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# Processing Rhythm in Speech and Music: Shared Mechanisms and Implications for Developmental Speech and Language Disorders

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***Objective:*** Music and speech are complex signals containing regularities in how they unfold in time. Similarities between music and speech/language in terms of their auditory features, rhythmic structure, and hierarchical structure have led to a large body of literature suggesting connections between the two domains. However, the precise underlying mechanisms behind this connection remain to be elucidated. ***Method:*** In this theoretical review article, we synthesize previous research and present a framework of potentially shared neural mechanisms for music and speech rhythm processing. We outline structural similarities of rhythmic signals in music and speech, synthesize prominent music and speech rhythm theories, discuss impaired timing in developmental speech and language disorders, and discuss music rhythm training as an additional, potentially effective therapeutic tool to enhance speech/language processing in these disorders. ***Results:*** We propose the *processing rhythm in speech and music* (PRISM) framework, which outlines three underlying mechanisms that appear to be shared across music and speech/language processing: Precise auditory processing, synchronization/entrainment of neural oscillations to external stimuli, and sensorimotor coupling. The goal of this framework is to inform directions for future research that integrate cognitive and biological evidence for relationships between rhythm processing in music and speech. ***Conclusion:*** The current framework can be used as a basis to investigate potential links between observed timing deficits in developmental disorders, impairments in the proposed mechanisms, and pathology-specific deficits which can be targeted in treatment and training supporting speech therapy outcomes. On these grounds, we propose future research directions and discuss implications of our framework.



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**Key Points**
***Question:*** The current article investigates whether shared mechanisms underlying rhythm processing in music and speech can be used to better understand speech and language processing in developmental disorders and to develop programs for treatment. ***Findings:*** We propose a new framework suggesting three common mechanisms underlying music and speech rhythm processing: Precise auditory timing, synchronization/entrainment of neural oscillations to external rhythmic stimuli, and sensorimotor coupling. ***Importance:*** The identification of these underlying mechanisms allows for a more targeted approach to future research investigating music and speech rhythm processing in typically developing children/adults and those with developmental speech and language impairments. ***Next Steps:*** We outline a number of avenues for future research, including the need to incorporate multiple sources of evidence for the investigation of potential links between music and speech rhythm processing, and different approaches to apply the current framework to speech and language disorders.

*Keywords:* music, speech, rhythm, language, developmental disorders

*Supplemental materials:* https://doi.org/10.1037/neu0000766.supp



Music and language are both structured means of communication that exhibit connections across multiple components, including acoustic parameters, hierarchical syntactic structure, and rhythm. Research has investigated the neural mechanisms supporting various aspects of music perception and production, speech perception and production, and some processes that appear to be shared between both domains. In the current theoretical review, we synthesize a number of independently developed theories and different sources of evidence that contain recurring and common elements. Our aim is to create a parsimonious framework based on three common underlying neural mechanisms supporting music and speech rhythm processing: The *processing rhythm in speech and music (PRISM)* framework. This framework aims to provide a solid foundation for both theoretical/empirical and applied future research, with implications for developmental speech and language disorders.

First, we define rhythm in music and speech. Second, we focus on the three mechanisms suggested to be common to rhythm processing as it occurs for music and speech: Precise auditory processing, synchronization/entrainment of neural oscillations to external rhythmic stimuli, and sensorimotor coupling. Third, we propose predictions and future directions derived from the PRISM framework. Within this section, we provide evidence for timing deficits across different developmental speech and language disorders and provide suggestions on how to apply the PRISM framework in both empirical and applied research. Finally, we provide a larger context and outlook for how to integrate different sources of evidence to better understand rhythm processing in music and speech. Although these suggested underlying mechanisms exist across different theories and within different domains, to our knowledge, they have not before been brought together in a framework to explain rhythmic processing in music and speech. The acoustic, sensory, and cognitive links between music and speech rhythm on the one hand, and developmental speech and language disorders and timing impairments on the other hand, suggest a promising research area that can be guided by the current evidence-based framework.

## Rhythm in Music and Speech

Rhythm is a fundamental element of both music and speech and is universally present across different cultures and languages (Brown & Jordania, 2013; Ding et al., 2017; Kotz et al., 2018; Savage et al., 2015). *Rhythm* refers to the temporal patterns created by the onsets and durations of acoustic events in an incoming sequence (London, 2012; McAuley, 2010). Fulfilling this definition, both music and speech are auditory signals that unfold in the temporal domain and contain periodic (and quasi-periodic) information structured by a number of similar acoustic cues, including duration (timing), frequency (pitch), amplitude/intensity (loudness), and timbre (instrument/voice quality) (Allen et al., 2017; Besson et al., 2011). These acoustic cues and the way they are structured in time form the basis of the bottom-up percept of auditory stimulus rhythm in both domains, which then has implications for higher-level processes of prediction and structure building.

Music is often perceived as having a clear, isochronous beat or pulse, defined as a salient point in time when an event is expected to occur (i.e., where listeners might naturally clap their hands, see Repp & Su, 2013). Although speech does not have such isochrony (see the unsuccessful history of the search for speech isochrony, Cummins, 2012; Knowles, 1974; Patel, 2008), speech rhythm emerges through a number of interacting lexical and prosodic factors. We will first discuss this difference in regularity and then the hierarchical nature of music and speech. This section thus focuses on acoustic aspects of music and speech and how they influence the sensory and cognitive processing of the auditory signals, which lay the foundation for musicality and speech/language skills (Honing, 2018). Note that we will primarily be focusing on Western concepts of music rhythm for the current discussion, as most music cognition research focuses on the Western tonal structure, but see Brown and Jordania (2013); Savage et al. (2015); and Stevens (2012) for cross-cultural perspectives aiming to confirm similar underlying perceptual and cognitive processes.

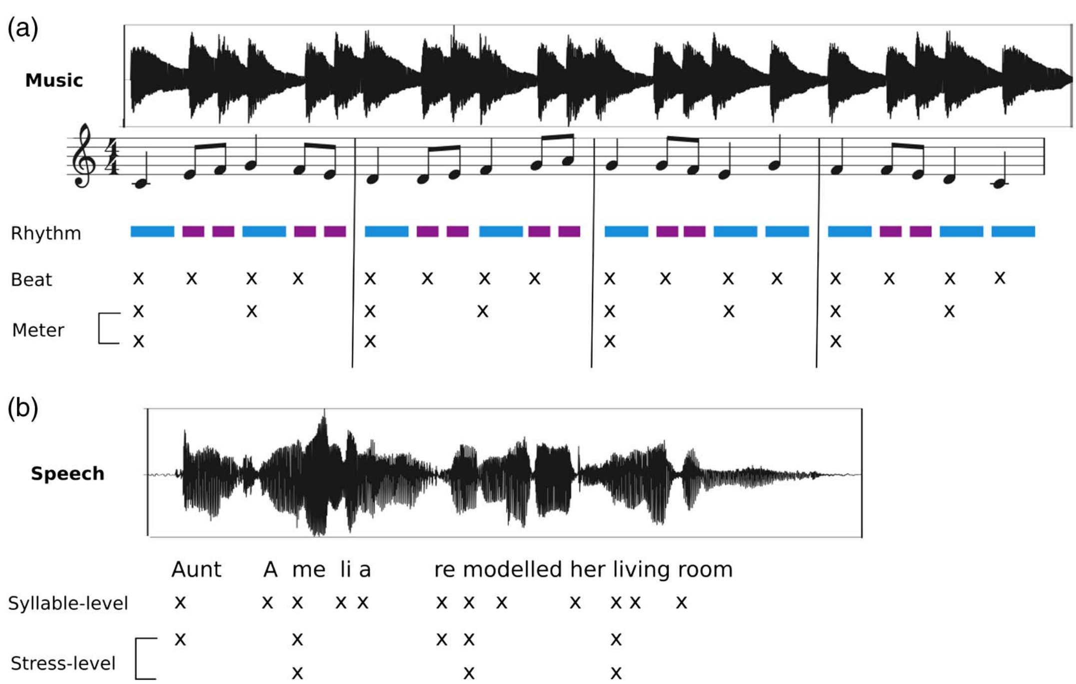
One key distinction between music rhythm and speech rhythm is the regularity by which the acoustic events are patterned in time (see Figure 1). Music rhythm largely consists of regular, recurring patterns that allow for quick synchronization and strong predictions of upcoming events at multiple embedded time levels (Huron, 2008; Jones, 2016; Patel & Morgan, 2017). Importantly, this strong predictability facilitates synchronization both to the music and among individuals when listening and performing music. The strong activation in motor areas when just *listening* to music (Grahn & Brett, 2007), and the urge to dance when a rhythm is played (Levitin et al., 2018) suggest strong connections between music rhythm and movement, perhaps driven by the perception–production or auditory–motor loop (Lezama-Espinosa & Hernandez-Montiel, 2020; Zatorre et al., 2007), and the role of music in social bonding and group cohesion (Bowling et al., 2013; Kotz et al., 2018; Savage et al., 2015, 2020).

