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Short- and long-term rhythmic interventions: perspectives for language rehabilitation

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This paper brings together different perspectives on the investigation and understanding of temporal processing and temporal expectations. We aim to bridge different temporal deficit hypotheses in dyslexia, dysphasia, or deafness in a larger framework, taking into account multiple nested temporal scales. We present data testing the hypothesis that temporal attention can be influenced by an external rhythmic auditory stimulation (i.e., musical rhythm) and benefits subsequent language processing, including syntax processing and speech production. We also present data testing the hypothesis that phonological awareness can be influenced by several months of musical training and, more particularly, rhythmic training, which in turn improves reading skills. Together, our data support the hypothesis of a causal role of rhythm-based processing for language processing and acquisition. These results open new avenues for music-based remediation of language and hearing impairment.

Keywords: music; rhythm; language; rehabilitation; entrainment

Dynamics of attending

Q1
Q2

Temporal expectations are linked to synchronization, entrainment, and phase coupling of external stimuli and internal oscillators. An illustrative example of phase coupling can be seen in a setup in which several metronomes set to the same tempo but with different phases, once placed on a moving table, will synchronize and end up sharing the same phase (see https://www.youtube.com/watch?v=Aaxw4zbULMs). Once energy can travel from one metronome to the other via the moving table, metronomes synchronize, and the minimal energy state of the system is reached. This example of phase coupling can be seen as a good metaphor of how music, that is, periodic and temporally structured sounds, can synchronize and entrain neural populations via traveling waves (first acoustic and then neuroelectric).

In regard to synchronization and entrainment, Jones[1] has started to develop a theoretical framework of temporal attention. The hypothesis of this dynamic attending theory (DAT) is that attention is not evenly distributed over time, but rather fluctuates (or oscillates) in time via cycles. These oscillations would be driven by a phase coupling between internal (neuronal) oscillators and (external) periodicities in the environment (e.g., music). There can be different frequency relationships with that of the external regulator, leading to metric hierarchical structures in music.[2] Thus, attentional energy would be maximal at most expected moments in time (that is, moments with high probability that an event would occur). The DAT was first described for and applied to music (see, in particular, Ref. 3), and then also to speech or movement. Large and Jones[4] have proposed a mathematical model describing entrainment phenomena in music perception. In this model, the periodic music structure entrains the attentional oscillatory cycles. Moreover, the metrical structure (the organization of strong and weak beats) also affects these attentional fluctuations, engendering larger peaks at strong beats.[2,4]

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The DAT has been empirically tested in the auditory domain for musical material, speech material, as well as cross-modal perceptual setups to test for interactions with visual perception. The various data sets have shown that perception is enhanced for musical events (tones, chords) that are presented at highly expected moments in time, notably on the beat.[5–7] More recently, a series of cross-modal experiments has shown that this enhancement is not only limited to the auditory modality but can also benefit visual processing. Indeed, when one is listening to an auditory regular sequence (e.g., a metronome), processing of visual stimuli is facilitated when the stimulus is presented on the beat in comparison to when it is presented off the beat.[8–10]

The facilitated processing is not limited to the comparison between presentations on the beat versus off the beat: it also depends on the structural hierarchy of beats. In a recent experiment, we presented visual or auditory targets simultaneously to a piece of music (e.g., a Bach Solo Sonata for violin). Presenting visual stimuli on the beat or off the beat had a relatively small effect. In contrast, targets presented on the strong beat or right before, showed shorter RT compared to those presented on or right before a weaker beat.[11] It thus seems that the rhythm of attention is locked to the occurrences of strong beat, with weak beats in the trough of the oscillation. With respect to neural substrates, this effect seems to rely on the left intraparietal lobule, a region that has been shown to be involved in the temporal orienting of attention, the ability to flexibly and voluntarily orient attention to moments in time.[12] More precisely, the functional connectivity between this region and a motor network (premotor and motor regions) as well as a sensory network (auditory and visual cortices) seems to fluctuate over time, notably with peaks of connectivity strength at strong beats. This possibly reflects a top-down attentional mechanism (highly coupled to the motor network) that modulates the metabolic activity in auditory and visual areas and influences event processing.[13]

