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Dynamic auditory processing, musical experience and language development

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Children with language-learning impairments (LLI) form a heterogeneous population with the majority having both spoken and written language deficits as well as sensorimotor deficits, specifically those related to dynamic processing. Research has focused on whether or not sensorimotor deficits, specifically auditory spectrotemporal processing deficits, cause phonological deficit, leading to language and reading impairments. New trends aimed at resolving this question include prospective longitudinal studies of genetically at-risk infants, electrophysiological and neuroimaging studies, and studies aimed at evaluating the effects of auditory training (including musical training) on brain organization for language. Better understanding of the origins of developmental LLI will advance our understanding of the neurobiological mechanisms underlying individual differences in language development and lead to more effective educational and intervention strategies. This review is part of the *INMED/TINS* special issue *Nature and Nurture in Brain Development and Neurological Disorders*, based on presentations at the annual *INMED/TINS* symposium (http://inmednet.com/).

Language-learning impairments

Parents eagerly await their infant's first words and track their language development with keen interest. Despite the complexity of language, most children learn language with apparent ease. However, epidemiological studies have demonstrated that language-based learning problems are among the most prevalent developmental disabilities, affecting ~20% of children [1].

Longitudinal studies have demonstrated a link between early spoken language impairments and subsequent literacy problems [2]. To acknowledge the continuum between spoken and written language impairments in many children, we will use the inclusive term 'language-learning impairment' (LLI) in this review. However, children with LLI exhibit considerable heterogeneity. Thus, further research is needed to understand better the similarities and differences between spoken and written language impairments, the neural mechanisms underlying individual differences in language learning, and how this new knowledge might lead to improved interventions for struggling learners [3].

Although considerable research supports the hypothesis that the core deficit underlying LLI is a phonological impairment [4], the precise etiology of this deficit remains the focus of intense research and debate. A central question is whether phonological deficits are 'speech specific' or derive, at least in part, from domain general perceptual, memory, attention and/or motor constraints. Research aimed at investigating sensorimotor deficits has led to the development of several different hypotheses, the most prominent of which are the rate-processing constraint hypothesis [5–7] and the magnocellular deficit hypothesis [8,9]. These have in common a constraint in the speed of information processing and/or production, and this is posited to disrupt essential components of language learning, beginning with the acquisition of phonological representations. Specifically, they suggest that central auditory processing mechanisms, particularly those involved in processing dynamic spectral and/or temporal change, underlie the core phonological deficits observed in LLI.

Why should slow spectrotemporal auditory processing be crucial in phonological development? Analysis of the acoustic properties of speech (Figure 1) demonstrates that an ability to track brief, rapidly successive (dynamic) acoustic changes within the complex acoustic waveform of speech is essential for speech processing. A link has recently been proposed between language learning, the ability to process dynamic spectrotemporal acoustic changes within ongoing speech, and Hebbian learning [7]. This hypothesis is based on the fact that each language has its own set of phonemes (composed of complex acoustic spectra) that must be learned from experience and represented as neural firing patterns in auditory cortex [10]. Physiological single-cell recordings in animals have demonstrated that spectral, temporal and 'inseparable' spectrotemporal acoustic features are exquisitely organized and mapped in the central auditory cortex, based on experience-dependent learning [11–13]. Hebb proposed that when neurons are excited by more than one sensory cue, nearly simultaneously in time, the firing pattern is remembered (represented) as a unit, guiding experience-dependent learning and consequently behavior [14]. Repeated exposure to consistent sensory inputs, such as the complex waveform of ongoing speech, will enhance the