In contrast to music, speech rhythm is less periodic and more variable, possibly related to the referential nature of speech (with its lexical properties) that does not allow for a strict rhythmic pulse. However, speech rhythm is nevertheless predictable (i.e., the prediction of syllable stress patterns; Beier & Ferreira, 2018), and the rhythm that emerges from speech improves perception and segmentation of the speech signal by providing cues to word boundaries (Cutler, 1994; Cutler & Butterfield, 1992; Cutler & Norris, 1988; Echols et al., 1997; Spinelli et al., 2010), enhancing communication between individuals (Hawkins, 2014; Kotz et al., 2018), and facilitating turn-taking in conversations (Garrod & Pickering, 2015; Wilson & Wilson, 2005). The perception–production loop is also important for speech, with motor areas activated in speech perception (Wilson et al., 2004). These different features and mechanisms should apply independently of language types. The different stress patterns and syllable types evident in different languages (perhaps also influencing syllable prominence patterns) resulted in the traditional separation of stress- and syllable-timed languages (i.e., see Ramus et al., 1999, for one of the initial metrics used to quantify stress- vs. syllable-timing and Patel, 2008, for a discussion). However, this distinction is less clear-cut than previously claimed, as suggested by the lack of supporting empirical data and inconsistencies regarding the metrics used to achieve this classification (Arvaniti, 2009), which ultimately may be more complex. Therefore, it has been suggested that speech rhythm should be discussed in relation to patterns of prominence, grouping, and lexical stress, which can also be more readily related to music (Arvaniti, 2009; Beier & Ferreira, 2018).

Though music and speech rhythm diverge in relation to regularity (periodic, nonperiodic) and individual elements (notes, chords, musical phrases, vs. syllables, words, sentences), they both have similar acoustic features, create top-down cognitive predictions of upcoming elements, and are organized in hierarchical structures (i.e., contain meter, where events are organized temporally along multiple time scales, McAuley, 2010), see Figure 1. In addition, music and speech can both generate strong syntactic predictions, with additional lexical and semantic predictions for speech (see also semantics in music; Koelsch, 2009, 2011). Patterning of strong and weak events allows for perception at multiple levels within a larger hierarchical framework, and the creation of top-down expectations. For music, patterns of strong and weak beats obtained by changes in acoustic and/or temporal parameters of the events (Lerdahl & Jackendoff, 1983; London, 2012; Povel & Essens, 1985) create this hierarchical structure, also referred to as metric hierarchy (see also evidence for rhythmic hierarchy in non-Western music with more complex metrical patterns; Magill & Pressing, 1997; Stevens, 2012). For speech, interacting lexical, prosodic, and accentual elements (Beier & Ferreira, 2018; Patel, 2008; Wagner & Watson, 2010) create a rhythmic hierarchy that is reflected in patterns of prominence, grouping, and lexical stress (Arvaniti, 2009; Beier & Ferreira, 2018). In both domains, rhythmic stress

**Figure 1**

*Representations of (a) Music (a Simple Melody) and (b) Speech (a Simple Sentence) Showing the Acoustic Waveforms, the Melody or Sentence Represented Within the Waveform, and the Hierarchical Structure for Each Element*




*Note*. For (a) the duration differences of each note are outlined in the rhythm row, the perceived beat is marked with an *x* in the beat row, and the higher-level metric structure of the melody is marked with *x*'s in the following two rows. For (b) each syllable is marked on the syllable-level row, and the higher-level structure of stressed syllables is marked on the following rows. See the online article for the color version of this figure.

patterns help to direct attention to more prominent events (music: Bharucha & Pryor, 1986; Jones et al., 1982; Palmer & Krumhansl, 1990; speech: Cutler & Foss, 1977; Gow & Gordon, 1993; Pitt & Samuel, 1990), engaging top-down temporal predictions. Although it is not entirely clear how top-down knowledge influences the perception of speech rhythm (with language background being one of the potential influences; Zhang & Francis, 2010), natural speech rhythm enhances comprehension, as altering speech rhythm through time-compression (Adank & Janse, 2009; Ghitza, 2012; Ghitza & Greenberg, 2009), or manipulating the stress structure (Bohn et al., 2013; Rothermich et al., 2012) lowers intelligibility and results in a cognitive processing cost, respectively. Music and speech therefore share similarities in terms of the acoustic signal itself, the sensory processing of the acoustic signal, and cognitive processing parallels in relation to prediction and hierarchical structure, which contribute to connections between musical and linguistic *skills* or *behavior*, and which are the focus of the present proposal.

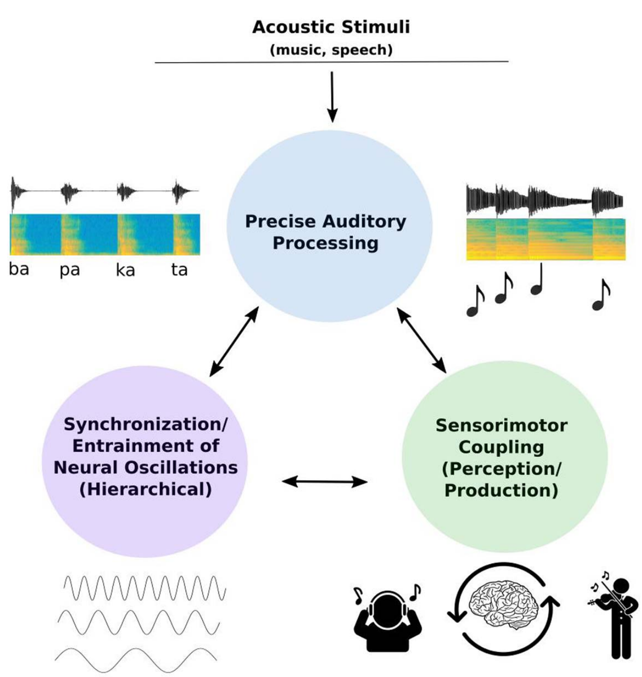
## Shared Neural Mechanisms for Rhythmic Processing

The commonalities between music and speech regarding acoustic elements, hierarchical organization, and the role of rhythm for perception and production suggest the involvement of shared neural mechanisms. Several theoretical frameworks (outlined below) have aimed to further understand and characterize various underlying neural mechanisms supporting *rhythmic* processing in music, speech, or music and speech together. However, most of these frameworks are limited in that they focus only on one or two elements or mechanisms supporting rhythmic processing, and often focus on one domain or from one perspective only. It is critical for future research to be directed by a more global understanding of rhythm processing that underlies both music and speech rhythm, with implications for connections between the two domains. We propose here the PRISM framework (see Figure 2): A parsimonious framework of three central mechanisms that emerge separately across theories from different research fields, and which appear critical for the processing of rhythm in music and speech. Our goal is to combine these mechanisms into an overarching theoretical framework that can inform and drive (a) fundamental research investigating the mechanisms underlying rhythm processing and (b) applied research investigating how music rhythm training can be mobilized in clinical-translational settings to support speech rhythm and language processing in normal and impaired populations. We propose that: (a) precise, fine-grained auditory processing; (b) synchronization/entrainment of neural oscillations to external rhythmic stimuli; and (c) sensorimotor coupling; are critical elements underlying speech and music rhythm processing (see Figure 2). The PRISM framework will be used as a basis to propose directions for future training on each of these mechanisms, with the goal to benefit speech and language processing.

