee. Participants were eligible for the study if they had normal IQ (measured using the same test presented in the previous chapter: PTONI; Ehrler & McGhee, 2008), if they had normal hearing (measured in a hearing screening test carried out on the Vanderbilt University campus), and if they did not have autism spectrum disorders (assessed using the Childhood Autism Rating Scale; Schopler, Van Bourgondien, Love, & Wellman, 2010). Eligible participants were assigned to the TD or DLD groups on the basis of the Sentence Imitation subtest of the Test of Language Development – Primary: 4th Edition (TOLD-P4; Newcomer, Hammill, & Pro-Ed, 2008) and of the screening probe of the Test of Early Grammatical Impairment (TEGI; Rice & Wexler, 2001) administered by certified Speech-Language Pathologists; in order to be included in the DLD group, children had to score below 85 on at least two quotients of the TOLD-P4 and score below criterion on the TEGI (see Table 1 to see the mean scores in each group).

As for the study presented in Chapter 5, parents were asked to provide information about their education and the child's musical activities. The highest level of education reached by the participants' mothers could go from 1, corresponding to no years in elementary school, to level 9, which corresponded to at least three or four years of graduate or professional school. In our sample, the mean maternal education score was 7.4 in the TD group and 7.06 in the DLD group, corresponding to three to four years of college or of technical school (the two were not significantly different between groups: *t*(22.12) = 1.315, *p* = .202).

In the questionnaire, parents also had to indicate whether their children had participated in musical lessons in school or outside of school, individually or in group; as for the previous study, positive answers were assigned a score of 1, negative answers a score of 0. Music experience, calculated by summing these scores, ranged from 0 to 4; the TD group had a mean score of 1.14 (SD = 0.93), whereas the DLD group had a mean musical experience score of 0.44 (SD = 0.63); the two were significantly different between groups (*t*(33.36) = 3.589, *p* = .001).

Non-verbal IQ was also significantly different between the participants who ended up assigned to the two groups: the TD group had a mean score of 120.75, while the DLD group had a significantly lower mean score (97.75; *t*(38.64) = 6.042, *p* < .001; see Table 1). However, these results are not surprising, given that cognitive ability in children with DLD is found to be slightly lower than in typically-developing populations (e.g., Reilly et al., 2014).

The study was approved by the Institutional Review Board of Vanderbilt University (Nashville, TN, United States of America). Before starting, the experimenter obtained the parents' written consent to the participation of their child and the child's separate assent. Eligible participants were asked to participate in two more visits for behavioral testing and electrophysiological (EEG) recordings; these took place over the span of three months from one another. Families were compensated for participation with a small toy for the children and a gift card at each of the three visits that they participated in.

Table 1

Participants' characteristics

Group	Statistic	N	Mean	SD
TD	Age (years)	66	6.593	0.855
	PTONI Index Score	60[1]	120.75	18.8
	PTONI raw score	60[1]	47.29	11.09
	TOLDP4 Index Score	66	115.43	10.38
DLD	Age	16	6.61	0.87
	PTONI Index Score	16	97.75	11.66
	PTONI raw score	16	37.62	9.64
	TOLDP4 Index Score	16	86.65	11.04

Note. [1]Seven PTONI scores were invalid, because in three cases they could not be obtained because of the participants' uncooperability, and in four cases they were administered incorrectly. In these cases, normal non-verbal IQ was assumed on the basis of the performance on the other cognitive and language assessments, and based on the clinical judgements of Speech-Language Pathologist collaborators.

Materials and procedure

Language ability. As in the previous study, the expressive grammatical skills of the participants were tested using the Structured Photographic Expressive Language Test (SPELT-3; Dawson, Stout, & Eyer, 2003). In this task, participants are presented with various photographs and asked, through specific questions, to describe what they see. The questions are designed so as to elicit specific morpho-syntactic constructions, such as irregular plural nouns or past tense verbs.

Rhythm discrimination. As in the previous study, the children's rhythm discrimination abilities were tested in two tests: the beat-based advantage assessment (BBA) and the rhythm section of the Primary Measures of Music Audiation (PMMA; Gordon, 1979). We used both tests, because they are complementary measures of rhythmic perception skills (see the Methods section in Chapter 5 for more details).

Electroencephalography. ***Stimuli.*** The auditory stimuli (in woodblock sound, this time) were organized and presented following the same paradigm presented in Chapter 5. Pairs of sounds were organized in accented sequences and were always followed by silence. In the first condition (PA1), sequences had a strong-weak-rest pattern: the accent, conveyed by doubling the intensity of the sound, was placed on the first tone; in the second condition (PA2), the accent was placed on the second tone, thus creating a weak-strong-rest pattern. Both types of sequences had each a duration of 600 ms. Each condition, which included forty-eight repetitions of the same tone sequence for a duration of 30 seconds, was presented nine times in random order, for a total of 864 items.

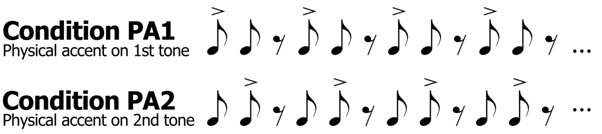

Figure 1. Rhythmic conditions in the experimental paradigm (figure from Yu et al. (in preparation), adapted from Iversen et al. (2009)). Participants heard tone sequences in two conditions (PA1: accented tone – tone – rest; PA2: tone – accented tone – rest).

EEG Acquisition. EEG data were recorded following the same criteria outlined in the previous chapters. Participants' EEG recordings were collected individually in a sound-dampened room at the EEG Lab at the Vanderbilt Kennedy Center in Nashville, Tennessee (USA). Brain activity was measured continuously by EEG using 124 Ag/AgCl electrodes embedded in soft sponges (EGI Geodesic Sensor Net). Lower eye channels were excluded. EEG signals were sampled at 500 Hz for temporal precision. Data was acquired in Net Station 4.4.2 (with a hardware filter of 0.1 to 200 Hz) with the first 6 DLD and 27 TD participants, before it was updated to Net Station 5 (with no hardware filter). The amplifier was also upgraded from NetAmps 200 to NetAmps 400; no nets were changed after the update. The data collected in Net Station 5 were filtered from 0.1 to 200 Hz offline, before any other filtering.

As in the study presented in Chapter 5, the entire session lasted about 10 minutes. Participants were instructed to sit as still as possible while we showed them a silent movie and played them some sounds. Stimuli were presented through speakers and were matched in loudness. EEG was recorded while participants listened passively to the auditory stimuli; no behavioral responses were required. To keep participants engaged but still during data acquisition, an age-appropriate video with muted sound was shown.

Data Preprocessing. As in the previous study, EEG data processing was performed using EEGLAB (Delorme & Makeig, 2004). Signals were smoothed using a 55-Hz low-pass filter and a 0.1-Hz high-pass filter to eliminate non-brain-related frequencies. Data were re-referenced to the average of the activity picked up from all channels. Line noise was cleaned using the pop_cleanline function. Bad electrodes characterized by consistently high noise levels were identified using the Artifact Subspace Reconstruction (ASR) approach (US 2016/0113587 A1, 2014) and interpolated using the spherical spline interpolation algorithm (Perrin, Pernier, Bertrand, & Echallier, 1989).

Artifacts in the data were identified using Individual Component Analysis (ICA); type of artifact was identified with the help of ICLabel (Pion-Tonachini, Kreutz-Delgado, & Makeig, 2019). Cardiac and ocular artifacts were removed. Next, data were divided into 1200-ms epochs with the interval of [-400, + 800], time-locked to the onset of the first tone (tone-tone-rest, in both conditions). Trials containing fifteen artifacts (i.e., eye blinks or bad channels) or more were removed. As in the previous study, ERP data were baseline-corrected with the baseline of [-100, 0] ms and calculated by averaging brain activity across trials for each stimulus condition.

6.2.2 Data Analysis

Behavioral tests

Language ability. Correct items were assigned a score of 1 and total raw scores were calculated by summing the correct responses. Standard scores were obtained by correcting raw scores for age (following Dawson et al. (2003)). Differences between groups were analyzed using independent t-tests.

Rhythm discrimination. PMMA accuracy was obtained by calculating the ratio of correct responses on the total, while BBA d’ prime was calculated using a signal detection analysis (which takes into account hit rate and false alarm rate; see Gordon et al. (2015) for more information). The scores obtained in the two tests were then z-scored and combined in a Rhythm Composite Score (calculated as the mean of the two previous tests). Differences between groups were analyzed using independent t-tests.

EEG

ERP analyses. As in the previous study, after EEG preprocessing, individual Event-Related Potentials (ERPs) for each subject were exported to MATLAB R2017b (The Mathworks Inc., 2017) and analyzed using the Fieldtrip Toolbox (Oostenveld, Fries, Maris, & Schoffelen, 2011) at the time window [-100, +500]. Statistical significance between groups and across conditions was assessed using cluster-based permutation tests (Maris & Oostenveld, 2007); in the plots differences are visualized by subtracting neural activity in the DLD group and in PA2 from neural activity in the TD group and in PA1, respectively.

Time-frequency analyses. As in the previous study, time-frequency analysis was conducted using Fieldtrip. Evoked (that is, phase-locked) activity for each condition was obtained by convolving the average ERP waveform with a Morlet wavelet with a width of five cycles. This was done with a frequency step of 2 Hz and a time step of 2 ms in the time window (-400, +850), with zero being the onset of the stimulus. Then, evoked activity was baseline-corrected to compensate for inter-individual variability in absolute power. Baseline values were calculated in relation to the relative power change from the average of the time-frequency data across conditions.

Individual differences and brain-behavior relationship. Individual differences in neural activity were calculated by summing up voltage of difference waves (for ERPs) and power values within each frequency band (for time-frequency data) for each participant in the time period of clusters with statistical significance. These measures are designed to reflect the magnitude of the difference in neural activity between conditions (cf. Lense et al., 2014). The relationship between our neural data and the grammar subcategories was analyzed in a set of hierarchical regressions (function “update”) and Spearman correlations (function “cor.test”) in R (R Development Core Team, 2016).

6.2.3 Results

Behavioral tests

Independent t-tests showed significantly different language and rhythm discrimination scores between the two groups (see Table 2 for more information). However, it should be noted that BBA could not be administered to seven children out of sixteen in the DLD cohort, and to eight participants in the TD cohort, because of difficulties understanding the instructions, despite the additional use of visual supports to better explain the task. Though differences between groups may also reflect their significantly different musical experiences, the validity of the comparisons of the BBA or Rhythm Composite scores (which are calculated as the mean of BBA and PMMA scores) between groups may also be affected by their different sample sizes.

Table 2

Mean scores in the language and rhythmic tests for the TD and DLD participants.

	TD	DLD	*t*	df	*p*
N	66	16			
SPELT standard score	115.51 (5.11)	91.5 (16.37)	5.801	15.72	< .001***
Complex Syntax	0.84 (0.12)	0.56 (0.26)	4.169	16.43	< .001***
Transformation	0.90 (0.09)	0.57 (0.19)	6.815	16.52	< .001***
BBA d' prime average	1.26 (0.81)	0.09 (0.28)	8.255	34.15	< .001***
PMMA accuracy	0.71 (0.11)	0.58 (0.12)	4.052	21.4	< .001***
Rhythm composite score[1]	0.24 (0.75)	-1.02 (0.53)	6.236	13.63	< .001***

Note. [1]The Rhythm Composite Score was obtained by calculating the mean of the z-scored BBA and PMMA scores.

EEG

ERP analysis. After running cluster-based permutation tests, results revealed a significant difference between the PA1 and PA2 conditions on both tones in the TD group. In PA1 participants showed a stronger response on the accented tone (i.e., the first one; *p* < .001); in PA2 participants showed a stronger response on the second tone (*p* < .001) (see Figures 2 and 3).