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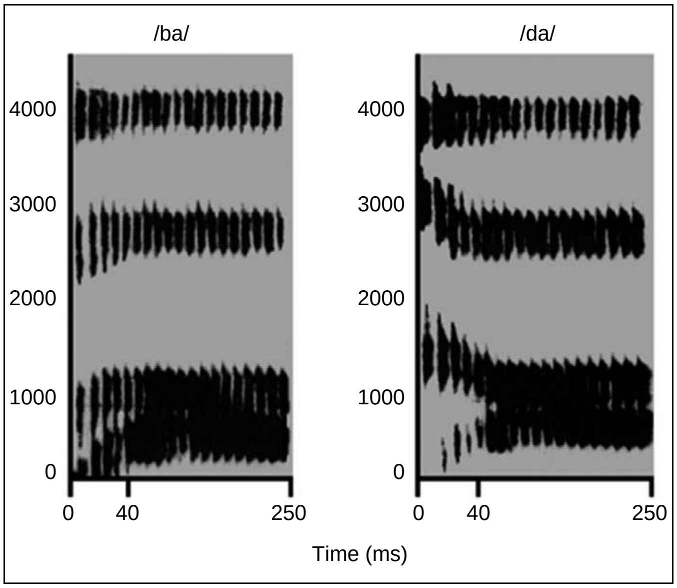

Figure 1. Two spectrograms (acoustic frequency changes across time) resulting from the production of the speech syllables, /ba/ and /da/. The consonant portions differentiating these syllables must be processed within the initial, brief (40 ms) acoustic changes (formant transition), which are followed rapidly in succession by the longer, louder, steady-state vowel.

likelihood that complex neural firing patterns (cell assemblies) will become generalized to represent the individual phonemes and syllables of a language, regardless of specific context or speaker. Furthermore, the order and precise timing (within tens of milliseconds) of successive neural firing patterns, and the segmentation of ongoing speech into syllables and words, derived from the spectrotemporal changes that occur frequently within speech, also will be coded. Such statistical learning is referred to as Hebbian learning or spike-timing-dependent neuroplasticity [15,16].

Substantial behavioral and physiological evidence shows that many young children (of 5–9 years) with specific language impairments (SLI) are less able to process the brief, rapidly successive non-linguistic spectrotemporal acoustic cues within the tens of milliseconds that would be needed, according to this theory, for optimal phoneme representation [7]. As predicted, these children also are less able than children without SLI to discriminate, sequence, remember and accurately produce those speech sounds that are characterized by rapidly changing acoustic cues [17,18]. In support of this theory, Breier *et al.* [19] showed that children (of 7–15 years) with dyslexia have a similar deficit in perceiving a phonemic contrast based on a brief (tens of milliseconds) acoustic cue controlled by voice-onset time, such as distinguishing between the syllables /ba/ and /pa/, and in perceiving a non-speech analog of this contrast using tone-onset time. These results demonstrated that dyslexic children are similarly impaired on tasks requiring rapid temporal processing, regardless of whether the stimuli are speech or non-speech.

A new and growing body of electrophysiological and neuroimaging research provides converging support for this potential link between rapid spectrotemporal auditory processing and phonological processing. Various studies have shown that left-hemisphere-specific activation patterns in regions traditionally associated with language processing are similar during processing of speech and processing of non-speech acoustic stimuli carefully designed to mimic the rapidly changing spectrotemporal acoustic cues that characterize ongoing speech [20–26]. For example, using functional magnetic resonance imaging (fMRI), Zaehle *et al.* [25] showed overlapping activation within primary and secondary auditory cortex, selectively in the left hemisphere, for temporal acoustic cues embedded in both non-speech and speech stimuli. Consistent with previous work [20–26], they concluded that the results from this fMRI study support a shared network within left superior temporal areas for rapid temporal information processing, of both speech and non-speech signals.

Examination of contradictory data

Despite this growing body of behavioral, physiological and neuroimaging evidence, several studies have challenged a 'causal' connection between auditory processing deficits and phonological deficits [27–32]. Because these studies report deficits in some but not all components of spectral and/or temporal processing, for many but not all subjects with LLI, it has been argued that these acoustic processing deficits cannot be either necessary or sufficient to cause phonological processing deficits. Rather, it has been proposed that LLI (especially dyslexia) is caused by a purely cognitive deficit that is specific to the representation and processing of speech sounds within words. It is further proposed that it is this cognitive deficit that directly interferes with forming the letter–sound correspondences that are essential for reading decoding in many languages [27–32]. It is argued that although individuals with LLI might have some general auditory processing constraints, these are not necessarily a cause of their phonological deficits.