These three underlying mechanisms have emerged from a critical reading and synthesis of elements discussed in previously proposed approaches. Specifically, we have drawn on the sound envelope processing and synchronization and entrainment to pulse hypothesis (SEP; Fujii & Wan, 2014), the precise auditory timing hypothesis (PATH; Tierney & Kraus, 2014), and the temporal sampling framework for developmental dyslexia (TSF; Goswami, 2011), which focus

**Figure 2**

*The Processing Rhythm in Speech and Music (PRISM) Framework Proposes Three Common Underlying Mechanisms for Music and Speech Processing Observed Across Different Theories: Precise Auditory Processing; Synchronization/Entrainment of Neural Oscillations to External Rhythmic Stimuli; and Sensorimotor Coupling*




*Note*. See the online article for the color version of this figure.

on different yet complementary approaches to understanding shared elements of music and speech rhythm. The PRISM framework is also informed by the broader Overlap, Precision, Emotion, Repetition, and Attention (OPERA) hypothesis, which suggests that these five conditions drive the influence of music training on speech processing (Patel, 2011, 2014). The three mechanisms proposed here as central are also informed by sensorimotor theories (e.g., action simulation for auditory prediction, ASAP, Patel & Iversen, 2014; active sensing, Morillon et al., 2015; Schroeder et al., 2010), dynamic attending theory; DAT (Jones, 1976, 2016, 2018; Large & Jones, 1999), and predictive coding (Friston, 2005, 2010). Drawing on this research, the following section will outline the three proposed mechanisms (precise auditory processing, synchronization/entrainment of neural oscillations to external rhythmic stimuli, and sensorimotor coupling) that appear integral to music and speech rhythm processing in more detail, as well as theoretical and empirical evidence that support them. Note that prediction as well as emotion are considered to be related to all mechanisms. The PRISM framework is both novel and parsimonious as it explicitly combines these three underlying mechanisms as directly applicable to the processing of music and speech rhythm. Bringing together these underlying mechanisms can provide the theoretical groundwork to inform further empirical and applied research investigating links between impaired timing in speech and language disorders, with the goal to better understand impaired timing in these disorders, and to inform applied research for music-training interventions.

While the three mechanisms proposed in the PRISM framework are deeply intertwined, each plays a distinct role within music and speech rhythm processing. Precise auditory processing is crucial for the discrimination of small timing deviations and accurate auditory perception, which lay the foundation for auditory processing. The synchronization and entrainment of neural oscillations to external stimuli allows for prediction of upcoming elements and the tracking of hierarchical structure at multiple levels. Sensorimotor coupling allows for a tight connection between perception and production in the brain, as well as links to the motor system, which also benefits timing and prediction mechanisms. However, each mechanism can also be involved in the functioning of the other mechanisms, as indicated in the bidirectional arrows in Figure 2. Throughout the following section, we will outline the contributions of these three mechanisms, signpost some important connections between them, and outline how they fit into the broader body of research on music and speech processing.

## Precise Auditory Processing

The capacity of the auditory system for precise auditory processing is unparalleled and is fundamental to music and speech rhythm perception. Precise or *fine-grained* auditory processing refers to the ability to discriminate very small deviations or changes in timing (i.e., on the millisecond level), pitch, and timbre (Kraus & Chandrasekaran, 2010). This ability is critical for accurate perception of acoustic events, such as discriminating between /ba/ and /pa/ in speech, and processing subtle timing deviations as well as synchronizing different instrumental parts in music perception and production (Patel, 2011). The auditory system also appears to be sensitive to timing deviations below the threshold of conscious change detection: Evidence suggests that participants can alter synchronization behavior to isochronous sequences with deviations as little as 3 ms (Madison & Merker, 2004), likely based on tight connections between the auditory and motor areas of the brain (see Repp, 2000; Tierney & Kraus, 2014). The capacity to track temporal information at different temporal integration windows (including precise processing of information, such as formant transitions to discriminate for instance /pa/ and /ta/, i.e., discriminations of 20–40 ms) is suggested to be supported by neural oscillations (e.g., in delta($\Delta$), theta($\theta$), and gamma ($\gamma$) frequency ranges; Giraud & Poeppel, 2012; Poeppel, 2003). Precise auditory processing is therefore also strongly intertwined with sensorimotor coupling and synchronization/entrainment of neural oscillations to external rhythmic stimuli.

Precise auditory processing has been proposed to be a mechanism underlying potential transfer between music and speech rhythm processing capacities (Fujii & Wan, 2014; Kraus & Chandrasekaran, 2010; Tierney & Kraus, 2014). In line with the OPERA hypothesis (Patel, 2011, 2012), it has been suggested that music training can enhance speech processing, based on *overlapping* brain circuits that process the acoustic signal, and the more *precise* timing necessary to process music rhythm compared to speech rhythm (Patel, 2011). Precise auditory processing is outlined also in the SEP and PATH hypotheses: Fujii and Wan (2014) suggest that the processing of sound envelopes in music requires enhanced temporal precision, which has carry-over effects to the processing of the less regular speech envelope and the neural encoding of speech sound. In PATH, Tierney and Kraus (2014) suggest that (a) the millisecond-level precision required for entrainment to music can sharpen brain networks responsible for speech processing, and (b) phonological processing and auditory–motor entrainment rely on precise timing in the auditory system to generate accurate predictions. The role of auditory–motor entrainment in generating precise auditory predictions is also in line with hypotheses of sensorimotor theories discussed below.

Supporting evidence has been provided by research showing that music training can actively enhance precise auditory processing, which may benefit speech processing across the lifespan (Kraus & Chandrasekaran, 2010). In addition to correlational studies (see Supplemental Table 1), longitudinal training studies have shown benefits of music rhythm training on precise temporal processing of the speech signal. For 9-month-old infants, 12 sessions of music training emphasizing rhythm (compared to a control group who engaged in nonmusical play activities) enhanced the neural response (the mismatch negativity, MMN)[1] to violations of temporal structure in both music and speech, suggesting that music rhythm training can improve speech rhythm processing (Zhao & Kuhl, 2016). Further, compared to a group who received painting training, 8-year-old children who received music training showed an increase in speech segmentation skills after 1 and 2 years (François et al., 2013). This music-training group also showed an enhanced MMN to syllable duration and vowel onset time deviants (but not frequency deviants) after 1 year of training (Chobert et al., 2014). The participants were pseudorandomly assigned to ensure matched groups in terms of age, school level, sex, socioeconomic status, and neuropsychological test scores, and did not differ on the measures of interest before the training, suggesting that the enhanced fine-grained speech processing can be attributed to effects from the music training.

Precise auditory processing has been also suggested to be critical for encoding of the speech envelope. In the TSF, Goswami (2011) suggests that impaired rise-time perception of syllables

[1] The MMN is an evoked neural response which is classically elicited within an oddball paradigm (i.e., when a sequence of similar events are interspersed with occasional deviant events), or when a unexpected event occurs (Garrido et al., 2009).

(i.e., occurring every ~200 ms or every ~500 ms for accented syllables) can affect the accurate encoding of the speech envelope, potentially resulting in deficits in phonological processing, segmentation, and phonological awareness, which in turn can impact reading skills in developmental dyslexia (Di Liberto et al., 2018; Goswami, 2011, 2018; Goswami et al., 2002, 2010). The TSF and related research suggest that the regularity of music rhythm could sharpen the precision of auditory processing and entrained neural oscillations, which could enhance phonological skills by improving the neural tracking of the speech envelope (Flaugnacco et al., 2015; Goswami, 2012). Compared to control groups (with sports training or no-training), music rhythm training, which was experimentally implemented over periods covering 14 weeks to 4 months, has been shown to enhance phonological processing in typically developing children, providing support for this hypothesis (Degé & Schwarzer, 2011, 5–6 year olds; Gromko, 2005, kindergarten; Patscheke et al., 2016, 4–6 year olds). Numerous positive correlations between rhythm production/perception skills and phonological awareness have also been reported for children (see Supplemental Table 1). Music and speech rhythm processing therefore builds on precise auditory timing, which is also linked to both synchronization and entrainment of neural oscillations to external stimuli and sensorimotor coupling (e.g., Morillon & Baillet, 2017; Peelle & Davis, 2012; ten Oever & Sack, 2015).