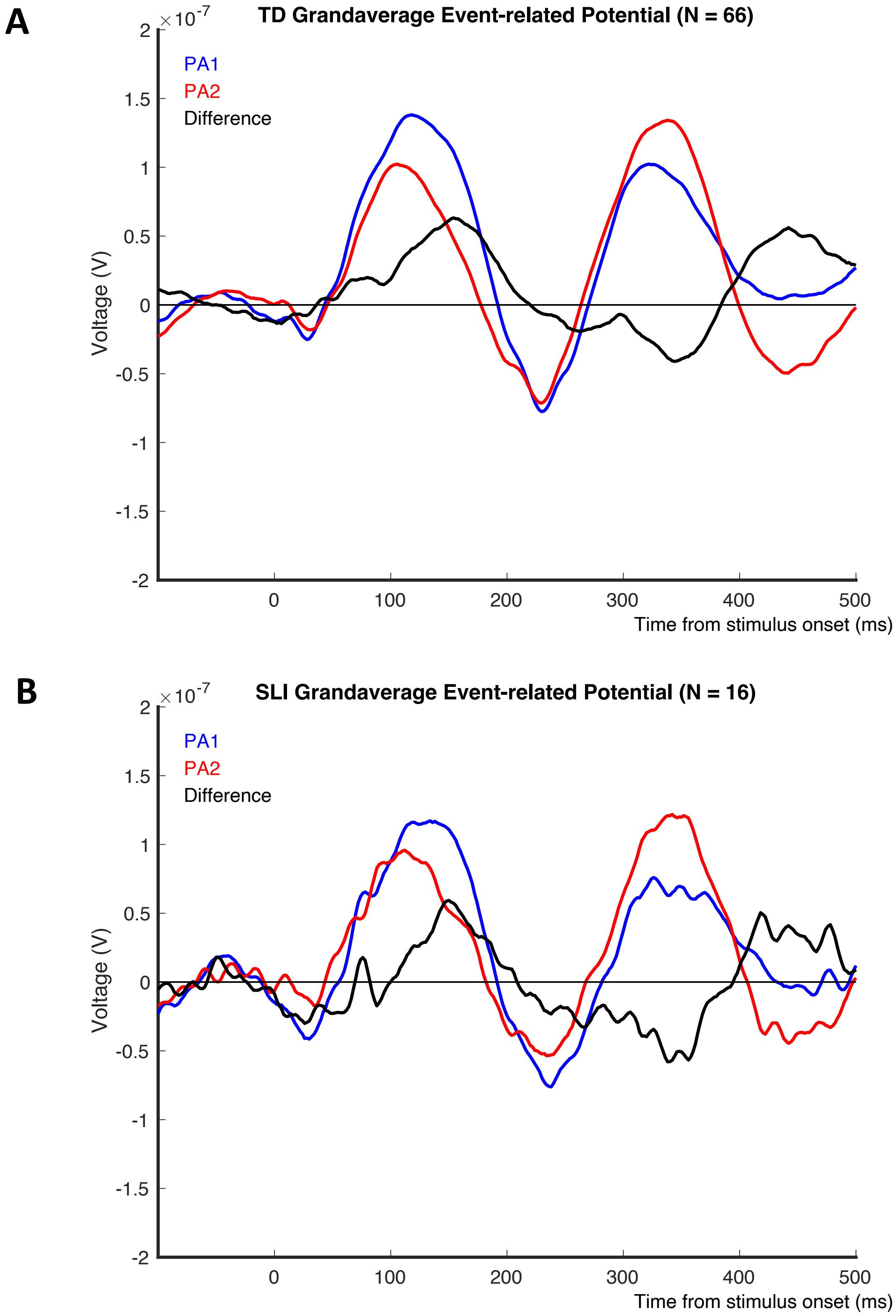

Figure 2. Grand average ERP for children with TD (A) and for children with SLI/DLD (B). The onsets of the first and second tone were at 0 and 200 ms, respectively, in both conditions. Condition PA1 (strong-weak-rest) is in blue, condition PA2 (weak-strong-rest) is in red; the difference between the two conditions

(PA1 - PA2, in μV) is shown in black. The horizontal black line shows power at 0 microvolts (μV). The plot shows a stronger response on the accented tone in each condition (i.e., on the first tone in PA1 and on the second tone in PA2) in both groups.

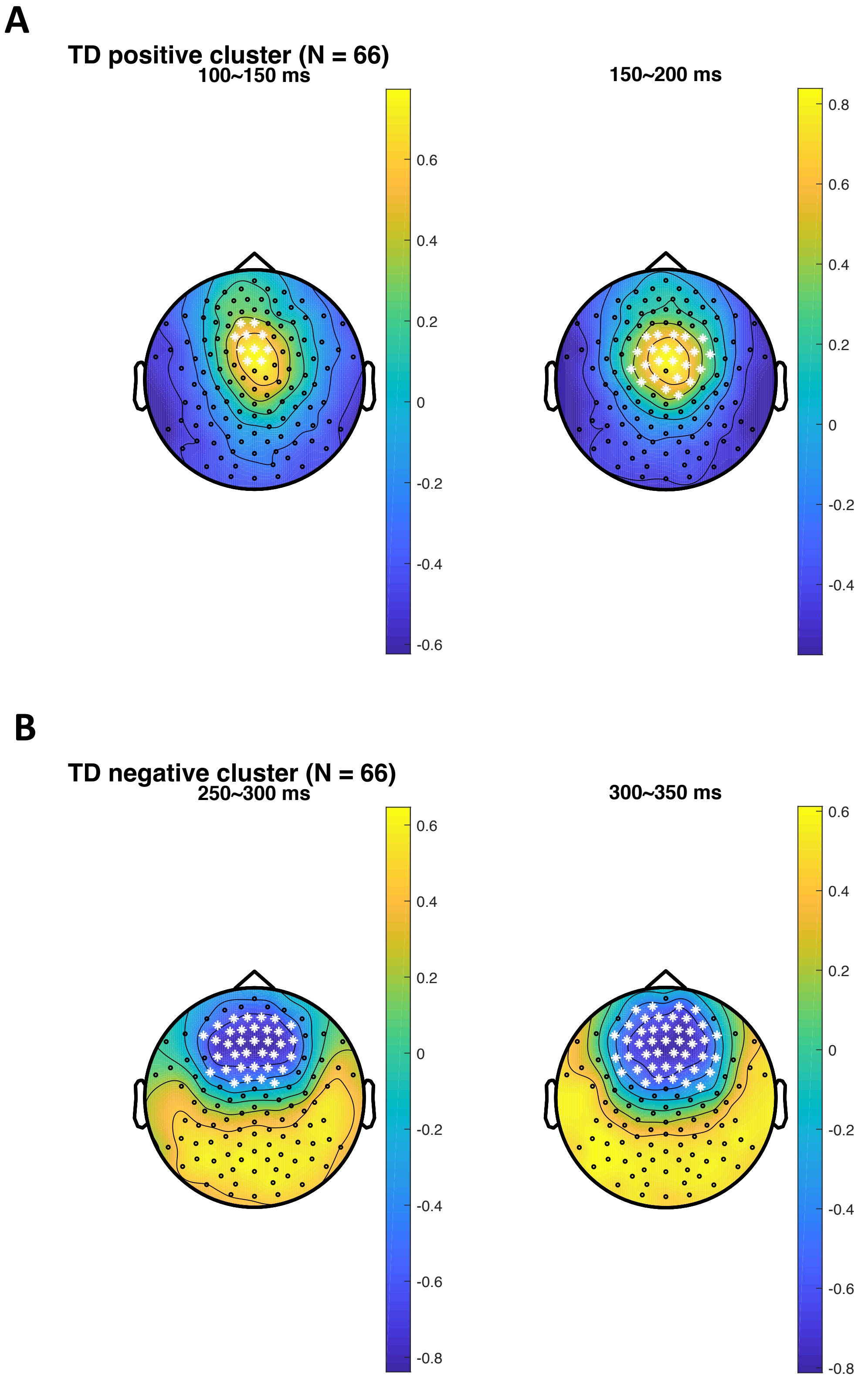

Figure 3. Significant positive (from positive t-values; 3A) and negative (from negative t-values; 3B) ERP clusters, which are found following the first (A) and second (B) tone, respectively. Topographies are shown for segments of 50 ms each; significant channels are marked in white. The color bars, going from dark blue to bright yellow,

represent the percent change from baseline; bright yellow and dark blue indicate positive and negative raw effects, respectively.

Time-frequency analysis. Results showed a positive and a negative cluster for each of the two frequency bands of interest (all *ps* < .001). As in the ERP analysis, we found positive significant beta and gamma clusters around the time window of the first tone (positive beta latency: from -100 to 182 ms; positive gamma latency: from -10 to 180 ms) and negative clusters around the time window of the second tone (negative beta latency: 178 to 466 ms; negative gamma latency: 196 to 382 ms). Cluster-based permutation tests showed no difference in neural activity between TD and DLD children. See Figures 4, 5, 6, and 7 to see the significant beta and gamma clusters in the TD group in timestep. Given that the two groups did not show significant differences, only the clusters found in the TD group (which are likely to be stronger and more reliable, given their larger sample size) are shown.

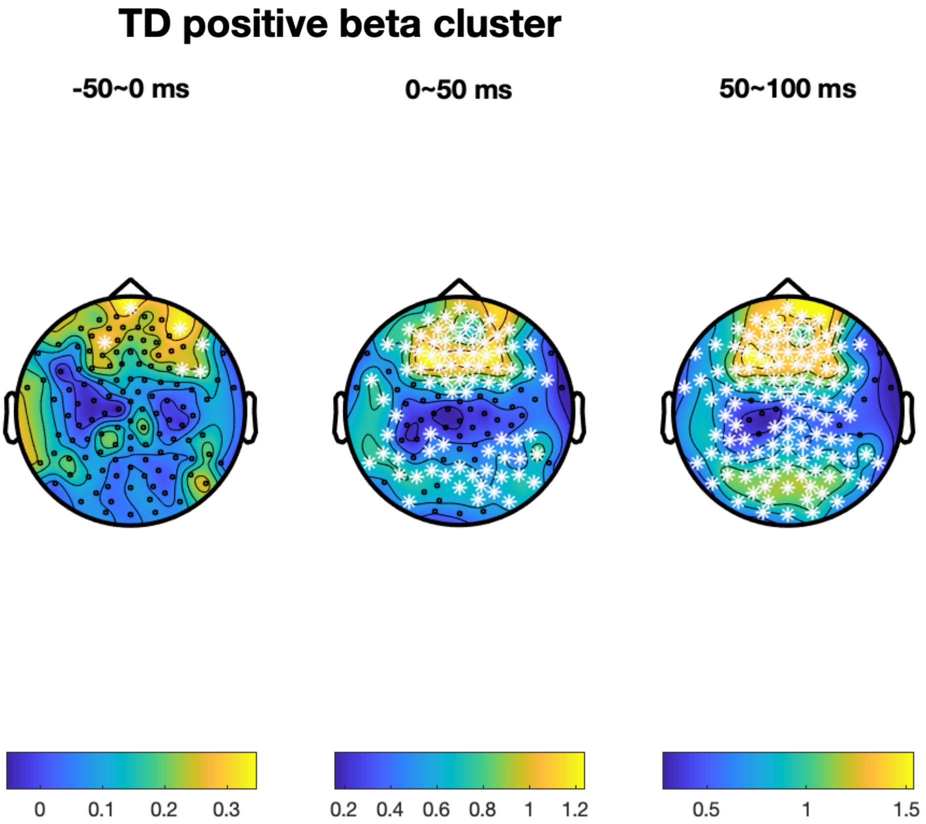

Figure 4. Positive beta cluster in timestep in the TD group. Beta activity is found in correspondence to the onset of the first tone (0 ms). The color bars, going from dark blue to bright yellow, represent the percent change from baseline; bright yellow and dark blue indicate positive and negative raw effects, respectively.