Whenever there are conflicting data, especially when they pertain to a heterogeneous, developmentally impaired population such as those with LLI, it is important to look at the methodological details of the studies, particularly subject selection criteria and age. It is important to recall that the original studies hypothesizing a link between rapid spectrotemporal processing and LLI included young children (of 5–8 years) who had severe oral language impairments (one or more standard deviation below the normal mean for their age on standardized language tests) [33,34]. The first significant challenge to this hypothesis, by Mody *et al.* [30], remains the most often cited study in which these findings could not be replicated. However, rather than studying comparable subjects who had specific language impairments, these authors included second-grade students described as 'poor readers'. Surprisingly, inspection of these children's standardized reading scores showed that they were actually reading at the expected (second grade) level for their age. They were only 'poor readers' compared with the aberrant control group of second graders selected, who had exceptional reading abilities (ranging from the fourth to eighth grade levels). As such, these were not appropriate subjects on which to test this important hypothesis, and the results cannot be generalized to children with LLI. For a more detailed critique of this influential study, see Ref. [35].

Another major difference across studies that might contribute to conflicting results is the age of subjects included. As already stated, although the original studies demonstrating links between sensorimotor and phonological deficits in LLI focused exclusively on young children (of 5–9 years), much of the conflicting research has focused on older individuals (primarily college students) with a life-long history of developmental language and/or reading problems [28]. However, it becomes increasingly difficult with increasing age to study the etiology of developmental disabilities such as LLI, because older individuals have spent a lifetime developing strategies to cope with their earlier disabilities [36]. Neuroplasticity research has demonstrated that altered sensory input during critical periods of development not only disrupts cellular organization within sensory neural maps, but also significantly alters brain structure [12]. However, studies using older LLI subjects have rarely taken into account the likely changes in brain structure and function that would result from altered learning during critical periods of development.

It is also important to emphasize that developmental disabilities are not homogeneous and it is likely that many different patterns of disability or distinct subgroups are included in LLI study populations. This poses additional constraints on interpreting data from group studies, especially those using small numbers of older subjects. Age of subjects might also confound the appropriateness of tasks and stimulus conditions. This is especially true for psychoacoustic paradigms that, in addition to the sensorimotor components under investigation, also require considerable attention, memory and other cognitive demands. These issues were the focus of a recent comprehensive review [36] that concluded that much of the controversy in this literature might derive from a failure to take a developmental neuroscience perspective.

Another methodological factor potentially contributing to contradictory results is that data from different studies are often combined when drawing conclusions, even though ‘temporal auditory processing’ is not a unitary function, and various aspects of it have been tested using different paradigms in different studies (e.g. simple gap detection, central gap detection, backward masking, and frequency and amplitude modulation) [27].

Finally, in addressing potentially conflicting evidence, it is important to note that significant differences have been found between LLI and control subjects using electrophysiological measurements that were not found when behavioral measurements were used, even within the same study population. A case in point is a series of studies by Bishop and McArthur [29,37–39], who initially investigated both frequency discrimination and backward recognition making (an auditory temporal processing task) in 10–19-year olds with SLI. They found that the masking task did not differentiate between individuals with SLI and controls, leading these authors to conclude that the data failed to support a role for auditory temporal processing in SLI, in consensus with other critics of this theory [27,28,30–32].