## Synchronization and Entrainment of Neural Oscillations to External Rhythmic Stimuli

Neural oscillations are regularly recurring inhibitory and excitatory patterns of electrical activity produced by neurons (Buzsáki, 2019; Buzsáki & Draguhn, 2004). They are ubiquitous throughout the brain (Buzsáki, 2006), and have been shown to play a central role in music and speech processing (Jones, 2018). Neural oscillations track auditory rhythms, and are suggested to underlie the perception of music (Fujioka et al., 2012; Nozaradan et al., 2011, 2012, 2015) and speech (Giraud & Poeppel, 2012; Kösem et al., 2018; Kösem & van Wassenhove, 2017), and to function similarly across the two domains (Harding et al., 2019). Neural oscillations have been linked to temporal attention (Jones, 2018), prediction (Arnal & Giraud, 2012), entrainment (Calderone et al., 2014), hierarchical processing (Jones, 2016; Poeppel & Assaneo, 2020), and communication between brain regions (i.e., auditory and motor cortices, Assaneo & Poeppel, 2018), which are all elements integral to music and speech processing. They have also been linked to precise auditory processing (Goswami, 2011; Poeppel, 2003) and sensorimotor coupling (Morillon & Baillet, 2017; van Wijk et al., 2012; Yang et al., 2018). Neural oscillations have been observed at several different frequency rates (Buzsáki & Draguhn, 2004), and can be hierarchically coupled, supporting the processing and integration of information at various embedded frequencies (Jones, 2016). Neural oscillations are also suggested to be involved in the generation and signaling of predictions and prediction errors (Arnal & Giraud, 2012; Chao et al., 2018; see also Buzsáki, 2019). Neural oscillations therefore appear to be a mechanism underlying predictive processing, temporal attention, and the tracking of external rhythmic stimuli, and could underlie the efficacy of music-based rhythm training for speech processing. Here, we will focus primarily on the role of neural oscillations in the synchronization and entrainment to external rhythmic stimuli.

The crucial role of neural oscillations in temporal attention and predictive processing, as well as applications to music and speech processing, is outlined clearly in the DAT proposed by Jones (1976, 2018). The central thesis of DAT is that endogenous neural oscillations entrain in phase to external rhythmic (or quasi-rhythmic) signals, which allow for the direction of temporal attention toward predicted points in time and enhanced predictive processing. Behavioral research has supported this theory with data on perception, learning, and memory. For example, perceptual judgments (and memory; Hickey et al., 2020) are facilitated for events occurring at expected points in time, in line with the hypothesis that neural oscillations entrain and direct attention to these moments for both auditory (Barnes & Jones, 2000; Jones et al., 2002, 2006; Large & Jones, 1999; McAuley & Kidd, 1998), and visual (Bolger et al., 2013; Escoffier et al., 2010) stimuli (see also Henry & Herrmann, 2014, for a review and link between behavioral and electrophysiological research).

One benefit of music is that it is highly rhythmic and predictable, thus defining an ideal stimulus to entrain neural oscillations. Neural oscillations entrained by music rhythm have been shown to persist and influence subsequent language processing. For example, short rhythmic cues matched to the syllabic structure of a subsequent sentence enhance phoneme detection (Cason et al., 2015; Cason & Schön, 2012) and the neural response (Falk et al., 2017) to subsequent sentences compared to nonmatching or temporally irregular cues. Though the effect of these shorter rhythmic cues may possibly be explained by auditory short-term memory of the same matching pattern, similar effects have been found with longer (~30 s) rhythmic primes that persist over six subsequent naturally pronounced sentences. Regular rhythmic primes facilitate grammatical judgments of orally presented sentences compared to irregular rhythmic primes for English (Chern et al., 2018), French (e.g., Canette et al., 2020; Fiveash, Bedoin, et al., 2020; Przybylski et al., 2013), and Hungarian (Ladányi, Lukács, & Gervain, 2020) children. These findings suggest that music rhythm can entrain temporal attentional cycles, which can persist after the music has ended and influence subsequent language processing, or even simple detection of events (Hickok et al., 2015). This evidence suggests that the synchronization/entrainment of neural oscillations can be targeted as a mechanism to extend the benefits of the regular music signal to the less regular speech signal.

The regularity of music rhythm is also beneficial for enhancing prediction and minimizing prediction error in line with predictive coding and predictive timing approaches (Arnal & Giraud, 2012; Friston, 2005, 2010). Predictive coding (i.e., predicting *what* will occur) and predictive timing (i.e., predicting *when* an event will occur) are based on the hypothesis that the brain constantly generates predictions about upcoming events based on incoming sensory evidence, with the goal to minimize prediction error (see also Friston & Kiebel, 2009; Jones, 2018; Jones & Boltz, 1989). If the sensory evidence does not match the prediction, this prediction error is sent up the cortical hierarchy, and subsequent predictions are updated. Predictive coding/timing is supported by both forward (i.e., bottom-up) and backward (i.e., top-down) processes to signal predictions and prediction errors based on sensory information. Importantly, neural oscillations have been suggested to support predictive coding (Arnal & Giraud, 2012; Chao et al., 2018), and prediction appears to work similarly across different hierarchically organized domains (Siman-Tov et al., 2019). Links between predictive neural networks and networks involved in rhythmic entrainment (i.e., Levitin et al., 2018; Merchant et al., 2015), as well as fluctuations in attention and entrainment as outlined in the DAT (Jones, 1976, 2018) have also been proposed (Siman-Tov et al., 2019). The strongly rhythmic and predictable nature of music could therefore be used to train domain-general predictive networks associated with predictions and prediction errors and to enhance predictive precision in speech processing. Along these lines, research has shown that sung sentences result in stronger cerebro-acoustic phase coherence compared to spoken sentences in difficult listening conditions (Vanden Bosch der Nederlanden et al., 2020), suggesting an added benefit of musical attributes to the processing of the speech signal.

The entrainment of neural oscillations is also implicated in representing the different hierarchical levels of music and speech rhythm. The DAT suggests that neural oscillations entrain at multiple hierarchical levels to external regularities, resulting in *nested* oscillations that track multiple levels of hierarchical structure simultaneously and provide benefits of metric binding (Jones, 1976, 2016). Indeed, different beat- and meter-related frequencies have been observed in the neural response of participants listening to music (Fiveash, Schön, et al., 2020; Nozaradan et al., 2012) as well as in response to an imagined meter that was not present in the acoustic stimulus (Nozaradan et al., 2011; see also Nozaradan, 2014; Nozaradan et al., 2012, 2015). For speech, phrasal, syllabic, and phonemic processing (i.e., covering time scales ranging from ~300–1,000 ms, to 125–250 ms, to ~30–40 ms) are suggested to be represented by coupled oscillations in the $\Delta$ (1–3 Hz), $\theta$ (4–8 Hz), and low $\gamma$ (25–35 Hz) frequency bands, respectively (Giraud & Poeppel, 2012, see also Ghitza, 2011 for slightly different timescales). Neural oscillations have been observed at these different levels not only with isochronous (Ding et al., 2016), but also with natural (Keitel et al., 2018) speech rhythms. Further, Ding et al. (2016) showed that higher-level (phrasal and sentence level) neural oscillations were only observed when participants could comprehend the language they were listening to, suggesting strong effects of top-down processing. Similarly, in music, behavioral (Large et al., 2015) and electrophysiological (Tal et al., 2017) evidence shows that participants both perceive and represent in the brain the underlying pulse (or beat) that is not present in the acoustic signal of the rhythm, suggesting top-down processing of hierarchical structure driven by neural oscillations.

Observing neural oscillations at hierarchical levels not physically present in the stimulus is particularly pertinent to the discussion of whether neural oscillations represent the entrainment of already-present endogenous oscillations to an external stimulus (*entrainment in the narrow sense*, Obleser & Kayser, 2019), or whether they only represent evoked neural responses to the acoustic (rhythmic) properties of the external stimulus (see Haegens, 2020; Haegens & Zion Golumbic, 2018; and Zoefel et al., 2018, for discussion). This distinction has implications for the active role of neural oscillations in the prediction of upcoming events via the entrainment of self-sustaining endogenous oscillations (see also links with predictive coding, Friston, 2018; Giraud & Arnal, 2018; Hovsepyan et al., 2018; Rao & Ballard, 1999). Despite an ongoing debate, accumulating evidence suggests that observed neural oscillations cannot be reduced to evoked responses, but include also the entrainment of neural oscillations with functional significance (e.g., Doelling et al., 2019; van Bree et al., 2021). The recruitment of endogenous neural oscillations for rhythmic processing suggests that entrainment to an external stimulus is an active process involving temporal attention and prediction, rather than a passive response to an external stimulus. The regular rhythmic structure and temporal precision of music makes it an ideal stimulus for enhancing neural entrainment and precise processing, with potential benefits for the speech signal.