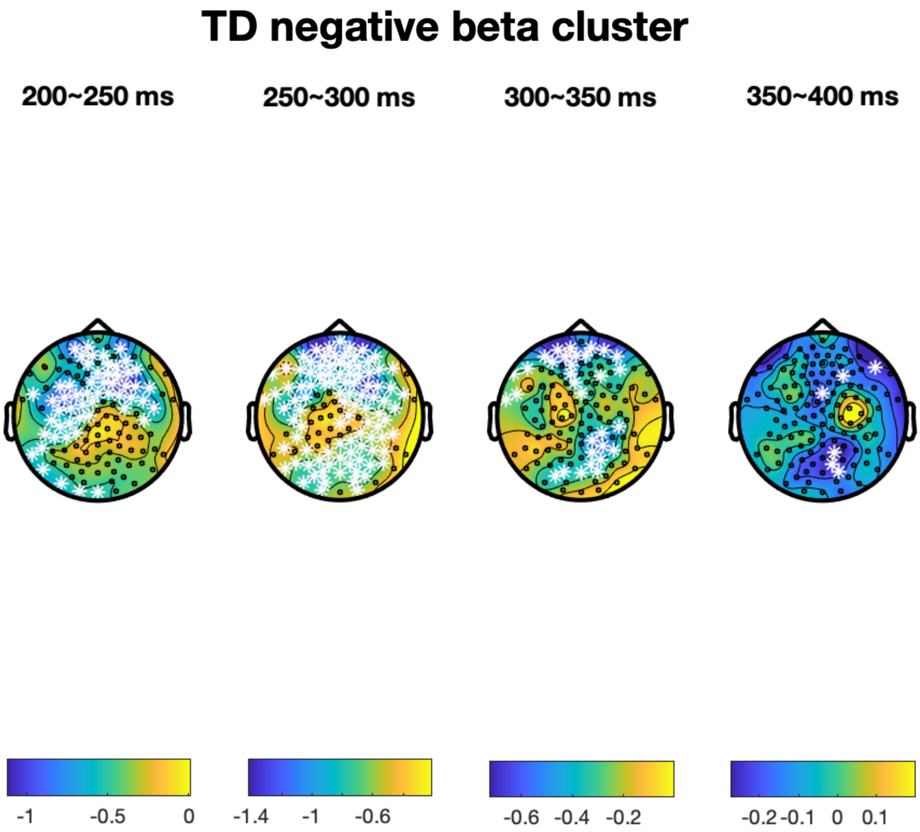

Figure 5. Negative beta cluster in timestep in the TD group. Beta activity is found in correspondence to the onset of the second tone (200 ms). The color bars, going from dark blue to bright yellow, represent the percent change from baseline; bright yellow and dark blue indicate positive and negative raw effects, respectively.

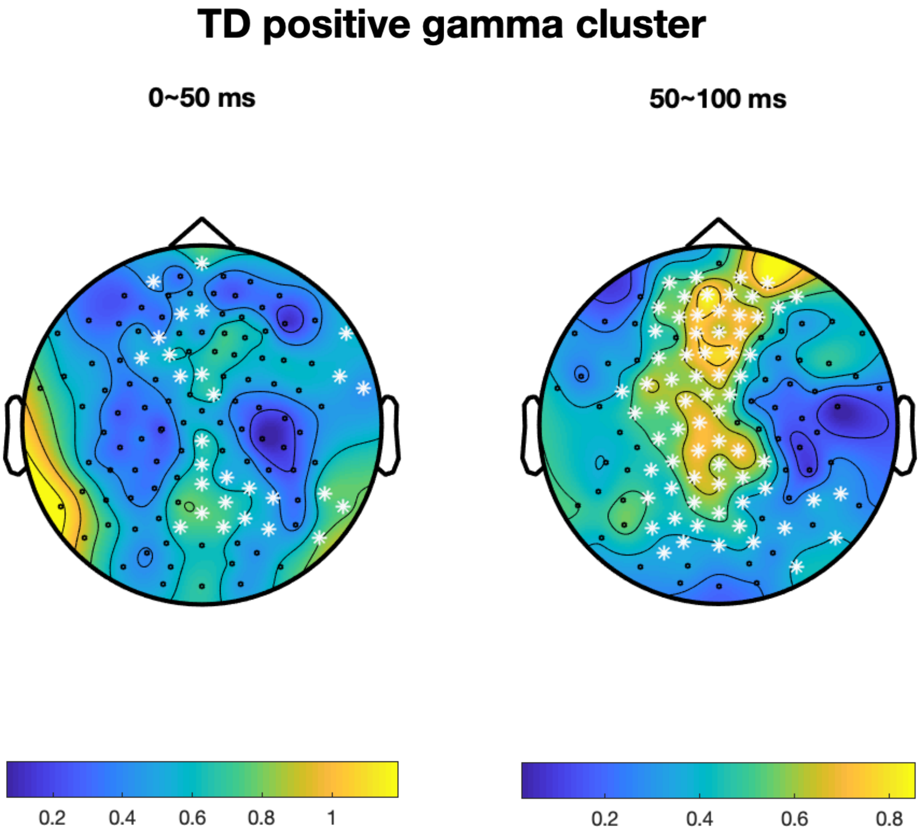

Figure 6. Positive gamma cluster in timestep in the TD group. Gamma activity is found in correspondence to the onset of the first tone (0 ms). The color bars, going from dark blue to bright yellow, represent the percent change from baseline; bright yellow and dark blue indicate positive and negative raw effects, respectively.

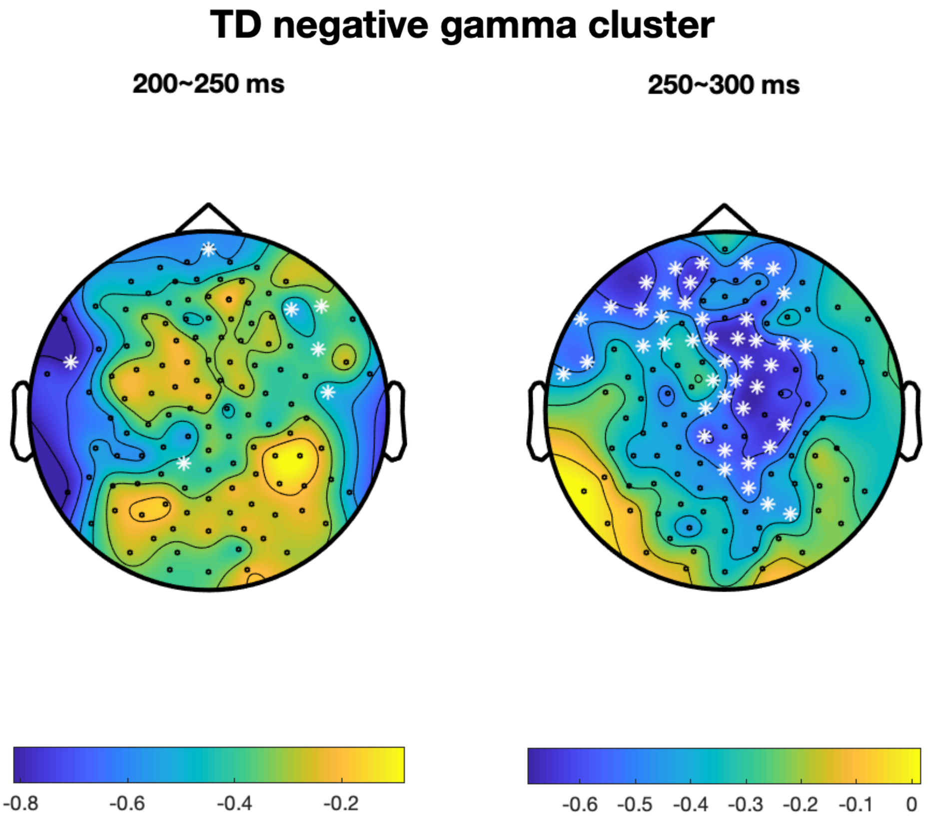

Figure 7. Negative gamma cluster in timestep in the TD group. Gamma activity is found in correspondence to the onset of the second tone (200 ms). The color bars, going from dark blue to bright yellow, represent the percent change from baseline; bright yellow and dark blue indicate positive and negative raw effects, respectively.

Brain-behavior relationship

Neural entrainment and expressive language ability: correlations. As in the study presented in Chapter 5, to investigate whether individual differences in performance in SPELT score, Transformation, and Complex Syntax corresponded to individual differences in neural response to rhythmic stimuli, we ran Spearman correlations between the total SPELT score or the scores in each of the SPELT subcategories of interest and the significant clusters of neural activity, while controlling for both age and non-verbal intelligence. Based on the findings in Chapter 5, here we only focused on correlations between syntax scores and evoked activity. As in Chapter 3, correlations were run within group, because the strength of the relationship between language and neural measures may differ between populations with typical and atypical language development.

Within-group Spearman correlations between SPELT scores (both total and within subcategories) and evoked clusters, while controlling for age and non-verbal intelligence, showed significant correlations only between negative beta and SPELT total score ($r_{(s)}$ = 0.193, p = .039) and Complex Syntax specifically (though smaller: $r_{(s)}$ = 0.203, p = .028) in the TD group. In the DLD group we only found a significant correlation between Complex Syntax and negative gamma ($r_{(s)}$ = 0.411, p = .022). No significant correlations were found between the other evoked variables (see Table 3).

Table 3

Correlations between SPELT scores and evoked variables

Group	SPELT scores	Evoked variables			
		Positive beta	Negative beta	Positive gamma	Negative gamma
TD	SPELT total	0.055	0.193*	0.044	-0.1
	Transformation	0.026	0.094	-0.077	0.138
	Complex Syntax	-0.046	0.203*	-0.072	0.022
DLD	SPELT total	0.272	0.174	0.024	0.232
	Transformation	-0.051	0.312	-0.049	0.196
	Complex Syntax	0.322	0.130	-0.079	0.411*

Note. p = .05 '.', p < .05 '*', p < .01 '**', p < .001 '***'.

Stepwise regression. Based on the findings of the study presented in Chapter 5, we also investigated whether performance in SPELT score, Transformation, and Complex Syntax was predicted by the behavioral rhythm measures and by the evoked brain data. To do so, we ran a series of stepwise regressions.

Results showed that adding the Rhythm Composite Score to the base model (which included Age as predictor) increased significantly (p < .001) by 24.4% the amount of SPELT variance explained (R^2 value change from 0.002 to 0.246), in line with previous studies (our study in Chapter 5, as well as Gordon, Jacobs, Schuele, & McAuley (2015) and Gordon, Shivers, et al. (2015)). However, in this case no additional variance was explained by the evoked variables. The same was found within Transformation (variance explained by the Rhythm Composite Score: 30.5%, p < .001), and within Complex Syntax (variance explained by the Rhythm Composite Score: 12.5%, p = .003).

However, since many of the DLD children did not have a Rhythm Composite Score, we also tested the effect of the evoked variables above age only. Results showed that positive beta explained significant (p = .021) and unique (6.6%) variance in the total SPELT score.

Again, the same was found within Complex Syntax (variance explained by the positive beta: 5.5%, *p* = .028), but not within Transformation (*p* = .084).

6.2.4 Discussion

This study aimed to identify neural oscillatory markers that may relate to individual differences in language performance in children with typical development and in children with Developmental Language Disorder (DLD). As in the previous chapter, we analyzed neural activity while children listened to rhythmic patterns that were designed to elicit different metrical hierarchical interpretations. We used both ERPs and oscillatory evoked activity in beta and gamma frequency bands. The participants' syntactic abilities were investigated using a standardized test of expressive abilities (SPELT; Perona, Plante, & Vance, 2005); both total scores and scores within the specific subcategories of Complex Syntax and Transformation (which require refined grammatical operations, especially Complex Syntax) were calculated. As explained in Chapter 5, we hypothesized that individual differences in neural entrainment to rhythm may result in individual differences in language skills, especially in hierarchical processing, and in rhythm (possibly as a result of mechanisms of internal entrainment (Jones, 2019) and of increased attention (Large & Jones, 1999)). In addition, in this study we included a group of children with DLD to explore whether differing language abilities correspond to different patterns of neural activity and whether children with language impairments show atypical neural activity.

Results showed that the two groups *did* differ on measures of syntactic expressive abilities, as well as in measures of rhythmic discrimination, as expected. On the other hand, the analysis of their neural responses showed that both groups of children were sensitive to the metrical structure of the rhythmic patterns (in fact, both groups showed a stronger response in correspondence to the beat), and that their neural responses did not differ significantly in beta or gamma bands between groups. These findings indicate that rhythmic exposure leads to the phase-resetting of oscillations in both typical and DLD populations. However, when we compared brain and behavioral responses, we found differing patterns of correlations in the two groups: while the TD group showed significant correlations between Complex Syntax and *beta* activity, the DLD group showed a significant correlation between the same syntactic category and *gamma* activity. The strength of the relationship between neural entrainment and hierarchical processing appears to differ in typical and DLD populations, possibly because children with DLD process hierarchical structures slightly differently as compared to typical children. It should be reminded that, while beta is thought to index metrical expectancy (Fujioka et al., 2015), gamma is more associated with language hierarchical processing (Ding et al., 2015). The finding that children with DLD with worse syntactic skills also show weaker gamma activity has important implications for the identification of disorders: it suggests that the use of a non-invasive and passive method in young children, and possibly, in infants, may allow to predict the later development of language disorders.