However, McArthur and Bishop [29] did note that a subset of the younger SLI subjects performed significantly more poorly than controls on frequency discrimination. Furthermore, directly investigating the issue of subject age, on retest 18 months later it was found that the frequency discrimination thresholds of the younger SLI subjects had improved, moving them into the normal range, suggesting an important role for maturation. In two subsequent studies [38,39], results from auditory event-related potentials (ERPs) in response to tones were reported for the same subjects. Importantly, different results and conclusions were reached based on these electrophysiological (ERP) data as compared with the previously reported behavioral psychoacoustic data. McArthur and Bishop predicted that abnormal ERPs would be observed only for those subjects who had poor frequency discrimination. In fact, most of the subjects with SLI had aberrant ERPs, regardless of their frequency discrimination performance on psychoacoustic measures. A second ERP study by Bishop and McArthur [39] aimed to test directly the original finding of Tallal and Piercy [33] that children with SLI needed a greater temporal separation between two tones to process them correctly. In contrast to the previous behavioral results with the same subjects [29], ERP results demonstrated that children with SLI were significantly different from controls in their physiological response to tone sequences. In addition, an interesting age effect was found across groups, with older participants (>14 years) showing less deviant ERP responses than younger subjects.

In conclusion, failure to find sensorimotor problems, or specifically rapid spectrotemporal deficits, in subjects with LLI might often result from methodological differences across studies, particularly subject characteristics, subject age, auditory stimulus characteristics, and differential sensitivity of assessment measures at different ages. Most compelling is the finding that it is possible to demonstrate significant differences between the responses of LLI and control subjects to dynamic auditory stimuli using electrophysiological methods (ERPs), even when differences are not apparent in the same subjects using behavioral paradigms.

Predicting later language development based on auditory processing in infants

The preceding discussion highlights that, if our goal is to understand the factors contributing to language-learning impairments, it would be most informative to document the developmental progression as it unfolds [36]. Thus, one of the newest trends in this field is to follow the developmental trajectories of infants with (FH+) or without (FH−) family history risk for LLI through the developmental stages of language and reading [40–48]. For example, using an operant-conditioned head-turn procedure, Benasich and Tallal [40] trained infants to discriminate between two tones differing in frequency, separated by various inter-stimulus intervals (ISIs), to obtain individual psychoacoustic thresholds. There were considerable individual differences across infants in both groups on this task, but the FH+ infants required significantly longer ISIs than FH− to discriminate the tones correctly. Longitudinal follow-up studies found that, among diverse behavioral, perceptual, cognitive and social variables assessed in infancy, the rapid spectrotemporal processing threshold at 7.5 months was the single best predictor, both within each group as well as across groups (FH+ and FH− combined), of language outcomes at 3 years of age. Remarkably, two variables, rapid temporal processing thresholds obtained in infancy and male gender, together predicted 40% of the variance in language outcomes across both groups at 3 years, based on standardized language tests. In addition, these same variables accurately classified >90% of these 3-year-old children who scored within the 'impaired' range on the verbal reasoning subscales of the Stanford Binet Intelligence Test for children. Importantly, no significant predictive correlations were found between rapid auditory processing thresholds and nonverbal subscales of this test, demonstrating the specificity of the relationship between individual differences in infant rapid auditory processing and subsequent individual differences in language and verbal intelligence.

These behavioral results recently have been replicated and extended using electrophysiological measurements of the same infants [41]. Results showed that differences in the electrophysiological measures obtained at 6 months were significantly related to language outcomes at 24 months across groups. Furthermore, infants in the FH+ groups compared with infants in the FH− group showed specific electrophysiological differences to rapidly presented tone sequences (separated by a 70 ms ISI), but not to the same tone sequences presented more slowly (separated by 300 ms ISI). These differences were observed for frontal, frontocentral and central areas, selectively in the left hemisphere (Figure 2). These results are consistent with several other electrophysiological studies conducted in Finland, Germany and the USA with newborn infants at risk for language delay [42–48], thus emphasizing that they are not specific to the language being learned.

Newborn and infant behavioral and electrophysiological studies demonstrate that rapid auditory processing differences are evident even in newborns at genetic or familial risk for developmental LLI. Furthermore, they are excellent predictors of the course of both normal and aberrant language development, regardless of the language being learned. These data also demonstrate that significant differences in rapid auditory processing, reflecting left-hemisphere-specific dysfunction, exists from early life in these populations, prior to language development, suggesting commonality between the neural mechanisms supporting rapid auditory processing and those supporting language development.