## Sensorimotor Coupling via Cross-Region Neural Connectivity

Sensorimotor (or auditory–motor) coupling refers to the connection between the auditory and motor cortices and is a central underlying mechanism for the perception and production of music and speech rhythm. Research has shown that just *listening* to music/rhythmic patterns (Chen et al., 2008; Fujioka et al., 2012; Gordon et al., 2018; Grahn & Brett, 2007; Stephan et al., 2018) or speech (Glanz Iljina et al., 2018; Möttönen et al., 2013; Wilson et al., 2004) activates areas within the motor cortex (largely the supplementary motor area (SMA), pre-SMA, and premotor cortex), suggesting a tight coupling between perception and production in each domain. For music, this sensorimotor link is evident with the urge to move to music (Janata et al., 2012), and moving with a rhythm enhances the subsequent perception of that rhythm (Chemin et al., 2014; Manning & Schutz, 2013). Sensorimotor coupling appears crucial to the perception and production of speech, with the motor system implicated also in speech perception, and the auditory system implicated also in speech production (Guenther & Hickok, 2015; Hickok et al., 2011). Speech production inherently involves movement, and speech perception partly utilizes similar networks in the brain (Fujii & Wan, 2014; Kotz & Schwartze, 2010). There appears to be specific synchronization between auditory and motor cortices at the syllable rate (4.5 Hz), suggesting the significance of the motor cortex for speech processing (Assaneo & Poeppel, 2018). Further, the sensorimotor connection plays a central role in the development of speech in infants (Bruderer et al., 2015). Recent evidence has also shown that participants who were classified as *high synchronizers* in a spontaneous synchronization of speech test differ from *low synchronizers* in the white matter pathways that connect frontal and auditory regions, suggesting a connection between auditory–motor coupling and neural synchronization (Assaneo et al., 2019). Importantly, this connection was also linked to enhanced word learning for high synchronizers compared to low synchronizers, suggesting implications for language learning. Further, speech perception has been shown to be enhanced by rhythmic speech production, but only for high synchronizers, suggesting the importance of individual differences in the connection between auditory and motor cortices (Assaneo et al., 2021).

The involvement of the motor system in sensorimotor coupling benefits the generation of precise sensory predictions for music and speech (Grahn & Rowe, 2013; Kotz & Schwartze, 2010; Large et al., 2015; Palva & Palva, 2018; Schubotz, 2007; Zatorre et al., 2007). Though the exact process by which this occurs is not fully known yet, one theory focusing on musical beat perception suggests that motor regions (including the premotor cortex, the SMA, pre-SMA, and the putamen) receive input from the auditory cortex, use this input for motor planning (even in the absence of movement), and then send timing predictions based on motor planning back to the auditory cortex (ASAP hypothesis, Patel & Iversen, 2014; see

Cannon & Patel, 2021, for a neurophysiological update on the ASAP hypothesis; see also Large et al., 2015; Ross et al., 2016). Similarly, the *active sensing* framework posits that neural oscillations are generated by the motor system and influence predictive timing and coding (Morillon et al., 2015; Schroeder et al., 2010). Active sensing is applicable to both speech and music, and suggests a role of neural oscillations in the communication between regions, and the amplification of sensory input arriving at predicted times (Morillon & Baillet, 2017; Morillon et al., 2015; Schroeder et al., 2008; Schroeder & Lakatos, 2009). The strong involvement of auditory and cortical motor areas for both speech and music processing points to the contribution of sensorimotor coupling for the processing of temporal regularities.

Findings suggesting shared sensorimotor mechanisms for music and speech materials lead to the prediction that training focusing on rhythm processing and in particular, entrainment to rhythm would strengthen the connection between auditory and motor cortices. This training could therefore be beneficial to both music and speech processing, particularly in relation to temporal attention and prediction. Entrainment satisfies all of the OPERA conditions (Patel, 2011, 2012), and has thus been suggested as an underlying plasticity mechanism behind training transfer from music to speech (PATH; Tierney & Kraus, 2014). The temporal regularity of music has also been suggested to enhance sensorimotor coupling also involved in the perception and production of speech (SEP, Fujii & Wan, 2014). In support of music enhancing sensorimotor coupling, a recent study has shown that just 24 weeks of piano training enhances functional connectivity between auditory and sensorimotor regions compared to a control group without training (Li et al., 2018; see also Hyde et al., 2009). It therefore appears likely that neural oscillations in the motor cortex and auditory cortex align to enhance perception (Bowers et al., 2014; Fujioka et al., 2012; Morillon et al., 2015), and that this connection can be trained.

## Predictions and Future Directions of the PRISM Framework

The PRISM framework brings together evidence from multiple research fields, focusing on separate aspects of music and speech rhythm. While previous research has focused on individual elements separately or in subsets, the PRISM framework provides a global, parsimonious combination of the underlying mechanisms that support rhythm processing in music and speech. One of the aims of this framework is to direct future research investigating the connections between music and speech rhythm processing, and to inform the development of specific music rhythm interventions and training that could be particularly pertinent to the treatment of developmental speech and language disorders. We propose that a better understanding of the contributions and connections between precise auditory processing, synchronization/entrainment of neural oscillations to external rhythmic stimuli, and sensorimotor coupling will provide a valuable perspective for future rhythm studies at the intersection between speech and music. We further suggest that these three underlying mechanisms support the connections observed between music rhythm and speech rhythm skills and should be targeted directly in future research on developmental speech and language disorders. Based on the neuroplasticity of the brain (Patel, 2011), training of the three suggested mechanisms should enhance precision of and connections between cortical and subcortical temporal processing networks, including the basal ganglia, auditory and motor cortices, and fronto-temporal connections, which serve both speech and music processing (Kotz & Schwartze, 2010; Rajendran et al., 2018).

The predictions of the current framework are that (a) deficits in one or more of the proposed underlying mechanisms should be related to deficits in both speech/language and music processing, (b) different expressions of speech/language difficulties in different disorders should be related to specific impairments in one (or more) of the underlying mechanisms proposed, and (c) targeted training of these mechanisms should enhance related skills in both music and speech/language processing. The following sections will outline some available evidence fitting with these predictions and suggest pathways for future research.

### Deficits in Shared Underlying Mechanisms of Music and Speech/Language Rhythm

Mounting evidence suggests that speech and language difficulties may be related to comorbid impairments in timing (Falk et al., 2015; Falter & Noreika, 2014; Goswami, 2011; Peter & Stoel-Gammon, 2008), and that atypical rhythm processing may be a risk factor for developmental speech and language disorders (*Atypical Rhythm Risk Hypothesis*, ARRH; Ladányi, Persici, et al., 2020).[2] Although developmental speech and language disorders may express differently (e.g., children often present with a heterogeneous constellation of perceptual and production deficits at the levels of phoneme awareness, phonological processing, articulation, fluency, suprasyllabic prosodic sensitivity, vocabulary, spoken grammar, and reading skills), the notable levels of comorbidity between disorders (Heaton et al., 2018; Kaplan et al., 2001; Nicolson & Fawcett, 2007; Puyjarinet et al., 2017; Zwicker et al., 2009), and the strong link between perception and production in the brain (Kotz & Schwartze, 2010) makes it likely that there are shared impairments in underlying neural mechanisms across different disorders. In the current section, we will focus primarily on developmental dyslexia, developmental language disorder (DLD), and stuttering. These three disorders have speech or language as a primary deficit, show a high prevalence in the population, with frequent persistence into adulthood, and have communication difficulties that exert a personal and professional toll. Notably, these three disorders have also been shown to have deficits in timing (Goswami, 2019; Ladányi, Persici, et al., 2020).