The findings that rhythm discrimination predicts syntactic performance, as shown by stepwise regressions in this and in the previous study (together with Gordon, Jacobs, Schuele, & McAuley, 2015; Gordon, Shivers, et al., 2015), highlights the importance of investigating rhythmic perception skills in children, as they are shown to be closely related to their expressive syntactic skills. However, the finding that beta activity can predict performance in syntactic tasks (though less strongly than in the previous study), even when behavioral rhythm measures are not available, further highlights the importance of looking at neural oscillations to rhythm to investigate syntactic performance. It is not always possible to collect behavioral rhythm measures, as they are often associated with difficulties in comprehending the instructions, especially with younger and with DLD children; neural measures, on the contrary, do not require responses and can be acquired even in young infants. The findings that neural activity can predict (some of the) syntactic performance has important implications, and suggests that the possible emergence of later language disorders may be identified at infancy using electrophysiological methods.

In particular, DLD seems to be associated to atypical gamma activity. In fact, the findings that (i) the worse syntactic abilities of the DLD children are, the weaker is their gamma activity in processing hierarchical structures, and that (ii) when groups are collapsed, only beta activity predicts performance in syntax, suggest that the DLD group might have different patterns of oscillations in the gamma band. Furthermore, preliminary results from our studies in collaboration with the Music Cognition Lab at the Vanderbilt University Medical Center seem to confirm this hypothesis: the inspection of induced (non-phase-locked) neural activity in the DLD group shows a more jittered and less stable pattern of oscillations than the one presented by TD children. These findings are in line with previous studies showing atypical oscillatory patterns in children at risk for familial language and literacy disorders (Cantiani et al., 2019), though the analysis of the specific neural oscillatory patterns of DLD children warrants further investigation.

6.2.5 References

Arnal, L. H., & Giraud, A. L. (2012). Cortical oscillations and sensory predictions. *Trends in Cognitive Sciences*. https://doi.org/10.1016/j.tics.2012.05.003

Bartolo, R., Prado, L., & Merchant, H. (2014). Information processing in the primate basal ganglia during sensory-guided and internally driven rhythmic tapping. *Journal of Neuroscience*, *34*(11), 3910–3923. https://doi.org/10.1523/JNEUROSCI.2679-13.2014

Bedoin, N., Brisseau, L., Molinier, P., Roch, D., & Tillmann, B. (2016). Temporally regular musical primes facilitate subsequent syntax processing in children with Specific Language Impairment. *Frontiers in Neuroscience*, *10*(JUN), 1–11. https://doi.org/10.3389/fnins.2016.00245

Bishop, D. V. M. (2017, November 1). Why is it so hard to reach agreement on terminology? The case of developmental language disorder (DLD). *International Journal of Language and Communication Disorders*. Wiley Blackwell. https://doi.org/10.1111/1460-6984.12335

Cantiani, C., Ortiz-mantilla, S., Riva, V., Piazza, C., Bettoni, R., Musacchia, G., … Benasich, A. A. (2019). Reduced left-lateralized pattern of event-related EEG oscillations in infants at familial risk for language and learning impairment. *NeuroImage: Clinical*, *22*(March), 101778. https://doi.org/10.1016/j.nicl.2019.101778

Chern, A., Tillmann, B., Vaughan, C., & Gordon, R. L. (2018). New evidence of a rhythmic priming effect that enhances grammaticality judgments in children. *Journal of Experimental Child Psychology*, *173*, 371–379. https://doi.org/10.1016/j.jecp.2018.04.007

Clegg, J., Hollis, C., Mawhood, L., & Rutter, M. (2005). Developmental language disorders--a follow-up in later adult life. Cognitive, language and psychosocial outcomes. *Journal of Child Psychology and Psychiatry, and Allied Disciplines*, *46*(2), 128–149. https://doi.org/10.1111/j.1469-7610.2004.00342.x

Conway, C. M., & Pisoni, D. B. (2008). Neurocognitive basis of implicit learning of sequential structure and its relation to language processing. In *Annals of the New York Academy of Sciences* (Vol. 1145, pp. 113–131). Blackwell Publishing Inc. https://doi.org/10.1196/annals.1416.009

Corriveau, K. H., & Goswami, U. (2009a). Rhythmic motor entrainment in children with speech and language impairments: Tapping to the beat. *Cortex*, *45*(1), 119–130.

https://doi.org/10.1016/j.cortex.2007.09.008

Corriveau, K. H., & Goswami, U. (2009b). Rhythmic motor entrainment in children with speech and language impairments: Tapping to the beat. *Cortex*, *45*(1), 119–130. https://doi.org/10.1016/J.CORTEX.2007.09.008

Corriveau, K. H., Pasquini, E., & Goswami, U. (2007). Basic Auditory Processing Skills and Specific Language Impairment: A New Look at an Old Hypothesis. *Journal of Speech, Language, and Hearing Research*, *50*, 647–666. https://doi.org/10.1044/1092-4388(2007/046

Cumming, R., Wilson, A., & Goswami, U. (2015). Basic auditory processing and sensitivity to prosodic structure in children with specific language impairments: a new look at a perceptual hypothesis. *Frontiers in Psychology*, *6*, 972. https://doi.org/10.3389/fpsyg.2015.00972

Cumming, R., Wilson, A., Leong, V., Colling, L. J., & Goswami, U. (2015). Awareness of Rhythm Patterns in Speech and Music in Children with Specific Language Impairments. *Frontiers in Human Neuroscience*, *9*, 672. https://doi.org/10.3389/fnhum.2015.00672

Dawson, J., Stout, C., & Eyer, J. (2003). *Structured Photographic Expressive Language Test-3*. Dekalb, IL: Janelle Publications.

Delorme A, & Makeig S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*. https://doi.org/10.1016/j.jneumeth.2003.10.009

Ding, N., Melloni, L., Zhang, H., Tian, X., & Poeppel, D. (2015). Cortical tracking of hierarchical linguistic structures in connected speech. *Nature Neuroscience*, *19*(1), 158–164. https://doi.org/10.1038/nn.4186

Ehrler, D. J., & McGhee, R. L. (2008). *PTONI: Primary Test of Nonverbal Intelligence*. (Pro-Ed, Ed.). Austin, TX.

Fujioka, T., Ross, B., & Trainor, L. J. (2015). Beta-Band Oscillations Represent Auditory Beat and Its Metrical Hierarchy in Perception and Imagery. *The Journal of Neuroscience*, *11*(NOV), 15187–15198. https://doi.org/10.3389/fnins.2016.00389

Fujioka, T., Trainor, L. J., Large, E. W., & Ross, B. (2012). Internalized timing of isochronous sounds is represented in neuromagnetic β oscillations. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *32*(5), 1791–1802. https://doi.org/10.1523/JNEUROSCI.4107-11.2012

Gordon, E. E. (1979). *Primary Measures of Music Audiation*. Chicago, IL: GIA

Publications.

Gordon, R. L., Jacobs, M. S., Schuele, C. M., & Mcauley, J. D. (2015). Perspectives on the rhythm-grammar link and its implications for typical and atypical language development. *Annals of the New York Academy of Sciences*, *1337*(1), 16–25. https://doi.org/10.1111/nyas.12683

Gordon, R. L., Jacobs, M. S., Schuele, C. M., & McAuley, J. D. (2015). Perspectives on the rhythm-grammar link and its implications for typical and atypical language development. *Annals of the New York Academy of Sciences*, *1337*(1), 16–25. https://doi.org/10.1111/nyas.12683

Gordon, R. L., Shivers, C. M., Wieland, E. A., Kotz, S. A., Yoder, P. J., & Devin Mcauley, J. (2015). Musical rhythm discrimination explains individual differences in grammar skills in children. *Developmental Science*, *18*(4), 635–644. https://doi.org/10.1111/desc.12230

Goswami, U. (2011). A temporal sampling framework for developmental dyslexia. *Trends in Cognitive Sciences*, *15*(1), 3–10. https://doi.org/10.1016/J.TICS.2010.10.001

Goswami, U., Cumming, R., Chait, M., Huss, M., Mead, N., Wilson, A. M., … Fosker, T. (2016). Perception of filtered speech by children with developmental dyslexia and children with specific language impairments. *Frontiers in Psychology*, *7*(MAY). https://doi.org/10.3389/fpsyg.2016.00791

Grahn, J. A., & Brett, M. (2007). Rhythm and beat perception in motor areas of the brain. *Journal of Cognitive Neuroscience*. https://doi.org/10.1162/jocn.2007.19.5.893

Grahn, J. A., & Brett, M. (2009). Impairment of beat-based rhythm discrimination in Parkinson's disease. *Cortex*, *45*, 54–61. https://doi.org/10.1016/j.cortex.2008.01.005

Hsu, H. J., & Bishop, D. V. M. (2014). Training understanding of reversible sentences: A study comparing language-impaired children with age-matched and grammar-matched controls. *PeerJ*, *2014*(1). https://doi.org/10.7717/peerj.656

Hulme, C., & Snowling, M. J. (2009). *Developmental disorders of language learning and cognition*. Wiley-Blackwell. Retrieved from https://psycnet.apa.org/record/2007-09153-000

Iversen, J. R., Repp, B. H., & Patel, A. D. (2009). Top-down control of rhythm perception modulates early auditory responses. *Annals of the New York Academy of Sciences*, *1169*, 58–73. https://doi.org/10.1111/j.1749-6632.2009.04579.x

Jones, M. R. (2019). *Time will tell: A theory of Dynamic Attending*. New York: Oxford University Press.

Kan, P. F., & Windsor, J. (2010). Word learning in children with primary language impairment: A meta-analysis. *Journal of Speech, Language, and Hearing Research*, *53*(3), 739–756. https://doi.org/10.1044/1092-4388(2009/08-0248)

Kothe, C. A. E., & Jung, T.-P. (2014). *US 2016/0113587 A1*. United States of America.

Kotz, S. A., Schwartze, M., & Schmidt-Kassow, M. (2009). Non-motor basal ganglia functions: A review and proposal for a model of sensory predictability in auditory language perception. *Cortex*, *45*(8), 982–990. https://doi.org/10.1016/j.cortex.2009.02.010

Krishnan, S., Watkins, K. E., & Bishop, D. V. M. (2016). Neurobiological Basis of Language Learning Difficulties. *Trends in Cognitive Sciences*, *20*(9), 701–714. https://doi.org/10.1016/j.tics.2016.06.012

Ladányi, E., Lukács, Á., & Gervain, J. (submitted). Rhythmic priming in children with and without Specific Language Impairment.

Ladányi, E., Persici, V., Fiveash, A., Tillmann, B., & Gordon, R. L. (submitted). Is atypical rhythm a risk factor for speech and language disorders?

Large, E. W., & Jones, M. R. (1999). The dynamics of attending: How people track time-varying events. *Psychological Review*. https://doi.org/10.1037/0033-295X.106.1.119

Lense, M. D., Gordon, R. L., Key, A. P. F., & Dykens, E. M. (2014). Neural correlates of cross-modal affective priming by music in williams syndrome. *Social Cognitive and Affective Neuroscience*, *9*(4), 529–537. https://doi.org/10.1093/scan/nst017

Leventhal, D. K., Gage, G. J., Schmidt, R., Pettibone, J. R., Case, A. C., & Berke, J. D. (2012). Basal ganglia beta oscillations accompany cue utilization. *Neuron*, *73*(3), 523–536. https://doi.org/10.1016/j.neuron.2011.11.032

Maris, E., & Oostenveld, R. (2007). Nonparametric statistical testing of EEG- and MEG-data. *Journal of Neuroscience Methods*, *164*(1), 177–190. https://doi.org/10.1016/j.jneumeth.2007.03.024

Merchant, H., Grahn, J., Trainor, L. J., Rohrmeier, M., & Fitch, W. T. (2015). Finding the beat: A neural perspective across humans and non-human primates. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *370*(1664). https://doi.org/10.1098/rstb.2014.0093

Newcomer, P. L., Hammill, D. D., & Pro-Ed. (2008). *Test of Language Development. Primary* (Forth). Austin, TX: Pro-Ed.