Auditory-based remediation programs for language-learning impairment

There is mounting evidence that many children with LLI are characterized by both phonological and sensorimotor deficits, specifically those affecting dynamic auditory processing. The causality and precise neural mechanisms

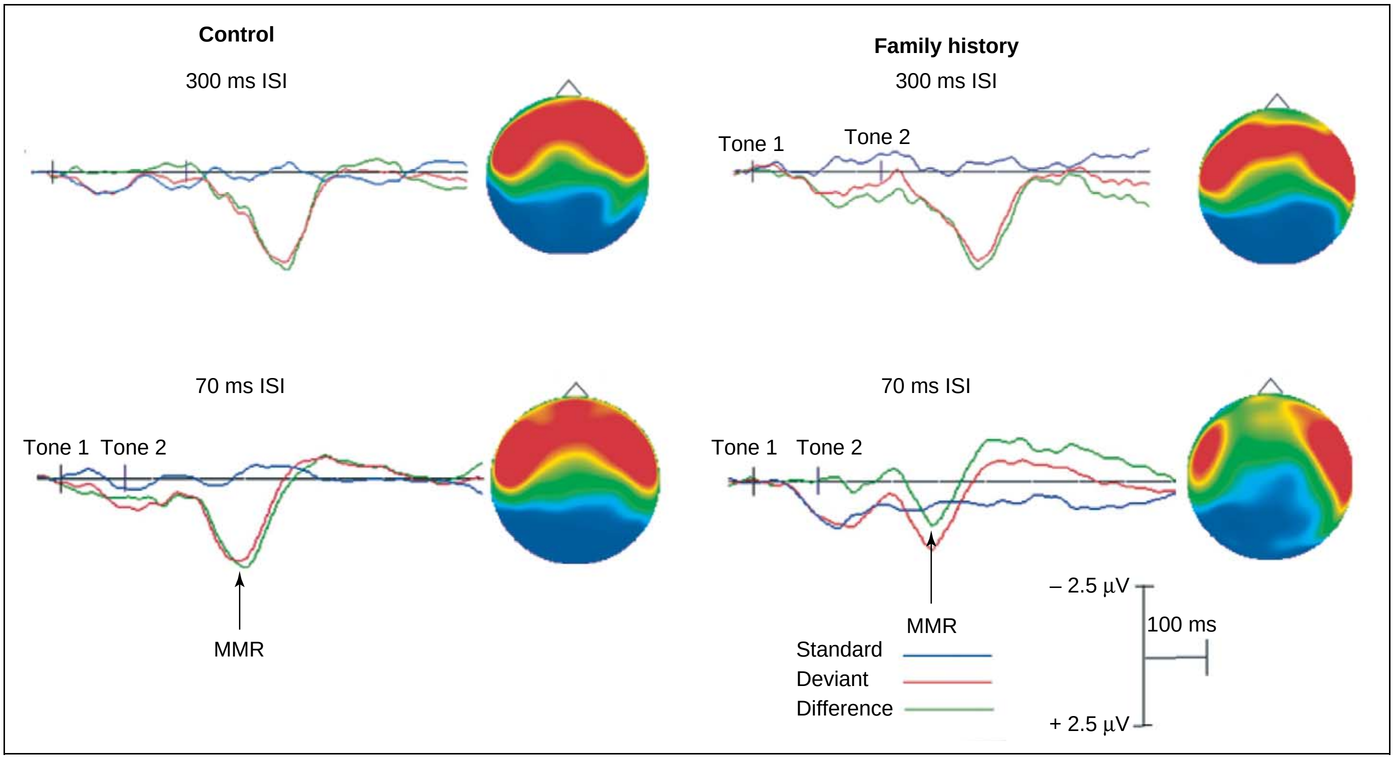

Figure 2. Grand average ERP waveforms for control infants (left) and infants with family history of language-learning impairment (right) in response to two tone sequences presented with a 300 ms interstimulus interval (ISI, top) and a 70 ms ISI (bottom). The amplitude of the mismatched response (MMR; i.e. the difference in the ERP in response to the deviant tone versus the standard tone) was significantly smaller in the family history group than in the control group for the 70 ms ISI, but not the 300 ms ISI condition. Topographic maps representing amplitude of the MMR over the entire surface of the head (red indicates greatest MMR amplitude and blue the smallest) are also shown for peak MMR latency (659 and 414 ms, respectively) for each group, with anterior to posterior represented top to bottom (nose at the top). There are no significant group differences for the 300 ms ISI, but for the 70 ms ISI condition the infants with family history of LLI show reduced positivity (MMR) at frontal, frontocentral and central channels as compared with the control infants. Additionally, the family history infants demonstrated a significantly smaller MMR (reduced positivity) in the left hemisphere than the control infants. There was no significant difference between the groups in MMR in the right hemisphere. Adapted, with permission, from data in Ref. [41].

that underlie these observations remain to be determined, but one can hypothesize that intensive training (incorporating many features of neuroplasticity training used in animal physiological studies [11]) designed to improve both dynamic auditory and phonological processing skills could improve the language abilities of children with LLI.

This hypothesis was tested with children with LLI in a series of well controlled studies using two novel approaches: rapid auditory sequencing training, and language training incorporating acoustically modified speech in which rapid spectrotemporal segments were amplitude-enhanced and extended in duration [49,50]. Children participating in the prototype training program (now called Fast ForWord®) showed substantial improvements in the rate of acoustic processing, and in speech discrimination and language comprehension, compared with a well matched control group of children with LLI who received the same language training, but