Individuals with developmental dyslexia present with learning difficulties for reading and spelling (Goswami, 2011; Lyon et al., 2003), usually associated with phonological processing deficits in the perceptual domain, whereas those with DLD generally have impaired oral language acquisition (McArthur et al., 2000; Ramus et al., 2013). DLD (previously termed specific language impairment, see Bishop et al., 2017 for specifications of the terminology) manifests primarily in delayed and disordered acquisition of morpho-syntax (grammar) and vocabulary, and may be characterized by solely expressive or expressive–receptive deficits. DLD has lifelong negative consequences for academic, economic, and social well-being (Conti-Ramsden et al., 2018; Hubert-Dibon et al., 2016; Law et al., 2009). Further, dyslexia and DLD very often co-occur (Bishop & Snowling, 2004; Snowling et al., 2019, 2020). In

[2] The genetic implications and risk factors that could be informed by the PRISM framework are outlined in Ladányi, Persici, et al. (2020).

contrast, individuals who stutter have difficulty producing fluent speech, and may prolong syllables and produce speech with irregular temporal patterns (Perez & Stoeckle, 2016) but generally have intact acquisition of vocabulary, grammar, and reading to the extent that language structure can be dissociated from motor speech. Note that for a diagnosis of these disorders, speech or language deficits cannot be attributed to low IQ, neurological damage, an inadequate learning environment, or hearing impairment.

Impairments in precise auditory processing and entrainment of neural oscillations to external stimuli have been observed for individuals with dyslexia and DLD, who show deficits in the processing of syllable rise-time and stress perception, as well as deficits in the larger-scale temporal sampling of the speech envelope (dyslexia: Goswami et al., 2016; Huss et al., 2011; Leong et al., 2011; Leong & Goswami, 2014; Molinaro et al., 2016; Power et al., 2016; Thomson et al., 2006; DLD: Corriveau et al., 2007; Cumming, Wilson, & Goswami, 2015; Richards & Goswami, 2015). This research has motivated the development of the TSF for developmental dyslexia (and extended to DLD), which links observed perceptual deficits with impaired synchronization across multiple neural oscillation bands in the brain (Goswami, 2011; Goswami et al., 2016). Based on the TSF, Cumming, Wilson, and Goswami (2015) proposed the *prosodic phrasing hypothesis*, which also suggests that children with DLD are impaired in the perception of amplitude rise-times and duration cues, and further focuses on implications for the perception of larger-scale prosodic structure and grammatical processing (see also Cumming, Wilson, Leong, et al., 2015). Support for the impairment of neural oscillations in individuals with dyslexia comes from research finding atypical neural entrainment to slow modulations in auditory signals in dyslexic children (Cutini et al., 2016; Power et al., 2016) and adults (Hämäläinen et al., 2012; Soltész et al., 2013). Therefore, dyslexia and DLD may be associated with fundamental impairments in precise auditory processing and synchronization of neural oscillations to the speech signal (Goswami, 2011, 2018).

Related impairments have been observed for the processing of music and music-like stimuli for these populations, supporting the hypothesis of shared underlying mechanisms for music and speech rhythm. Individuals with dyslexia appear to show a general impairment in synchronization to an external beat (Colling et al., 2017; Overy et al., 2003; Thomson & Goswami, 2008), and perform poorly on measures of rhythm perception, rhythm production, and synchronization (e.g., Degé et al., 2015; Flaugnacco et al., 2014; Meyler & Breznitz, 2005; Thomson & Goswami, 2008; Wolff, 2002). Similarly, individuals with DLD show difficulties in both speech rhythm and music rhythm processing (Cumming, Wilson, Leong, et al., 2015; Sallat & Jentschke, 2015), are poorer at paced rhythmic tapping (Corriveau & Goswami, 2009), and have poorer singing ability (Clément et al., 2015) compared with controls. Children with DLD also perform worse than controls on a semantic judgment task when natural sentences are spoken fast or are time-compressed (Guiraud et al., 2018).

Timing and synchronization impairments have been observed not only for children with dyslexia and DLD, but also for individuals who stutter. Individuals who stutter exhibit impairments in synchronized tapping (Falk et al., 2015), show impaired rhythm perception with musical material (Wieland et al., 2015), and are impaired in unpaced tapping tasks, which rely on internal time keeping (Olander et al., 2010). These results suggest similar impairments across music and speech and open up the possibility that training in music rhythm could enhance both music and speech processing in these populations by co-opting shared neural circuitry. For stuttering, reduced sensorimotor coupling may affect the perception/production loop (Chang et al., 2016; Hickok et al., 2011), and impaired internal beat generation may be related to deficient production of internal timing cues from the basal ganglia (Alm, 2004; Toyomura et al., 2011). By better understanding how impairments in these underlying temporal processing mechanisms are involved across different developmental speech and language problems, it may be possible to directly target (and train) specific mechanisms for improvement.

Impaired timing mechanisms also often co-occur in developmental disorders that are frequently characterized by speech and language impairments (see Lense et al., in press, for a review). Timing impairments have been observed, for example, in Autism Spectrum Disorder (Duffield et al., 2013; Green et al., 2009; Hardy & LaGasse, 2013; Isaksson et al., 2018; Morimoto et al., 2018; Mostofsky et al., 2009; Rinehart et al., 2001; Tryfon et al., 2017), Attention Deficit Hyperactivity Disorder (Hove et al., 2017; Noreika et al., 2013; Puyjarinet et al., 2017; Rubia et al., 1999; Shapiro & Huang-Pollock, 2019; Slater & Tate, 2018; Valera et al., 2010; Zelaznik et al., 2012), and Developmental Coordination Disorder (DCD; Chang et al., 2021; Rosenblum & Regev, 2013; Trainor et al., 2018). In the adult-focused brain pathology literature, comorbid timing deficits have also been observed linked to basal ganglia dysfunction/impairments, such as in Parkinson's disease and patients with basal ganglia lesions (Kotz et al., 2005; Kotz & Gunter, 2015). Future research could search for similarities in timing impairments across different disorders that could be trained using common and/or specific music rhythm interventions (e.g., see the success of auditory cueing in individuals with Parkinson's disease; Dalla Bella, 2018; Kotz & Gunter, 2015; and the key role of rhythm in melodic intonation therapy for patients with aphasia, Stahl et al., 2011).

## Targeting Shared Underlying Mechanisms for Music and Speech Rhythm

### *Music Rhythm to Stimulate and Train Speech/Language Processing*

Research has started to show that using music rhythm as a stimulation or training tool can be beneficial to language processing in dyslexia, DLD, and stuttering. Current music training studies tend to provide general rhythmic or music training, or combined pitch and rhythm music training, so it is difficult to assess the direct effects of training specific underlying mechanisms. Rhythm training in general should enhance precise auditory processing, as well as training temporal attention, sequencing, and predictive timing skills, which may then also indirectly influence the processing of the less regular speech signal. This transfer could occur by sharpening and directing attention to relevant points in time, thereby enhancing various aspects of sentence processing such as phonological, syllable and word processing, as well as prosody, syntax, and reading (see also the OPERA hypothesis; Patel, 2011). The majority of experimental studies implementing music rhythm training alongside a control condition have been conducted in individuals with dyslexia. These studies have shown that rhythm training (of various types) can enhance the perception of the speech signal (e.g., voice onset time; Frey et al., 2019), phonological awareness (Flaugnacco et al., 2015; Thomson et al., 2013), and reading skills (Bonacina et al., 2015; Flaugnacco et al., 2015) compared to painting or no-training control groups. Even though a full, systematic review of this literature is beyond the scope of the current article,[3] these dyslexia studies are a promising proof of concept that rhythm training can impact speech and language task performance. Meanwhile, more research is needed to investigate the effect of rhythm training in other developmental speech and language disorders.