Oostenveld, R., Fries, P., Maris, E., & Schoffelen, J. M. (2011). FieldTrip: Open source software for advanced analysis of MEG, EEG, and invasive electrophysiological data.

Computational Intelligence and Neuroscience. https://doi.org/10.1155/2011/156869

Perona, K., Plante, E., & Vance, R. (2005). Diagnostic accuracy of the structured photographic expressive language test: third edition (SPELT-3). *Language, Speech, and Hearing Services in Schools*, *36*(2), 103–115.

Perrin, F., Pernier, J., Bertrand, O., & Echallier, J. F. (1989). Spherical splines for scalp potential and current density mapping. *Electroencephalography and Clinical Neurophysiology*. https://doi.org/10.1016/0013-4694(89)90180-6

Pion-Tonachini, L., Kreutz-Delgado, K., & Makeig, S. (2019). ICLabel: An automated electroencephalographic independent component classifier, dataset, and website. *NeuroImage*, *198*, 181–197. https://doi.org/10.1016/j.neuroimage.2019.05.026

Power, A. J., Colling, L. J., Mead, N., Barnes, L., & Goswami, U. (2016). Neural encoding of the speech envelope by children with developmental dyslexia. *Brain and Language*, *160*. https://doi.org/10.1016/j.bandl.2016.06.006

Przybylski, L., Bedoin, N., Krifi-Papoz, S., Herbillon, V., Roch, D., Léculier, L., … Tillmann, B. (2013). Rhythmic auditory stimulation influences syntactic processing in children with developmental language disorders. *Neuropsychology*, *27*(1), 121–131. https://doi.org/10.1037/a0031277

R Development Core Team. (2016). R: A Language and Environment for Statistical Computing. Retrieved from https://www.researchgate.net/publication/312455832_R_A_Language_and_Environment_for_Statistical_Computing

Reilly, S., Tomblin, B., Law, J., McKean, C., Mensah, F. K., Morgan, A., … Wake, M. (2014). Specific language impairment: a convenient label for whom? *International Journal of Language & Communication Disorders*, *49*(4), 416. https://doi.org/10.1111/jlcd.1460-6984.12102

Rice, M. L., & Wexler, K. (2001). *Rice/Wexler Test of Early Grammatical Impairment*. Lawrence, KS: The Psychological Corporation. Retrieved from https://cldp.ku.edu/rice-wexler-tegi

Richards, S., & Goswami, U. (2015). Auditory processing in specific language impairment (SLI): Relations with the perception of lexical and phrasal stress. *Journal of Speech, Language, and Hearing Research*, *58*(4), 1292–1305. https://doi.org/10.1044/2015_JSLHR-L-13-0306

Sallat, S., & Jentschke, S. (2015). Music Perception Influences Language Acquisition: Melodic and Rhythmic-Melodic Perception in Children with Specific Language

Impairment. *Behavioural Neurology*, *2015*, 1–10. https://doi.org/10.1155/2015/606470

Schopler, E., Van Bourgondien, M. E., Love, S. R., & Wellman, G. J. (2010). *Childhood Autism Rating Scale: CARS 2* (Second). Los Angeles, CA: Western Psychological Services (WPS).

Schuele, C. M., & Tolbert, L. (2001a). Omissions of obligatory relative markers in children with specific language impairment. *Clinical Linguistics and Phonetics*. https://doi.org/10.1080/02699200010017805

Schuele, C. M., & Tolbert, L. (2001b). Omissions of obligatory relative markers in children with specific language impairment. *Clinical Linguistics and Phonetics*, *15*(4), 257–274. https://doi.org/10.1080/02699200010017805

The Mathworks Inc. (2017). MATLAB - MathWorks. *Www.Mathworks.Com/Products/Matlab*. https://doi.org/2016-11-26

Vasilyeva, M., Waterfall, H., & Huttenlocher, J. (2008). Emergence of syntax: Commonalities and differences across children. *Developmental Science*, *11*(1), 84–97. https://doi.org/10.1111/j.1467-7687.2007.00656.x

Vuolo, J., Goffman, L., & Zelaznik, H. N. (2017). Deficits in Coordinative Bimanual Timing Precision in Children With Specific Language Impairment. https://doi.org/10.1044/2016_JSLHR-L-15-0100

Weinert, S. (1992). Deficits in acquiring language structure: The importance of using prosodic cues. *Applied Cognitive Psychology*, *6*(6), 545–571. https://doi.org/10.1002/acp.2350060607

Yu, L., Persici, V., Boorom, O., Schuele, C. M., McAuley, J. D., Camarata, S., & Gordon, R. L. (in preparation). Musical rhythm processing in children with typical and atypical language development.

Zanto, T. P., Large, E. W., Fuchs, A., & Kelso, J. A. S. (2005). Gamma-band responses to perturbed auditory sequences: Evidence for synchronization of perceptual processes. *Music Perception*, *22*(3), 531–547. https://doi.org/10.1525/mp.2005.22.3.531

Zelaznik, H. N., Vaughn, A. J., Green, J. T., Smith, A. L., Hoza, B., & Linnea, K. (2012). Motor timing deficits in children with Attention-Deficit/Hyperactivity disorder. *Human Movement Science*, *31*(1), 255–265. https://doi.org/10.1016/J.HUMOV.2011.05.003

Chapter 7

General Discussion

The present work focused on the investigation of prediction mechanisms and neural entrainment in children as the possible elements underlying both rhythm and syntactic processing. Chapters 2, 3, and 4 reported the results of three research studies in which we investigated rhythmic and morphosyntactic predictions in children with typical development (TD), with Developmental Dyslexia (DD), and who received early exposure to music. In Chapters 5 and 6 we presented two studies with electroencephalography (EEG) that we conducted to investigate the neural markers of rhythmic processing that relate to syntactic processing in TD children and in children with Developmental Language Disorder (DLD).

7.1 Prediction mechanisms for morphosyntactic and rhythm processing

Language processing, reading, and rhythmic perception and production are thought to be carried out efficiently only if hierarchical representations are accessed and predictions about incoming material are made. In language and reading building expectations based on processed input allows to restrict the number of possible alternatives for incoming material; this makes processing (and word decoding) faster and less costly in terms of computational efforts (Grüter, Rohde, & Schafer, 2014; Guasti, Pagliarini, & Stucchi, 2017); in rhythm, efficient sensorimotor synchronization would not be possible without the formation of precise structure-based predictions about the timing of future inputs (Miyake, Onishi, & Pöppel, 2004). In all cases, predictions are activated automatically and unconsciously by the combinatory features of the structure that is processed, and individuals are sensitive to violations of these expectations (gender agreement: Barber, Salillas, & Carreiras, 2004; Gunter, Friederici, & Schriefers, 2000; reading: (Frazier & Rayner, 1982); rhythm: Sun, Liu, Zhou, & Jiang, 2018).

In our studies we showed better rhythmic and morphosyntactic prediction abilities in older TD children than in younger ones. Though all children were able to synchronize their taps to the auditory stimuli regardless of whether or not physical cues were placed on the beat, younger children seemed to build weaker hierarchical representations and/or not to be able to use those representations as efficiently as older children to predict incoming material. This idea was further confirmed by the language data: younger children were worse at anticipating linguistic material in morphosyntactic processing, especially when there were no other cues than the grammatical lexical information of gender. We argue that differences between younger and older children and between children and adults are due to differing stages of maturation of the strategies for hierarchical processing that are subserved by specific neural networks. As shown in studies using EEG (Atchley et al., 2006; Friederici & Hahne, 2001), children and adults show the same type of neural responses to syntactic violations; however, adults show earlier and stronger responses as compared to children. Taken together, our findings and those of above-mentioned studies suggest that children are ‘slower’ and less efficient in processing hierarchical linguistic structures (and their violations), possibly because of less efficient neural networks.

However, hierarchical processing deficits can also be found in older children, when these have DD. In Chapter 3 we showed that children with reading impairments make less accurate predictions in both rhythm and morphosyntactic processing: children with dyslexia were significantly less precise in synchronizing their taps to the beat than TD age-matched peers; moreover, they showed worse performance in anticipating incoming nouns based on the information of the preceding gender-marked clitic pronouns, especially when no semantic cue to the gender information of the noun was available. That is, children with DD were less able to anticipate nouns than TD children, especially when the pictures that they were presented with did not depict human characters with a biological gender, i.e., for instance, women vs. men. In line with previous studies (e.g., Cantiani et al., 2015), these results suggest the presence of subtle morphosyntactic deficits in dyslexia: children with DD perform like TD peers when semantic cues to gender are available, but show impaired anticipation skills when they have no other alternative than using grammatical and phonological information. This suggests weaker mechanisms of hierarchical processing. Nonetheless, these mechanisms may be improved: as shown in the tapping task, children with DD had improved rhythmic performance when the placement of the beat was marked by physical accents and with more exposure to the rhythmic structures. These results suggest that auditory cues and incremental exposure to rhythmic sequences enhances temporal predictions even in children with sensorimotor synchronization deficits; improved timing skills in rhythm may then transfer to language and possibly attenuate hierarchical processing deficits.

Evidence for the hypothesis that more exposure to rhythm leads to improved structure-based predictions was provided in Chapter 4. In that study we showed that, in typical development, anticipation skills in rhythm and morphosyntactic processing are enhanced with early and continuous musical training: children who received musical training from an early age performed better than age-matched peers both in rhythm production (in line with previous studies (e.g., Drake, 1993) and in morphosyntactic processing. The findings that musician children are significantly faster in anticipating incoming linguistic material than their peers, and that they are not affected by the presence or absence of additional cues to gender information suggest stronger hierarchical representations and processing in this group. Since musician and non-musician children did not differ in age or on auditory short term memory, enhanced processing of hierarchical structures in language may be interpreted as the result of the prolonged exposure to hierarchical structures in rhythm and to transfer effects from one domain to the other.

Crucially, in all of the three studies we found structure-based predictions to correlate across domains: the ability to make temporal predictions in music based on the mental representation of the meter correlated with the ability to anticipate nouns based on the sole grammatical lexical gender feature of its preceding determiner in typical development. The latter requires hierarchical processing and anticipation mechanisms to be especially efficient, since no other cue is available. Importantly, hierarchical processing abilities in language also correlated with pseudoword decoding skills: in all studies the better the participants were in anticipating nouns in the grammatical condition, the faster they were in decoding pseudowords, an ability that is important for literacy acquisition but also for vocabulary learning. We interpret the absence of significant, linear correlations in the DD children across domains as due to their less stable hierarchical processing behaviors in both types of tasks (implications are further discussed in the next section). Taken together, our studies provide evidence for structure-based prediction processes being critical for efficient rhythmic and morphosyntactic processing and for reading; if these are impaired, deficits are likely to appear across domains.

Finally, we argue that the mechanism linking rhythmic and morphosyntactic prediction abilities is constituted by neural entrainment. As shown by Iversen, Repp, and Patel (2009), an increase in beta (non-phase-locked) activity is registered *before* the onset of predictable stimuli, which implicates that the processing of the next stimulus is carried out when beta activity is at its peak. Beta activity thus appears to reflect mechanisms of prediction and anticipation of an incoming stimulus and its efficiency seems to be important for the adequate processing of successive predictable stimuli. More exposure to rhythmic patterns from an early age (as in our Suzuki group) in typical development might lead to enhanced mechanisms of neural entrainment at multiple levels of the structure that is processed, and by consequence, to more efficient hierarchical processing across domains.