Extending the DAT from music to speech

The DAT framework was first developed for musical material for both pitch and time dimensions, that is, listeners' expectations for what kind of pitch will come next and when in time it will occur. This attentional framework (temporal expectations) has been also applied for speech material, even though the periodicity (isochrony) in the speech signal is less pronounced than the periodicity in the musical signal.[14] Although quasi-isochronous beats are found across all music cultures (and allow motor synchronization), in conversational speech, and although rhythmic grouping certainly shapes speech perception, the degree of regularity is certainly weaker.[15] Nonetheless, when one is listening to speech, the temporal regularity of the alternating stressed and unstressed syllables would cause the listener's attention to time-lock (couple) to this temporal pattern going from one stress to the following. Interestingly, this effect goes beyond the physical salience of the phonemes and, rather, seems to rely on the fact that the perception of salient events, such as stressed syllables, generates expectancies concerning later events (position of the next stress).[16]

Thus, similarly to what has been suggested above in the musical domain, attention is directed to points at which stressed syllables are expected to occur. In a similar manner, as pitches are better processed when they occur at expected time points, syllables and words are better processed when they occur at expected time points. Temporal regularity and predictability of speech can enhance different aspects of speech processing, going from phoneme perception over lexical processing to syntax and semantic processing.[17–20]

On the basis of these findings, namely the effects of temporal regularity and predictability on both music and speech processing, we now present three possible ways of combining music and speech in different experimental designs. The aim of these designs is to see whether, and to what extent, music can entrain attentional processes and affect speech (and language) perception and production and possibly explain the potential underlying mechanisms. These designs differ with respect to their time scale, going from short over medium to longer time periods, and with respect to the role of the participant with respect to the music (active or passive listening). The hypothesis that musical structures might boost temporal processing that benefits linguistic processing even in an impaired language system fits with the conclusion of Thomson and Goswami[21] stating, "... there is value in the use of rhythmic interventions for children with both developmental dyslexia and SLI."

Rhythmic speech cuing

We recently investigated whether complex metrical rhythms corresponding to the prosodic structure of sentences can enhance phonological processing via rhythmic expectations. In this paradigm, participants listen to a metrical sequence immediately followed by a word or a sentence and perform a phoneme detection task. [illegible]s, the metrical sequence is a sort of cue to the temporal structure of the following speech, and we refer to this paradigm as rhythmic cuing, to distinguish it from rhythmic priming, which we describe in the next section. The cue's meter can either match or mismatch the prosody of the sentence with respect to both stress patterns and number of elements. We collected both behavioral and electrophysiological data using a phoneme detection task (e.g., "say whether the last syllable of the sentence contains the sound [a]").

Providing a matching rhythmic cue resulted in faster reaction times, thus revealing a cross-domain effect of the musical metrical structure on the phonological processing of speech. This effect was larger when participants received audiomotor training with the rhythmic sequences before the task. In this training, participants were asked to reproduce the rhythmic pattern several times. This possibly allowed them to internalize more finely the temporal structure of the cues. Electrophysiological data confirmed these behavioral effects, showing a mismatch-like negative component, possibly originating in the auditory associative cortices, clearly visible when the speech target did not match the metrical structure of the previous temporal sequence.[22,23]