Music training research in general (across both typically developing and clinical populations) is in need of clear, hypothesis-driven experiments that aim to train the precise mechanisms predicted to be shared between music and speech/language processing. Although there are a limited number of studies investigating pure rhythmic training, current meta-analyses and systematic reviews of music training (not specific to rhythm) report beneficial transfer effects on speech/language skills, albeit weak to moderate (Cooper, 2020; Gordon et al., 2015; Pesnot Lerousseau et al., 2020; Román-Caballero et al., 2021). These reviews and related discussions (see Schellenberg, 2020) also underline the need for more systematic research, in particular including the use of random assignment to groups and an active control group to investigate causal effects of music training on related abilities (see also the series of exchanges in Bidelman & Mankel, 2019; Mankel & Bidelman, 2018 and Schellenberg, 2019, for a discussion of musical aptitude vs. training). Such controlled designs are particularly important to investigate the effect of training the three mechanisms proposed in the current framework. Note that reported correlations in the literature can also provide some first insights into potential links between music rhythm and language processing. However, correlations between different music rhythm and speech/language skills should be taken with some caution as they may be driven by other predisposition-related factors (Schellenberg, 2019; Swaminathan et al., 2017; Swaminathan & Schellenberg, 2020). With this caveat in mind, numerous correlations have been found between various rhythmic abilities and phonological awareness/reading skills in both typically developing children (see Supplemental Table 1) and clinical populations (e.g., Flaugnacco et al., 2014; Forgeard et al., 2008; Goswami et al., 2013; Huss et al., 2011; Thomson & Goswami, 2008). Much less is known about possible benefits of rhythm-based treatment in DLD (see Wiens & Gordon, 2018), and it will be important to explore whether speech-rhythm or musical-rhythm-focused training could impact spoken grammar and potentially extend to vocabulary, key areas of difficulty for children with DLD.

An important source of converging evidence comes from other research that has adapted short-term stimulation approaches. Benefits of rhythm regularity in priming stimuli and rhythmic cueing have been observed across these three speech and language disorders. Presenting a regular rhythm before a set of sentences has been shown to enhance grammatical processing for children with DLD and dyslexia compared to both irregular primes (Ladányi, Lukács, & Gervain, 2020; Przybylski et al., 2013) and environmental sound scenes (Bedoin et al., 2016). These findings suggest a role for sustained neural oscillations stimulated by musical rhythm (i.e., in the prime) in improving temporal expectations for various aspects of the subsequently presented speech signal (e.g., morphosyntactic cues for enhanced grammatical processing) even in developmental disorders. Rhythmic cueing or auditory stimulation has also been suggested to be valuable for individuals who stutter, notably by providing an external structure for internal time keeping, enhancing temporal attention allocation and predictive processing, strengthening the auditory–motor networks, and training the generation of an internal rhythm (Thaut, 2005). Supporting this suggestion, individuals who stutter appear to benefit from external auditory stimulation (Frankford et al., 2021; Toyomura et al., 2011), and asking individuals who stutter to sing enhances fluency in speech, potentially by regulating the temporal structure of the words (Falk et al., 2016; Glover et al., 1996; Wan et al., 2010). Both short- and long-term music rhythm stimulation and training therefore appear able to enhance precise auditory processing, synchronization/entrainment of neural oscillations to external rhythmic stimuli, and sensorimotor coupling, and could be valuable therapeutic tools to be used alongside speech therapy for these pathologies, especially with targeted interventions.

Music rhythm training could be particularly valuable to complement traditional speech or neuropsychological therapy as it contains a number of additional components that could be beneficial across the two domains (including links to attention, emotion, and motor functions; e.g., Särkämö et al., 2008). Importantly, music training is an enjoyable, easily administered, motivating, and cost-effective intervention, and can be used in group sessions (see Tamplin et al., 2013 and Tierney et al., 2013, for examples of group applications), as well as in individual sessions. Group sessions have the additional advantage of benefiting from joint motivation and joint action, social coherence and synchronization, enhancing potential entrainment (see Cross & Morley, 2008; Kokotsaki & Hallam, 2007; Miendlarzewska & Trost, 2014). The use of music rhythm training in treatment has also been developed in the SEP hypothesis, which focuses on applications to Parkinson's disease, stuttering, aphasia, and Autism. Studies in both typically developing children (Degé & Schwarzer, 2011; Patscheke et al., 2016) and children with dyslexia (Thomson et al., 2013) suggest that music training may provide comparable improvements in phonological awareness to direct training in phonology (Bhide et al., 2013; see also Bigand & Tillmann, 2021). Such results would suggest that music (rhythm) training could be used to complement more direct approaches, allowing for more diverse training, potentially increased motivation, and enhanced progress (Schön & Tillmann, 2015).

Music (rhythm) training can therefore be a motivating and engaging way to train associated neural timing mechanisms (Thaut, 2005; Thaut & Hoemberg, 2014) in combination with traditional evidenced-based speech and language therapeutic techniques. It can also be used to improve motor-related functioning such as coordination in motor speech disorders and motor-focused treatment of apraxia of speech (Lee et al., 2019). Additionally, music rhythm training could also be effective in training infant rhythm processing, as newborns are sensitive to rhythm and beat in music-like material (Cirelli et al., 2016; Winkler et al., 2009), as well as the linguistic rhythm of speech in different languages (Nazzi & Ramus, 2003; Ramus, 2002). Such results suggest that rhythm processing might be a risk indicator for the development of speech and language difficulties (ARRH; Ladányi, Persici, et al., 2020) and that music rhythm training might be able to shape the underlying neural mechanisms involved in timing at a young age (Gerry et al., 2012).

[3] See Table 1 in Ladányi, Persici, et al. (2020), for an overview of research investigating connections between rhythm and speech/language impairments.

### *Future Directions for Research and Training*

We suggest that a fruitful research direction would be to target more directly the three underlying mechanisms proposed in the current framework along two parallel axes: both theoretical/empirical and applied. Theoretically and empirically, the link between these three underlying mechanisms and different speech/language disorders needs to be systematically investigated to clarify potential links between the underlying mechanisms and specific speech/language impairments. Developing on insights from perceptual and production behavioral tasks and commonalities across different disorders, neuroscience methods such as electroencephalography, magnetoencephalography, and functional magnetic resonance imaging can be applied in a more targeted way to detect deficits in underlying neural mechanisms. These deficits may manifest as (a) impaired or reduced responses to fine-grained/precise auditory information (i.e., see the work on rise-time perception and speech envelope encoding in individuals with dyslexia as well as early evoked electrophysiological potentials; Chobert et al., 2012; Power et al., 2016; Van Hirtum et al., 2019), (b) reduced phase alignment and connectivity of neural oscillations to external stimuli (i.e., see the work on phase locking, coherence, and entrainment in dyslexia: Hämäläinen et al., 2012; Soltész et al., 2013, and Fiveash, Schön, et al., 2020, for more natural stimuli), or (c) reduced connectivity between auditory and motor regions (e.g., in stuttering: Chang et al., 2016; Hickok et al., 2011). Such already available methods and paradigms could be used to investigate neural processing underlying timing deficits across different disorders involving some deficit in speech perception/production. Further insight could be gained by investigating whether musical training enhances the precision of the proposed mechanisms and extends to speech/language processing (i.e., Assaneo et al., 2021; Doelling & Poeppel, 2015).

These research lines should aim to clarify links between impaired speech/language functioning in developmental disorders and the three underlying mechanisms proposed in the PRISM framework. It might be argued that a potential alternative hypothesis is that there are no observable links between the three mechanisms proposed in the PRISM framework and developmental speech and language disorders. Such evidence would necessitate a revisit of the mechanisms proposed and the links between music and speech rhythm. However, the evidence presented above (including first findings of timing deficits in developmental speech/language disorders) suggests that impaired timing, based on the mechanisms proposed, might be a crucial deficit occurring in developmental speech and language disorders (Ladányi, Persici, et al., 2020).

Within our here proposed approach, it would be particularly interesting to investigate the patterns of impairment within different developmental disorders across the three mechanisms. Because of the links and interactions between the mechanisms, it is possible that all three mechanisms might be impaired compared to a control group, or that only one or two mechanisms or their combination could be impaired. An example of this pattern could be impaired sensorimotor coupling for individuals who stutter, but intact precise auditory processing and neural entrainment to external stimuli. Another example could be the use of rhythm training or stimulation to improve temporal attention and hierarchical processing in children with DLD, with the aim to test a potential mediating role of speech and music rhythm on the enhancement of syntactic skills. It should be noted that individual differences are expected in these outlined investigations (related also to the large variance in language impairments exhibited within different developmental speech and language disorders), so large samples of participants for each disorder would be required to fully understand these links, as well as comparisons with an appropriate control group of children with typical development. Strong methodological approaches should also be used, including the appropriate tracking of treatment fidelity (i.e., tracking the implementation and administration of the rhythmic training; Wiens & Gordon, 2018). With precision medicine approaches made possible by well-powered high-quality data sets, treatment plans combining traditional speech therapy and rhythm-based training can eventually be individualized, that is, tailored to the specific needs of the individual (Ginsburg & Phillips, 2018).