Interestingly, exposure to rhythmic sequences (and possibly, neural entrainment to them) are also of benefit to the children with deficits in hierarchical processing: as shown in Chapter 3, short term exposure to rhythmic patterns, especially if they contain physical cues marking the beat, is enough for children with dyslexia to show improved hierarchical processing. Though meter perception is an automatic process (Bolton, 1894), physical cues and incremental exposure might facilitate neural entrainment for participants with atypical neural oscillatory activity (as in the case of children with dyslexia; e.g., see Power, Mead, Barnes, & Goswami, 2013); it might help participants access hierarchical structures more easily and make more accurate structure-based predictions.

7.2 Neural entrainment

As already discussed, neural entrainment is thought to be crucial for hierarchical processing, both in the case of rhythm and in the case of syntactic constituencies (Ahissar et al., 2001; Ding, Patel, et al., 2017; Ghitza, 2012; Ladányi, Persici, et al., submitted; Luo & Poeppel, 2007); efficient tracking of hierarchical structures, possibly through mechanisms of internal entrainment between multiple oscillators at different levels of the structure (Jones, 2019), is thought to increase attention to important parts of the signal (Large & Jones, 1999) and to facilitate processing. Based on this, we expected individual differences in neural entrainment to correspond to and predict individual differences in syntactic performance. This hypothesis is important, because it could also contribute to explain why better rhythm perception skills correspond to better syntactic production abilities in children (Gordon, Jacobs, et al., 2015; Gordon, Shivers, et al., 2015).

To investigate neural oscillatory markers that may relate to individual differences in syntactic performance, in Chapters 5 and 6 we analyzed children’s neural activity, while participants listened to rhythmic patterns that were designed to elicit different metrical (hierarchical) interpretations; their neural responses, analyzed using both ERPs and time-frequency analyses, were then compared to their ability to produce syntactic constructions that required refined linguistic operations.

Both studies confirmed the well-established finding in the literature that auditory stimuli produce a phase-resetting of oscillations so that they are phase-locked to the onset of the stimuli. Moreover, in line with previous studies investigating neural responses to rhythm (Iversen et al., 2009), we showed that oscillatory activity is modulated by top-down processes of metrical interpretation: participants showed stronger responses in correspondence to the perceived beat.

In addition, both studies showed that the ability to discriminate different rhythmic patterns predicts syntactic performance, in line with previous findings in the literature (Gordon, Jacobs, Schuele, & McAuley, 2015; Gordon, Shivers, et al., 2015). Individual differences in neural rhythms may lead to individual differences in strength of predictive processes, and thus to different abilities in processing hierarchical structures. As discussed in Chapter 6, this link between rhythm perception and syntactic production is important, as measures of rhythmic skills in younger children may offer insight into the possible development of later language or reading disorders. Of even greater importance are the findings that *neural activity* to rhythmic stimuli predicts syntactic skills. In fact, rhythmic stimuli are perceived already at infancy (see section 7.4 below) and are not subjected to language-related differences (e.g., between different countries); therefore, these findings may implicate the possibility of using the same neural paradigms (across countries) at infancy to predict the possible emergence of later language disorders.

Finally, by comparing neural activity across groups, we showed that TD and DLD children show different oscillatory patterns in the beta and gamma band in relation to rhythmic stimuli (Chapter 6). In particular, children with DLD appear to show atypical gamma activity. Since gamma oscillations are thought to track hierarchical structures in language (Ding, Melloni, Zhang, Tian, & Poeppel, 2015), this result reinforces our hypothesis that impairments in hierarchical processing may follow from impaired cortical tracking of hierarchical structures. Deficits in neural tracking of hierarchical structures, and in the structure-based predictions associated with those structures, would be the cause for which children with DLD show both syntactic (Hulme & Snowling, 2009; Schuele & Tolbert, 2001) and rhythmic deficits (e.g., tapping: Corriveau & Goswami, 2009; rise time perception: Corriveau, Pasquini, & Goswami, 2007; prosody discrimination: Fisher, Plante, Vance, Gerken, & Glattke, 2007; Wells & Peppé, 2003).

7.3 Neural entrainment and predictions as part of the network subserving rhythm and language

Though the link between neural entrainment and predictions was only indirectly tested in this work, our findings provide support for the idea that neural entrainment subserves prediction-making mechanisms. In agreement with Fiveash et al. (submitted) and Ladányi, Persici, et al. (submitted), we argue that neural entrainment and sensorimotor coupling (reflected by beta oscillations), together with fine-grained auditory processing, might constitute the network that supports both surface-level feature and hierarchical processing in both music and language. Impairment of at least one of these mechanisms would correspond to deficits in hierarchical processing that appear in language (and/or reading) and rhythm processing. On the other hand, enhancement of at least one of these mechanisms (e.g., through music exposure and musical training) may lead to improved skills in both domains (as seen in intervention and rhythmic priming studies; see Chapter 1).

These findings have important implications for clinical interventions. Dyslexia (Finn et al., 2014) and DLD (Krishnan, Watkins, & Bishop, 2016) have been associated with weaker functional connections between frontal and temporal language areas, which leads to weaker information integration processes between different areas of the brain. Interestingly, musical training, which requires fine coordination between sensory and motor processes for adequate performance, has been shown to stimulate functional connectivity (Halwani, Loui, Rüber, & Schlaug, 2011; Paraskevopoulos, Kraneburg, Herholz, Bamidis, & Pantev, 2015), even in patients with severe impairments such as schizophrenia (Yang et al., 2018). These results, together with intervention studies showing improved language and reading performance after musical training (Moreno et al., 2009; Overy, 2003), support the use of music as a useful tool for the remediation of language and reading deficits. Short-term (e.g., Chern, Tillmann, Vaughan, & Gordon, 2018; Ladányi, Lukács, & Gervain, submitted) and long-term exposure to rhythmic structures (e.g., Habibi, Wirantana, & Starr, 2014) is shown to transfer from music to language, even in populations with language and/or reading disorders. As already mentioned, this effect may be due, in the first place, to enhancement of neural entrainment to auditory stimuli. Importantly, neural entrainment to rhythm can be studied even with participants who are not yet able to speak, that is, with infants. Since interventions for the remediation of language and reading disorders are most effective when they take place early in life (e.g., Snowling, 2013), neural entrainment to rhythm at infancy may provide an important insight into whether language and/or reading disorders are likely to be developed later in life, and thus allow for earlier interventions.

7.4 Rhythm as a possible risk factor for the development of speech and language disorders

Given the importance of early identification of disorders and early intervention (e.g., Snowling, 2013), finding risk factors at infancy that may indicate later speech/language deficits is of great importance. Crucially, research with infants has shown that ‘rhythm’, broadly, may serve as a risk factor for the development of later language and reading deficits (see Ladányi, Persici, et al., submitted). Rhythmic cues are processed from a very early age (Cirelli, Spinelli, Nozaradan, & Trainor, 2016), and are crucial for language acquisition, as they facilitate word segmentation (Jusczyk, 1999) and grammar acquisition (Gervain & Werker, 2013). Notably, studies have shown that rapid auditory processing skills (Benasich, Thomas, Choudhury, & Leppänen, 2002) and temporal processing abilities (Kalashnikova, Goswami, & Burnham, 2019) at infancy predict later language skills at childhood. For instance, a recent study by Cantiani et al. (2019) has shown that vocabulary (which is a measure of language development) can be predicted by the oscillatory brain activity that is shown at infancy, and that infants at familial risk of language and literacy impairment already show atypical oscillatory activity at 6 months. These findings suggest that temporal processing deficits may be identified at infancy through the use of rhythmic tasks.

Interestingly, associations between rhythm and language and reading deficits are found not only in the typically-developing population and in dyslexia and DLD (see Table 1 in Chapter 1), but also in developmental speech and motor disorders such as developmental stuttering (Falk, Müller, & Dalla Bella, 2015; Olander, Smith, & Zelaznik, 2010; Wieland, McAuley, Dilley, & Chang, 2015), attention deficit hyperactivity disorder (Carrer, 2015; Hove, Gravel, Spencer, & Valera, 2017; Noreika, Falter, & Rubia, 2013; Slater & Mc, 2018), and developmental coordination disorder (Puyjarinet, Bégel, Lopez, Dellacherie, & Dalla Bella, 2017; Rosenblum & Regev, 2013). Moreover, although the possible effect of rhythm training has not been investigated in all of the above-mentioned disorders, external auditory stimulation has been shown to positively affect stuttering (Falk, Maslow, Thum, & Hoole, 2016; Toyomura, Fujii, & Kuriki, 2011). These findings suggest that similar neural and cognitive mechanisms may underlie speech and language disorders. This idea is further supported by the fact that these disorders are highly comorbid (see, e.g., Bishop & Snowling, 2004; Catts, Adlof, Hogan, & Weismer, 2005; Donaher & Richels, 2012; Kaplan, Dewey, Crawford, & Wilson, 2001; Mueller & Tomblin, 2012; Redmond, 2016). Impairments in the shared network subserving both language and rhythm processing may (see also Fiveash, Bedoin, and Tillmann (submitted) and Ladányi, Persici, et al., submitted) lead to timing perception and hierarchical processing deficits, and to the development of one or more speech and/or language disorders.

Studying entrainment to rhythmic stimuli at infancy may offer an important insight into whether speech and language deficits are likely to be developed. Together with heritable and environmental factors (cf. Ladányi, Persici, et al., submitted), 'rhythm' may be used as a possible early indicator for the development of later speech/language and/or reading deficits (see our *Atypical Rhythm Risk Hypothesis*; Ladányi et al., submitted); this may contribute to earlier identifications, to the attenuation of deficits through earlier interventions (Snowling, 2013), and thus to the improvement of the academic, social, and economic conditions (Hubert-Dibon, Bru, Gras Le Guen, Launay, & Roy, 2016) of the populations with speech and/or language disorders.

7.5 References

Ahissar, E., Nagarajan, S., Ahissar, M., Protopapas, A., Mahncke, H., & Merzenich, M. M. (2001). Speech comprehension is correlated with temporal response patterns recorded from auditory cortex. *Proceedings of the National Academy of Sciences of the United States of America*, *98*(23), 13367–13372. https://doi.org/10.1073/pnas.201400998

Atchley, R. A., Rice, M. L., Betz, S. K., Kwasny, K. M., Sereno, J. A., & Jongman, A. (2006). A comparison of semantic and syntactic event related potentials generated by children and adults. *Brain and Language*, *99*(3), 236–246. https://doi.org/10.1016/j.bandl.2005.08.005

Barber, H., Salillas, E., & Carreiras, M. (2004). Gender or genders agreement? In *The On-line Study of Sentence Comprehension: Eyetracking, ERPs and Beyond* (pp. 309–327). New York: Psychology Press. https://doi.org/10.4324/9780203509050

Benasich, A. A., Thomas, J. J., Choudhury, N., & Leppänen, P. H. T. (2002). The importance of rapid auditory processing abilities to early language development: evidence from converging methodologies. *Developmental Psychobiology*, *40*(3), 278–292. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/11891639

Bishop, D. V. M., & Snowling, M. J. (2004). Developmental dyslexia and specific language impairment: same or different? *Psychological Bulletin*, *130*(6), 858–886. https://doi.org/10.1037/0033-2909.130.6.858

Bolton, T. L. (1894). Rhythm. *American Journal of Psychology*, *6*, 145–238.