with natural speech and no auditory sequencing training. Benefits from Fast ForWord® training have also been reported for children with serious academic weaknesses [51], who showed greater gains in oral language tasks and certain tests of phonological awareness, and a greater decline in behavioral problems, following 4–8 weeks of training compared with controls. Positive gains following Fast ForWord® training also were reported by Gillam and colleagues [52–54], albeit with only a few subjects, and Hook *et al.* [55] found that gains achieved with Fast ForWord® training were commensurate with those obtained using the well established Orton Gillingham reading remediation method [56].

Whereas the previous studies focused on spoken language skills, Temple and colleagues [57,58] were the first to report significant improvements in both reading and language scores in dyslexic children following training with Fast ForWord®. In addition to standardized reading tests, dyslexic children and typical readers received two fMRI scans at ~8 weeks apart while performing a letter-rhyming task. Between scans, the dyslexic children completed the Fast ForWord® language training program. After training, performance on all measures of oral language and reading showed significant improvement. The control group showed no significant change, suggesting that these behavioral changes cannot be attributed to improvements resulting from repeated testing, practice effects or maturation. Furthermore, before training the dyslexic subjects showed an absence of metabolic activity in the temporoparietal language regions while performing the letter-rhyming activation task, compared with robust activation in this area in the control group. After training, fMRI results demonstrated that the dyslexic readers showed increased metabolic activity in left hemisphere temporoparietal language regions, bringing their brain activation closer to that seen in typical readers (Figure 3). Electrophysiological and fMRI changes after other acoustic and/or phonological intervention methods have also been reported [59,60], demonstrating that these sensitive physiological assessments might prove to be a powerful new tool in evaluating the efficacy of behavioral interventions in clinical populations.

Not all studies have found significant effects following Fast ForWord® training [61,62], and some have failed to document sustained benefit over time [55]. However, some of these studies had exceptionally few subjects, no control group and other methodological weaknesses, such as poor adherence to the required highly intensive, neuroplasticity-based training protocol, that compromise the