Building on these findings on speech perception, we decided to study whether speech production may also benefit from rhythmic cuing, because this may have important implications about how rhythm can be used in speech therapies. More precisely, we studied whether metrical cuing has an effect on phonological production abilities in prelingually deaf children (wearing a hearing device). In our study, children listened to a rhythmical isochronous sequence (drum sounds) and had to reproduce it vocally (using two phonemes: ([ti] and [pa]). Then, they listened to a sentence and had to repeat it. The sentence either matched or mismatched the metrical structure of the rhythmical sequence (i.e., same number of syllables but with a different stress pattern). There was also a baseline condition wherein sentences were not preceded by a rhythmical sequence. Matching conditions resulted in a greater phonological accuracy of spoken sentences compared to baseline and mismatching conditions at several levels of phonological measurements (the production of vowels, consonants, syllables, and words), suggesting that rhythmic cuing can enhance phonological production. This facilitation may take place via an enhanced perception of the target sentence, similarly to the studies presented above. Nonetheless, on the basis of previous findings described above,[23] we suggest that both an enhanced entrainment of speech motor rhythms through rhythmic listening and a greater familiarity of speech motor rhythms through rhythmic training contribute to the greater accuracy in speech imitation.

Rhythmic priming of language processing

Another way of combining music and speech is to use the musical material as an auditory rhythmic stimulation to boost language processing, in particular language processing that requires temporal sequencing and segmentation (at local and/or global levels). In this case, in contrast to rhythmic cuing wherein the stimulation is short and mimics the temporal structure of the following sentence, the stimulation is typically longer and does not necessarily have a "precise" temporal relation with the following linguistic task.

Linguistic meter has been described as a good candidate to support segmentation,[24] and regular predictable presentation has been shown to influence syntax processing.[19,25] As successful metric processing allows for the prediction of when a subsequent element will occur, a metric pattern serves as a "framework" enabling listeners to sequence linguistic input and to build up syntactic hierarchies. Kotz *et al.*[26] have shown that metrical stimulation makes it possible to compensate for a sequencing deficit in sentence processing in patients with focal basal ganglia lesions, suggesting that metrical stimulation is likely to act as a therapeutic tool modulating sequencing capacities. The authors suggested a compensation of the basal ganglia impairment with the help of an overactivation in premotor areas. Kotz *et al.*[27] proposed that the basal ganglia (or more generally the medial pre-SMA–basal ganglia circuit) and the cerebellar–thalamic–pre-SMA pathway have important roles in the processing of timing in spoken sequences. They play a role in sequencing and segmentation of incoming information streams, in attention formation of sensory predictions, as well as in beat perception and syntax processing. When the contribution of the basal ganglia is impaired, nonlinguistic stimulation (via the metric prime) might stimulate the cerebellar–thalamic–pre-SMA pathway and boost the development of internal oscillators and their synchronization to the external (stimulus) oscillations.

These findings suggest the use of external oscillators as compensatory mechanisms in patients with syntactic integration deficits or, more generally, in sequencing and segmentation deficits. In a recent work,[28] we have extended this benefit of a metrical prime to syntax processing in children with developmental language disorders: children with SLI and children with dyslexia (and their age-matched and reading-age-matched control participants). Even though recent research has revealed that children with SLI and children with dyslexia have deficits in rhythm and meter processing,[21,29–32] we formed the hypothesis that these populations might benefit from the musical prime, as did the basal ganglia patients (for whom deficits in temporal processing have also been reported).[3]

In our study, we compared the influence of two rhythmic structures (played by two percussion instruments) on syntax processing: a regular prime and an irregular prime, for which meter extraction was easy and difficult, respectively. In the experimental paradigm, children listened for 30 seconds to the musical excerpt, and this music presentation was followed by a block of experimental trials of the language task requiring grammaticality judgments. Sentences (presented auditorily) were either syntactically correct or incorrect, and children indicated whether a given sentence was correct or not. Over the experimental session, blocks of the language task were preceded by either regular primes or irregular primes. The results showed an influence of the prime on the subsequent language task: children's performance in the grammaticality judgments was better after a regular prime than after an irregular prime.