Cantiani, C., Lorusso, M. L., Perego, P., Molteni, M., & Guasti, M. T. (2015). Developmental Dyslexia With and Without Language Impairment: ERPs Reveal Qualitative Differences in Morphosyntactic Processing. *Developmental Neuropsychology*, *40*(5), 291–312. https://doi.org/10.1080/87565641.2015.1072536

Cantiani, C., Ortiz-mantilla, S., Riva, V., Piazza, C., Bettoni, R., Musacchia, G., … Benasich, A. A. (2019). Reduced left-lateralized pattern of event-related EEG oscillations in infants at familial risk for language and learning impairment. *NeuroImage: Clinical*, *22*(March), 101778. https://doi.org/10.1016/j.nicl.2019.101778

Carrer, L. R. J. (2015). Music and Sound in Time Processing of Children with ADHD. *Frontiers in Psychiatry*, *6*, 127. https://doi.org/10.3389/fpsyt.2015.00127

Catts, H. W., Adlof, S. M., Hogan, T. P., & Weismer, S. E. (2005). Are specific language impairment and dyslexia distinct disorders? *Journal of Speech, Language, and Hearing Research : JSLHR*, *48*(6), 1378–1396. https://doi.org/10.1044/1092-4388(2005/096)

Chern, A., Tillmann, B., Vaughan, C., & Gordon, R. L. (2018). New evidence of a rhythmic priming effect that enhances grammaticality judgments in children. *Journal of Experimental Child Psychology*, *173*, 371–379. https://doi.org/10.1016/j.jecp.2018.04.007

Cirelli, L. K., Spinelli, C., Nozaradan, S., & Trainor, L. J. (2016). Measuring neural entrainment to beat and meter in infants: Effects of music background. *Frontiers in Neuroscience*, *10*(MAY), 1–11. https://doi.org/10.3389/fnins.2016.00229

Corriveau, K. H., & Goswami, U. (2009). Rhythmic motor entrainment in children with speech and language impairments: Tapping to the beat. *Cortex*, *45*(1), 119–130. https://doi.org/10.1016/J.CORTEX.2007.09.008

Corriveau, K. H., Pasquini, E., & Goswami, U. (2007). Basic Auditory Processing Skills and Specific Language Impairment: A New Look at an Old Hypothesis. *Journal of Speech, Language, and Hearing Research*, *50*, 647–666. https://doi.org/10.1044/1092-4388(2007/046

Ding, N., Melloni, L., Zhang, H., Tian, X., & Poeppel, D. (2015). Cortical tracking of hierarchical linguistic structures in connected speech. *Nature Neuroscience*, *19*(1), 158–164. https://doi.org/10.1038/nn.4186

Ding, N., Patel, A. D., Chen, L., Butler, H., Luo, C., & Poeppel, D. (2017). Temporal modulations in speech and music. *Neuroscience and Biobehavioral Reviews*, *81*, 181–187. https://doi.org/10.1016/j.neubiorev.2017.02.011

Donaher, J., & Richels, C. (2012). Traits of attention deficit/hyperactivity disorder in school-age children who stutter. *Journal of Fluency Disorders*, *37*(4), 242–252. https://doi.org/10.1016/j.jfludis.2012.08.002

Drake, C. (1993). Reproduction of musical rhythms by children, adult musicians, and adult nonmusicians. *Perception & Psychophysics*, *53*(1), 25–33. Retrieved from https://link.springer.com/content/pdf/10.3758/BF03211712.pdf

Falk, S., Maslow, E., Thum, G., & Hoole, P. (2016). Temporal variability in sung productions of adolescents who stutter. *Journal of Communication Disorders*, *62*, 101–114. https://doi.org/10.1016/J.JCOMDIS.2016.05.012

Falk, S., Müller, T., & Dalla Bella, S. (2015). Non-verbal sensorimotor timing deficits in children and adolescents who stutter. *Frontiers in Psychology*, *6*, 847. https://doi.org/10.3389/fpsyg.2015.00847

Finn, E. S., Shen, X., Holahan, J. M., Scheinost, D., Lacadie, C., Papademetris, X., … Constable, R. T. (2014). Disruption of functional networks in dyslexia: A whole-brain, data-driven analysis of connectivity. *Biological Psychiatry*, *76*(5), 397–404. https://doi.org/10.1016/j.biopsych.2013.08.031

Fisher, J., Plante, E., Vance, R., Gerken, L. A., & Glattke, T. J. (2007). Do children and adults with language impairment recognize prosodic cues? *Journal of Speech, Language, and Hearing Research*, *50*(3), 746–758. https://doi.org/10.1044/1092-4388(2007/052)

Fiveash, A., Bedoin, N., & Tillmann, B. (submitted). Rhythmic processing of music and language: A review and implications for developmental disorders.

Frazier, L., & Rayner, K. (1982). Making and correcting errors during sentence comprehension: Eye movements in the analysis of structurally ambiguous sentences. *Cognitive Psychology*, *14*(2), 178–210. https://doi.org/10.1016/0010-0285(82)90008-1

Friederici, A. D., & Hahne, A. (2001). Development patterns of brain activity reflecting semantic and syntactic processes. In J. Weissenborn & B. Houle (Eds.), *Approaches to bootstrapping: Phonological, lexical, syntactic, and neurophysiological aspects of early language acquisition* (pp. 231–246). Amsterdam/Philadelphia: John Benhamin.

Gervain, J., & Werker, J. F. (2013). Prosody cues word order in 7-month-old bilingual infants. *Nature Communications*, *4*. https://doi.org/10.1038/ncomms2430

Ghitza, O. (2012). On the role of theta-driven syllabic parsing in decoding speech: intelligibility of speech with a manipulated modulation spectrum. *Frontiers in Psychology*, *3*, 238. https://doi.org/10.3389/fpsyg.2012.00238

Gordon, R. L., Jacobs, M. S., Schuele, C. M., & McAuley, J. D. (2015). Perspectives on the rhythm-grammar link and its implications for typical and atypical language development. *Annals of the New York Academy of Sciences*, *1337*(1), 16–25. https://doi.org/10.1111/nyas.12683

Gordon, R. L., Shivers, C. M., Wieland, E. A., Kotz, S. A., Yoder, P. J., & Devin Mcauley, J. (2015). Musical rhythm discrimination explains individual differences in grammar skills in children. *Developmental Science*, *18*(4), 635–644. https://doi.org/10.1111/desc.12230

Grüter, T., Rohde, H., & Schafer, A. J. (2014). The role of discourse-level expectations in non-native speakers' referential choices. In *Proceedings of the 38th Annual Boston University Conference on Language Development (BUCLD).* Cascadilla Press.

Guasti, M. T., Pagliarini, E., & Stucchi, N. (2017). Language, reading and motor control: Get rhythm! *Biolinguistics*, *11*(1), 1–12.

Gunter, T. C., Friederici, A. D., & Schriefers, H. (2000). Syntactic gender and semantic expectancy: ERPs reveal early autonomy and late interaction. *Journal of Cognitive Neuroscience*, *12*(4), 556–568. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/10936910

Habibi, A., Wirantana, V., & Starr, A. (2014). Cortical activity during perception of musical rhythm: Comparing musicians and nonmusicians. *Psychomusicology: Music, Mind, and Brain*, *24*(2), 125–135. https://doi.org/10.1037/pmu0000046

Halwani, G. F., Loui, P., Rüber, T., & Schlaug, G. (2011). Effects of practice and experience on the arcuate fasciculus: comparing singers, instrumentalists, and non-musicians. *Frontiers in Psychology*, *2*, 156. https://doi.org/10.3389/fpsyg.2011.00156

Hove, M. J., Gravel, N., Spencer, R. M. C., & Valera, E. M. (2017). Finger tapping and pre-attentive sensorimotor timing in adults with ADHD. *Experimental Brain Research*, *235*(12), 3663–3672. https://doi.org/10.1007/s00221-017-5089-y

Hubert-Dibon, G., Bru, M., Gras Le Guen, C., Launay, E., & Roy, A. (2016). Health-Related Quality of Life for Children and Adolescents with Specific Language Impairment: A Cohort Study by a Learning Disabilities Reference Center. *PloS One*, *11*(11), e0166541. https://doi.org/10.1371/journal.pone.0166541

Hulme, C., & Snowling, M. J. (2009). *Developmental disorders of language learning and cognition*. Wiley-Blackwell. Retrieved from https://psycnet.apa.org/record/2007-09153-000

Iversen, J. R., Repp, B. H., & Patel, A. D. (2009). Top-down control of rhythm perception modulates early auditory responses. *Annals of the New York Academy of Sciences*, *1169*, 58–73. https://doi.org/10.1111/j.1749-6632.2009.04579.x

Jones, M. R. (2019). *Time will tell: A theory of Dynamic Attending*. New York: Oxford University Press.

Jusczyk, P. W. (1999, September 1). How infants begin to extract words from speech. *Trends in Cognitive Sciences*. https://doi.org/10.1016/S1364-6613(99)01363-7

Kalashnikova, M., Goswami, U., & Burnham, D. (2019). Sensitivity to amplitude envelope rise time in infancy and vocabulary development at 3 years: A significant relationship. *Developmental Science*, e12836. https://doi.org/10.1111/desc.12836

Kaplan, B. J., Dewey, D. M., Crawford, S. G., & Wilson, B. N. (2001). The term comorbidity is of questionable value in reference to developmental disorders: data and theory. *Journal of Learning Disabilities*, *34*(6), 555–565. https://doi.org/10.1177/002221940103400608

Krishnan, S., Watkins, K. E., & Bishop, D. V. M. (2016). Neurobiological Basis of Language Learning Difficulties. *Trends in Cognitive Sciences*, *20*(9), 701–714. https://doi.org/10.1016/j.tics.2016.06.012

Ladányi, E., Lukács, Á., & Gervain, J. (submitted). Rhythmic priming in children with and without Specific Language Impairment.

Ladányi, E., Persici, V., Fiveash, A., Tillmann, B., & Gordon, R. L. (submitted). Is atypical rhythm a risk factor for speech and language disorders?

Large, E. W., & Jones, M. R. (1999). The dynamics of attending: How people track time-varying events. *Psychological Review*. https://doi.org/10.1037/0033-295X.106.1.119

Luo, H., & Poeppel, D. (2007). Phase Patterns of Neuronal Responses Reliably Discriminate Speech in Human Auditory Cortex. *Neuron*, *54*(6), 1001–1010. https://doi.org/10.1016/j.neuron.2007.06.004

Miyake, Y., Onishi, Y., & Pöppel, E. (2004). Two types of anticipation in synchronization tapping. *Acta Neurobiologiae Experimentalis*, *64*(3), 415–426. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/15283483

Moreno, S., Marques, C., Santos, A., Santos, M., Castro, S. L., & Besson, M. (2009). Musical Training Influences Linguistic Abilities in 8-Year-Old Children: More

Evidence for Brain Plasticity. *Cerebral Cortex*, *19*(3), 712–723. https://doi.org/10.1093/cercor/bhn120

Mueller, K. L., & Tomblin, J. B. (2012, July). Examining the comorbidity of language impairment and attention-deficit/ hyperactivity disorder. *Topics in Language Disorders*. https://doi.org/10.1097/TLD.0b013e318262010d

Noreika, V., Falter, C. M., & Rubia, K. (2013). Timing deficits in attention-deficit/hyperactivity disorder (ADHD): Evidence from neurocognitive and neuroimaging studies. *Neuropsychologia*, *51*(2), 235–266. https://doi.org/10.1016/J.NEUROPSYCHOLOGIA.2012.09.036

Olander, L., Smith, A., & Zelaznik, H. N. (2010). Evidence that a motor timing deficit is a factor in the development of stuttering. *Journal of Speech, Language, and Hearing Research*, *53*, 876–886.