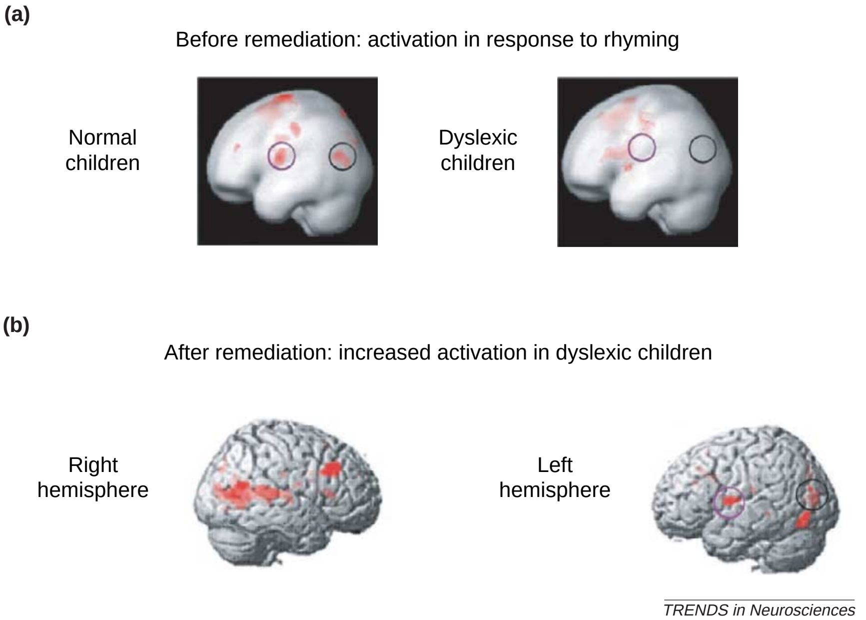

Figure 3. Brain activation of normal and dyslexic 8–12-year-old readers before and after remediation. **(a)** Statistical differences between left-hemisphere metabolic activity of control children and children with dyslexia while determining whether two printed letters, when spoken, would rhyme (subtracting the metabolic activity while matching the same letters). **(b)** Areas of the right and left hemispheres that showed statistically significant increases in activity for rhyming (compared with matching) letters after (compared with before) training with Fast ForWord® in children with dyslexia. The black circles highlight the left temporoparietal region, which is disrupted in dyslexics and most affected by intervention. The purple circles show a frontal region that is also activated by intervention. Adapted, with permission, from data in Ref. [58].

interpretation of these results. For example, a randomized control trial in Scotland recently reported by Cohen *et al.* [62] had parents (rather than trained professionals) supervising their own child's intensive daily training at home, limiting the extent to which these results can be generalized to the more typical delivery by trained professionals in clinics and classrooms.

The significant improvements in language and reading immediately following Fast ForWord® training can be interpreted in several ways. On the one hand, they might demonstrate the importance of rapid auditory processing not only for language development but also for reading success. On the other hand, because Fast ForWord® aims to cross-train multiple cognitive functions, it might improve auditory attention and memory in general, and also phonological perception and grammatical comprehension, all of which are explicitly and intentionally trained in an attempt to address the multifaceted patterns of deficits characterizing the heterogeneity of individuals with LLI. Finally, improved performance might reflect other novel components of the methodology used in Fast ForWord®, which are not specific to auditory processing. These include the intensity of intervention and use of technology that can provide highly timed stimulus presentation, reward and feedback, and can also enable stimulus presentation difficulty and content to be adapted, trial by trial, based on each participant's ongoing responses.

What is becoming clear as we begin to translate research out of the neuroscience laboratory into classrooms is that different factors might affect the success of behavioral interventions in these two different environments, depending on the clinical profiles and ages of individuals. Improvement in intervention and remediation programs will benefit from increased research focused on designing more 'real world' translational educational trial methodologies.