In this first study we have compared the influence of regular and irregular musical primes to establish the potential effect of prior music on subsequent language processing. This comparison does not yet allow conclusions about compensatory benefits of the regular prime in comparison to children's performance without music. We have chosen this procedure as a first approach because the comparison of a regular prime with a no-music condition is inadequate for their unequal levels of arousal and the unknown temporal persistence (or carryover effects) of the regular prime. We have now started to introduce a baseline condition aiming to investigate whether the benefit observed for regular musical primes (in comparison to the irregular primes) actually represents a benefit in comparison to a normal/silent listening situation. The first results obtained with children with SLI showed better performance after the regular musical prime than after the baseline condition (here we used an environmental sound scene). These findings are encouraging for the use of musical primes to boost language processing, suggesting their potential use for rehabilitation purposes.

Along the same lines, we are now extending this research to reading performance, aiming to test whether the beneficial effect of a regular rhythmic prime extends to syllable segmentation in a reading task. Children were asked to read words and pseudowords. The items of both types of stimuli were constructed to differ in their syllabic complexity as instilled by sonority cues, which allowed us to manipulate the difficulty level of segmentation.[34,35] We tested dyslexic and SLI children and their matched controls by comparing regular and irregular contexts first.[34] Results showed some improvement for syllable segmentation in reading after regular primes. For the more difficult items (containing the ambiguous syllable boundaries), SLI children produced more correct syllable boundaries after regular than irregular primes. For SLI and dyslexic children, the quality of reading increased after the regular prime, for example, with reduced phoneme omissions (i.e., the entire stimulus was read; /vukti/ versus /vyki/ or /vyti/). This work now needs also to be completed with the addition of a neutral (baseline) context to further determine the beneficial effect of the regular prime.

Long-term rhythmic training

The third example of an experimental design assessing the links between musical rhythm and language processing is a long-term training of rhythmic skills. In contrast to the short-term effects described above, this type of design implies both an active involvement—with respect to training—and a long-term intervention, typically over several weeks, months, or, even better, years. In the case of clinical studies, this corresponds to randomized control trials, requiring a strict observance of several methodological issues. Although these studies are of utmost interest insofar as they speak of the causal role of music training on nonmusical abilities (e.g., language), they are rather difficult to carry out. This is why most literature on the effects of music training on language skills essentially relies on correlational or cross-sectional studies. However, more recently, various long-term approaches using musical training have been proposed, mainly confirming conclusions coming from cross-sectional studies comparing musicians and nonmusicians.[36]

Another difficulty of the long-term approach is linked to the choice of the content of musical activity. Indeed, most of the time a general music training is chosen, often barely defined and relying on all properties of a music activity: timbral, melodic, harmonic, rhythmic, emotional, social, and so on. Although this is done for the obvious reasons of maximizing the chances of success and to get close to a more realistic musical training, results cannot disentangle the contribution of each of these different musical features to speech processing. Thus, the ideal design should compare the effects of different types of music intervention, both with respect to effects on speech and language processing and to covariance of the different measures. In other terms, one should first show that rhythmic training has an impact on grammatical skills, for instance, and then also show that among other musical competences (e.g., harmonic, melodic skills) the changes in performance in rhythmic tasks are the best predictor of the changes in performance in language tasks.

We now briefly present an example of long-term rhythmic training on a population of children with developmental dyslexia. One explanation of the poor performance in rhythmic tasks described above is a deficit in processing the amplitude envelope and more precisely in processing rise time.[37] Rise times are critical in speech perception because they facilitate syllabic segmentation and prosodic processing. Poor auditory perception of slow temporal modulations may thus cause poor perception of speech rhythm and syllable stress.[38] Interestingly, phase locking between the speech envelope and low-frequency oscillations in the auditory cortex implements a mechanism for efficient sampling and segmentation of speech.[39]

Going back to the phase-coupling model described above with the DAT, one possibility would be that although a "normal" neural oscillatory activity will phase lock to speech modulation patterns,[40,41] in developmental dyslexia there may be a poor phase alignment between speech and neural activity.[42] We recently collected data from a highly selected sample of Italian children with developmental dyslexia to investigate, on one hand, the relation among musical temporal, phonological, and decoding skills and, on the other hand, the causal effects of music rhythmic training on phonological and reading abilities. Results clearly show both a larger improvement in several phonological and reading abilities compared to the control group (here trained in visual arts) and a similar developmental trajectory of rhythmic and phonological abilities.[43,44] This adds evidence to previous studies showing a potential benefit of music training to improve phonological abilities.[45–48]