Overy, K. (2003). Dyslexia and music: From timing deficits to musical intervention. *Annals of the New York Academy of Sciences*, *999*, 497–505. https://doi.org/10.1196/annals.1284.060

Paraskevopoulos, E., Kraneburg, A., Herholz, S. C., Bamidis, P. D., & Pantev, C. (2015). Musical expertise is related to altered functional connectivity during audiovisual integration. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(40), 12522–12527. https://doi.org/10.1073/pnas.1510662112

Power, A. J., Mead, N., Barnes, L., & Goswami, U. (2013). Neural entrainment to rhythmic speech in children with developmental dyslexia. *Frontiers in Human Neuroscience*, *7*, 777. https://doi.org/10.3389/fnhum.2013.00777

Puyjarinet, F., Bégel, V., Lopez, R., Dellacherie, D., & Dalla Bella, S. (2017). Children and adults with Attention-Deficit/Hyperactivity Disorder cannot move to the beat. *Scientific Reports*, *7*(1). https://doi.org/10.1038/s41598-017-11295-w

Redmond, S. M. (2016, February 1). Language impairment in the attention-deficit/hyperactivity disorder context. *Journal of Speech, Language, and Hearing Research*. American Speech-Language-Hearing Association. https://doi.org/10.1044/2015_JSLHR-L-15-0038

Rosenblum, S., & Regev, N. (2013). Timing abilities among children with developmental coordination disorders (DCD) in comparison to children with typical development. *Research in Developmental Disabilities*, *34*(1), 218–227. https://doi.org/10.1016/J.RIDD.2012.07.011

Schuele, C. M., & Tolbert, L. (2001). Omissions of obligatory relative markers in children with specific language impairment. *Clinical Linguistics and Phonetics*. https://doi.org/10.1080/02699200010017805

Slater, J. L., & Mc, T. (2018). Timing Deficits in ADHD: Insights From the Neuroscience of Musical Rhythm. *Frontiers in Computational Neuroscience | Www.Frontiersin.Org*, *1*. https://doi.org/10.3389/fncom.2018.00051

Snowling, M. J. (2013). Early identification and interventions for dyslexia: a contemporary view. *Journtal of Research in Special Educational Needs*, *13*(1), 7–14. https://doi.org/10.1111/j.1471-3802.2012.01262.x

Sun, L., Liu, F., Zhou, L., & Jiang, C. (2018). Musical training modulates the early but not the late stage of rhythmic syntactic processing. *Psychophysiology*, *55*(2), 1–10. https://doi.org/10.1111/psyp.12983

Toyomura, A., Fujii, T., & Kuriki, S. (2011). Effect of external auditory pacing on the neural activity of stuttering speakers. *NeuroImage*, *57*(4), 1507–1516. https://doi.org/10.1016/J.NEUROIMAGE.2011.05.039

Wells, B., & Peppé, S. (2003). Intonation abilities of children with speech and language impairments. *Journal of Speech, Language, and Hearing Research*, *46*(1), 5–20. https://doi.org/10.1044/1092-4388(2003/001)

Wieland, E. A., McAuley, J. D., Dilley, L. C., & Chang, S.-E. (2015). Evidence for a rhythm perception deficit in children who stutter. *Brain and Language*, *144*, 26–34. https://doi.org/10.1016/J.BANDL.2015.03.008

Yang, M., He, H., Duan, M., Chen, X., Chang, X., Lai, Y., … Yao, D. (2018). The Effects of Music Intervention on Functional Connectivity Strength of the Brain in Schizophrenia. *Neural Plasticity*, *2018*. https://doi.org/10.1155/2018/2821832

Appendix

A. List of sentences in the determiner processing task

Practice trials

Devi	*toccare*	*un*	*piatto*
(You) have to	touch	a	plate

Adesso	*devi*	*toccare*	*una*	*ragazza*
Now	(you) have to	touch	a	girl

Una	*bellissima*	*collana*
A	beautiful	necklace

Un	*bellissimo*	*cappello*
A	beautiful	hat

Una	*grande*	*macchina*
A	big	car

Una	*grande*	*palla*
A	big	ball

Un	*grande*	*orologio*
A	big	watch

Un	*grande*	*scarpa*
A	big	shoe

Un	*grande*	*regalo*
A	big	gift

Experimental trials

	Condition 1 (G)	
	Target	***Competitor***
1	*la grande vite* the.FEM big nail.FEM	*il grande limone* *the.MASC big lemon.MASC*
2	*il grande trattore* the.MASC big tractor.MASC	*la grande lavatrice* the.FEM big washing machine.FEM
3[1]	*il grande aquilone* the.MASC big kite.MASC	*la grande chitarra*
4	*la grande piramide* the.FEM big pyramid.FEM	*il grande pettine* the.MASC big comb.MASC
5	*la grande rete* the.FEM big net.FEM	*il grande bicchiere* the.MASC big glass.MASC
6	*il grande fiore* the.MASC big flower.MASC	*la grande chiave* the.FEM big key.FEM

	Condition 2 (GP)	
	Target	***Competitor***
1	*Il grande coltello* The.MASC big knife.MASC	*la grande forchetta* the.FEM big fork.FEM
2	*la grande chiesa* the.FEM big church.FEM	*il grande castello* the.MASC big castle.MASC
3	*il grande fungo* the.MASC big mushroom.MASC	*la grande foglia* the.FEM big leaf.FEM
4	*la grande barca* the.FEM big boat.FEM	*il grande aereo* the.MASC big plane.MASC
5	*la grande borsa* the.FEM big bag.FEM	*il grande zaino* the.MASC big backpack.MASC
6	*il grande secchio* the.MASC big bucket.MASC	*la grande scopa* the.FEM big broom.FEM

	Condition 3 (GPS)	
	Target	***Competitor***
1	*il grande marinaio* the.MASC big sailor.MASC	*la grande principessa* the.FEM big princess.FEM
2	*il grande poliziotto* the.MASC big policeman.MASC	*la grande ballerina* the.FEM big ballerina.FEM
3	*il grande mago* the.MASC big wizard.MASC	*la grande strega* the.FEM big witch.FEM

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[1] This item pair was removed because of a methodological problem.

4	*la grande suora* the.FEM big nun.FEM	*il grande ladro* the.MASC big thief.MASC
5	*la grande fatina* the.FEM big fairy.FEM	*il grande ragazzo* the.MASC big boy.MASC
6	*la grande regina* the.FEM big queen.FEM	*il grande soldato* the.MASC big soldier.MASC

B. List of sentences in the clitic processing task

Practice trials

Pinky	*tocca*	*velocemente*	*la*	*collana*
Pinky	touches	quickly	the.FEM	necklace.FEM

Pinky	*tocca*	*velocemente*	*la*	*ragazza*
Pinky	touches	quickly	the.FEM	girl.FEM

Pinky	*lo*	*tocca*	*velocemente*	*il*	*piatto*
Pinky	the.CL	touches	quickly	the.MASC	plate.MASC

Pinky	*lo*	*tocca*	*velocemente*	*il*	*regalo*
Pinky	the.CL	touches	quickly	the.MASC	gift.MASC

Pinky	*la*	*tocca*	*velocemente*	*la*	*macchina*
Pinky	the.CL	touches	quickly	the.FEM	car.FEM

Experimental trials

Condition 1 (G)

1.

Target

Pinky	*la*	*tocca*	*velocemente*	*la*	*vite*
Pinky	the.CL.FEM	touches	quickly	the.FEM	nail.FEM

Competitor

Pinky	*lo*	*tocca*	*velocemente*	*il*	*limone*
Pinky	the.CL.MASC	touches	quickly	the.MASC	lemon.MASC

2.

Target

Pinky	*lo*	*tocca*	*velocemente*	*il*	*trattore*
Pinky	the.CL.MASC	touches	quickly	the.MASC	tractor.MASC

Competitor

Pinky	*la*	*tocca*	*velocemente*	*la*	*lavatrice*
Pinky	the.CL.FEM	touches	quickly	the.FEM	washing machine.FEM

3.

Target

Pinky	*la*	*tocca*	*velocemente*	*la*	*piramide*
Pinky	the.CL.FEM	touches	quickly	the.FEM	pyramid.FEM

Competitor

Pinky	*lo*	*tocca*	*velocemente*	*il*	*pettine*
Pinky	the.CL.MASC	touches	quickly	the.MASC	comb.MASC

4.

Target

Pinky	*la*	*tocca*	*velocemente*	*la*	*rete*
Pinky	the.CL.FEM	touches	quickly	the.FEM	net.FEM

Competitor

Pinky	*lo*	*tocca*	*velocemente*	*il*	*bicchiere*
Pinky	the.CL.MASC	touches	quickly	the.MASC	glass.MASC

5.

Target

Pinky	*lo*	*tocca*	*velocemente*	*il*	*fiore*
Pinky	the.CL.MASC	touches	quickly	the.MASC	flower.MASC

Competitor

Pinky	*la*	*tocca*	*velocemente*	*la*	*chiave*
Pinky	the.CL.FEM	touches	quickly	the.FEM	key.FEM

6. [2]

Target

Pinky	*lo*	*tocca*	*velocemente*	*l'*	*aquilone*
Pinky	the.CL.MASC	touches	quickly	the.MASC	kite.MASC

Competitor

Pinky	*la*	*tocca*	*velocemente*	*la*	*torre*
Pinky	the.CL.FEM	touches	quickly	the.FEM	tower.FEM

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[2] This item pair was removed because of a methodological problem.

Condition 2 (GP)

1.

Target

Pinky	*lo*	*tocca*	*velocemente*	*il*	*coltello*
Pinky	the.CL.MASC	touches	quickly	the.MASC	knife.MASC

Competitor

Pinky	*la*	*tocca*	*velocemente*	*la*	*forchetta*
Pinky	the.CL.FEM	touches	quickly	the.FEM	fork.FEM

2.

Target

Pinky	*la*	*tocca*	*velocemente*	*la*	*chiesa*
Pinky	the.CL.FEM	touches	quickly	the.FEM	church.FEM

Competitor

Pinky	*lo*	*tocca*	*velocemente*	*il*	*castello*
Pinky	the.CL.MASC	touches	quickly	the.MASC	castle.MASC

3.

Target

Pinky	*lo*	*tocca*	*velocemente*	*il*	*fungo*
Pinky	the.CL.MASC	touches	quickly	the.MASC	mushroom.MASC

Competitor

Pinky	*la*	*tocca*	*velocemente*	*la*	*foglia*
Pinky	the.CL.FEM	touches	quickly	the.FEM	leaf.FEM

4.

Target

Pinky	*la*	*tocca*	*velocemente*	*la*	*barca*
Pinky	the.CL.FEM	touches	quickly	the.FEM	boat.FEM

Competitor

Pinky	*lo*	*tocca*	*velocemente*	*il*	*treno*
Pinky	the.CL.MASC	touches	quickly	the.MASC	train.MASC

5.

Target

Pinky	*la*	*tocca*	*velocemente*	*la*	*borsa*
Pinky	the.CL.FEM	touches	quickly	the.FEM	bag.FEM

Competitor

Pinky	*lo*	*tocca*	*velocemente*	*il*	*sacco*
Pinky	the.CL.MASC	touches	quickly	the.MASC	sack.MASC

6.
Target

Pinky	*lo*	*tocca*	*velocemente*	*il*	*secchio*
Pinky	the.CL.MASC	touches	quickly	the.MASC	bucket.MASC

Competitor

Pinky	*la*	*tocca*	*velocemente*	*la*	*scopa*
Pinky	the.CL.FEM	touches	quickly	the.FEM	broom.FEM

Condition 3 (GPS)

1.
Target

Pinky	*lo*	*tocca*	*velocemente*	*il*	*marinario*
Pinky	the.CL.MASC	touches	quickly	the.MASC	sailor.MASC

Competitor

Pinky	*la*	*tocca*	*velocemente*	*la*	*principessa*
Pinky	the.CL.FEM	touches	quickly	the.FEM	princess.FEM

2.
Target

Pinky	*lo*	*tocca*	*velocemente*	*il*	*poliziotto*
Pinky	the.CL.MASC	touches	quickly	the.MASC	policeman.MASC

Competitor

Pinky	*la*	*tocca*	*velocemente*	*la*	*ballerina*
Pinky	the.CL.FEM	touches	quickly	the.FEM	ballerina.FEM

3.
Target

Pinky	*lo*	*tocca*	*velocemente*	*il*	*mago*
Pinky	the.CL.MASC	touches	quickly	the.MASC	wizard.MASC

Competitor

Pinky	*la*	*tocca*	*velocemente*	*la*	*strega*
Pinky	the.CL.FEM	touches	quickly	the.FEM	witch.FEM

4.
Target

Pinky	*la*	*tocca*	*velocemente*	*la*	*suora*
Pinky	the.CL.FEM	touches	quickly	the.FEM	nun.FEM

Competitor

Pinky	*lo*	*tocca*	*velocemente*	*il*	*ladro*
Pinky	the.CL.MASC	touches	quickly	the.MASC	thief.MASC

5.
Target

Pinky	*la*	*tocca*	*velocemente*	*la*	*fatina*
Pinky	the.CL.FEM	touches	quickly	the.FEM	fairy.FEM

Competitor

Pinky	*lo*	*tocca*	*velocemente*	*il*	*ragazzo*
Pinky	the.CL.MASC	touches	quickly	the.MASC	boy.MASC

6.
Target

Pinky	*la*	*tocca*	*velocemente*	*la*	*regina*
Pinky	the.CL.FEM	touches	quickly	the.FEM	queen.FEM

Competitor

Pinky	*lo*	*tocca*	*velocemente*	*il*	*soldier*
Pinky	the.CL.MASC	touches	quickly	the.MASC	soldato.MASC