For applied research, we predict that a rhythm training program focusing explicitly on direct training of precise auditory processing, the entrainment of neural oscillations to external stimuli, and the strengthening of sensorimotor coupling could have direct benefits on the speech/language skills that draw on these same underlying mechanisms. This research can start to be developed based on the PRISM framework and would be directly informed by the research discussed above. The goal of such training programs would be to investigate, with appropriate control groups, the effect of training that targets these three mechanisms on different speech and language skills. Examples of tasks that could specifically target these underlying mechanisms include as follows: (a) discrimination of small timing differences and rise-time perception training (precise auditory processing); (b) hierarchical structure tracking at multiple levels (neural entrainment to external stimuli and structure-based predictions); and (c) rhythmic production with auditory feedback (sensorimotor coupling). Beat and meter perception and production would be particularly valuable to such training, as it can span the three mechanisms. It might be possible that specific clinically distinct speech or language impairments would be more or less sensitive to modulation via training of different mechanisms (i.e., focus on neural entrainment for dyslexia and DLD, focus on sensorimotor coupling for stuttering); this possibility should be explored in future research. However, considering the connections between the three mechanisms, targeting all mechanisms should still be a valuable approach, especially for preliminary research.

The implementation of such potential training programs should be guided by research showing that rhythm and rhythmic skills are not a single entity; but rather a constellation of various subprocesses that may draw on different underlying processing mechanisms and neural correlates (Bonacina et al., 2019; Bouwer et al., 2020; Kotz et al., 2018; Thaut et al., 2014; Tierney & Kraus, 2015). Current evidence is revealing distinctions between beat-based versus memory-based rhythmic tasks/expectations (Bonacina et al., 2019; Bouwer et al., 2020; Tierney & Kraus, 2015), between periodic motor pattern generation, beat extraction, entrainment, and meter perception (Kotz et al., 2018), between neural signatures of rhythmic pattern, meter, and tempo processing (Thaut et al., 2014), and between rhythm and meter processing (Liégeois-Chauvel et al., 1998). Such distinctions should be further investigated in both typically developing individuals and those with developmental disorders, and should be considered when developing future training programs, in line with the current framework. Appropriate tasks and training programs still need to be developed, but can be guided by the PRISM framework and further research investigating impaired underlying timing mechanisms across different developmental disorders, with the goal to develop a strong evidence base for targeted music rhythm training.

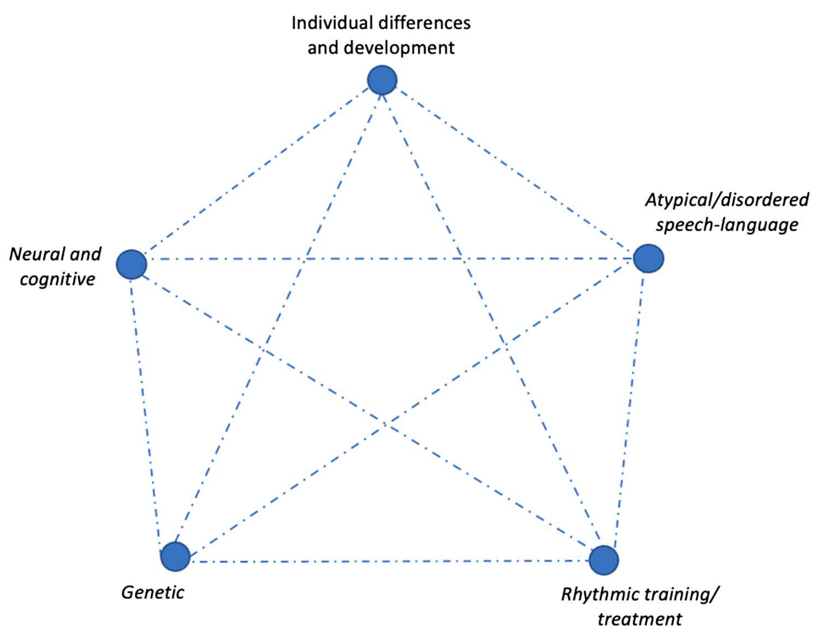
## Larger Context and Outlook

Finally, we propose to situate the here presented research and PRISM framework within a larger context of putative cognitive and biological similarities between rhythm processing in music and speech. Integrating evidence across different methods and techniques will allow for a more complete understanding of rhythm processing in the typical and disordered brain. We suggest that five major evidence types should be considered for a more complete understanding of connections between music and speech rhythm (see Figure 3). Converging with (1) neural and cognitive evidence outlined here in detail for our underlying mechanisms approach, it is important to incorporate (2) individual differences research and developmental evidence that have reported strong associations between performance on tasks measuring sensitivity to musical rhythm and speech rhythm, as well as links between musical rhythm and language skills such as phonological awareness, grammar, and reading. Although the full extent of Point 2 has not been presented here (though see Supplemental Table 1, for an outline of selected correlational studies), it is important to keep in mind that a comprehensive understanding of rhythm processing in speech and language should include findings from individual differences research in populations with diverse demographic characteristics to increase the chances of potential generalizability (see Jones, 2010). Furthermore, the efficacy of music-based interventions could differ across individuals (and depending on age, e.g., see greater sensitivity to foreign rhythms in 12-month-old infants compared to adults (Hannon & Trehub, 2005).

As outlined above, evidence from (3) *atypical* or *disordered* speech and language development in children and (4) initial promising outcomes of rhythm priming and training to influence speech and language outcomes in these populations and in typically developing populations provide further evidence for links between music and speech rhythm. Potentially shared genetic influences (5) should also be examined in the future, given that musical rhythm skills are moderately *heritable* (meaning a portion of the phenotypic variance can be attributed to genetic factors) as shown with genomic and twin methods (Niarchou et al., 2021; Ullén et al., 2014). Neural oscillatory mechanisms (measured from resting state) are also known to be highly heritable (Smit et al., 2005), though the heritability of neural entrainment mechanisms to rhythm in speech or music have not to our knowledge been studied. Further, while the heritability of *speech* rhythm traits (i.e., prosody-related tasks) has not been studied to our knowledge, correlated individual differences at the behavioral level often reflect shared underlying genetic architecture (Sodini et al., 2018) and other language-related traits are also moderately heritable (Deriziotis & Fisher, 2017). Moreover, potentially shared underlying biology and increased prevalence of comorbid rhythm problems in developmental speech and language disorders have led to the proposition that atypical rhythm traits partially share genes with speech and language development (see Ladányi, Persici, et al., 2020, for an in-depth framework). Genetic evidence, therefore, appears to be an interesting avenue for future research that remains to be explored. The integration of these five sources of evidence will allow for a more complete understanding of the connections between music and speech rhythm and how they can be exploited to develop effective tools for treatment and training in

**Figure 3**

*Five Different Cognitive and Biological Evidence Types That Should Be Considered for a More Comprehensive Contextual Understanding of Music and Speech Rhythm*




*Note*. See the online article for the color version of this figure.

light of patient centered, precision medicine approaches, which are neuroscience informed.

## Conclusion

The similarities between music and speech in relation to rhythm have spurred a large amount of research interest. Based on a synthesis of theoretical and empirical work, the present article proposed the PRISM framework, consisting of three mechanisms underlying the processing of music and speech rhythm: Precise auditory processing, synchronization/entrainment of neural oscillations to external rhythms, and sensorimotor coupling. Based on observed timing impairments across developmental speech and language disorders including dyslexia, DLD, and stuttering, we suggest that focusing on impairments to these neural mechanisms may accelerate our understanding of potentially shared timing deficits across different disorders and inform the development of training and treatment programs. Based on the strong regularity of music rhythm, the shared neural circuitry between music and speech rhythm processing, and overlapping mechanisms involved in encoding, perception, prediction, and production of the speech signal, rhythmic training, in particular when exploiting metrical structures and other benefits of musical material, appears to be a promising avenue for future research to enhance speech and language processing in both unimpaired and impaired populations.

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