Temporal scales and perspectives for rehabilitation

When we consider the use of music and rhythm to improve linguistic skills, it is important to keep in mind that several temporal scales come into play. These levels possibly rely on different neural circuitry and are affected to a certain extent in different language pathologies. Table 1 proposes an overview. This is not an exhaustive list of all possible temporal levels that may be relevant but is an overview to show the diversity and complexity of the processes involved and, possibly, to stimulate further research to better define these temporal levels and suggest new ones.

The shortest temporal scale (<3 ms) is important to ensure a high consistency in neural responses to sounds in the brain stem. A low brain-stem response consistency has been observed in poor readers,[49] and a high-response consistency is typically associated with proficient sensorimotor synchronization skills.[50] Next, we have a temporal scale (approximately 40 ms) that is important in perceiving consonantic contrasts that are known to be poorly perceived by children with developmental dyslexia,[51] whereas musician children discriminate similar consonants better than nonmusician children.[52] Q3

Table 1. Nonexhaustive overview of different levels of analyses involved in speech and language comprehension and an approximate corresponding temporal scale

Function	Scale	Effect of music training	Language disorders
Consistency of spectrotemporal analysis	< 3 ms	√	X
Consonantic contrasts	$\sim$40 ms	√	X
Amplitude modulation: speech rate and speech rhythm	50–500 ms	√	X
Word segmentation and prosodic boundaries	> 500 ms	√	X
Bayesian cognition and predictive coding	> 1 s	?	X

NOTE: : The two columns on the right indicate whether there is evidence that music training benefits this level of processing (√ indicates Yes) and whether this level may be impaired in individuals suffering language disorders (X indicates Yes, impaired).

We have described the next two levels concerning amplitude modulation, word segmentation, and prosodic boundaries (approximately from 50 ms to above 500 ms). These levels can be impaired in speech disorders[48] and are typically processed more efficiently by musicians than by nonmusicians.[53,54] The last level is on a rather long time scale, above 1 second. Prediction as well as cognition based on Bayesian inference are what allow readers to decode "Aoccdrnig to rscheearch at Cmabrigde Uinervtisy" without difficulties. Actually, readers are not able to refrain from reading the correct words and imagining the correct sounds. Although this level is also impaired in developmental dyslexia, we are not aware of any study testing whether musicians have an advantage compared to a nonmusician population.

Overall, one can predict that by improving these different levels of temporal processing via rhythmic stimulation, children with language disorders might also benefit to some extent and improve their language processing. This hypothesis, together with the rather encouraging set of findings presented above, can be integrated in the temporal sampling framework recently proposed by Goswami for dyslexia and by extension for SLI.[38] Together with the DAT, postulating internal oscillators guiding attention over time, Goswami suggests that an impaired rhythmic entrainment leads to difficulties in developing attention over time, engendering in turn deficits in syllabic segmentation and other sequential processes.[38] Goswami discusses the potential benefits of therapeutic interventions or educational practices based on rhythm and music (e.g., metrical poetry or singing nursery rhymes) as those might entrain the impaired oscillatory networks. In line with this framework, the data described above provide new grounds and motivations for further testing the benefit of rhythmic stimulation on language processing and its underlying mechanisms. The perspective of using music might also exploit the motivational advantages and pleasantness that musical material can provide in a rehabilitation setting beyond its stimulating effect for impaired temporal processing networks. Q4

Figure 1. Example of four different matching rhythmical primes preceding a spoken sentence. The participant sees a target vowel on the screen and hears a rhythm followed by a sentence (matching or mismatching). The task is to say whether the vowel is present or not in the last word of the sentence.

Conflicts of interest

The authors declare no conflicts of interest.

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Queries

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