Influence of musical training on auditory temporal processing and language learning

As already described in this review, previous studies indicate that acoustic training might be beneficial for individuals with LLI. Musical training has also previously been shown to improve many aspects of auditory processing [63,64] and to improve cognitive [65–68], language and literacy skills [69–74] (Figure 4a), while also leading to earlier maturation of auditory-evoked responses and to alterations of functional anatomy in brain areas that are used while performing various auditory tasks [63,64]. So far, only two studies have examined the influence of musical training on language

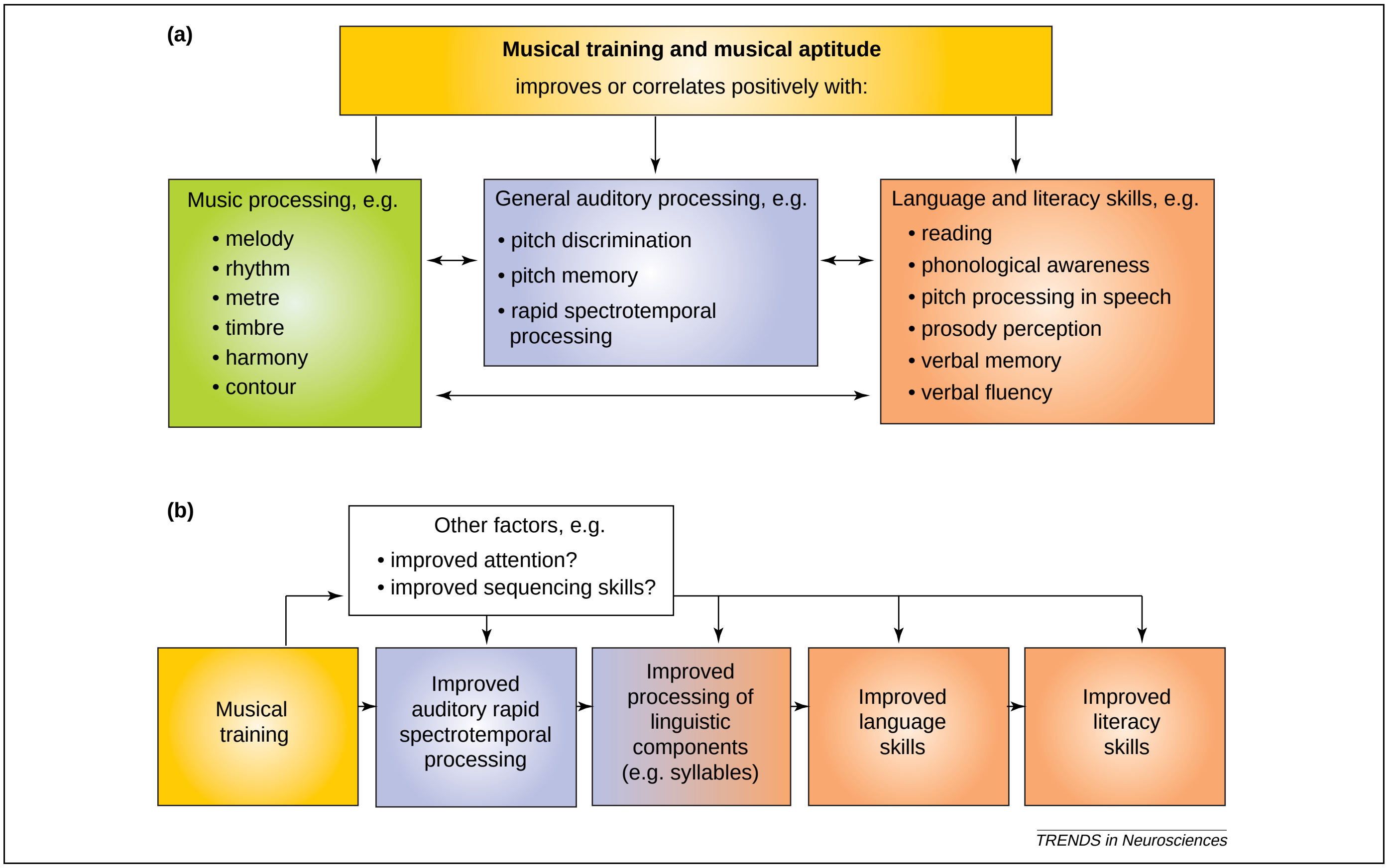

Figure 4. Suggested relationships between musical training, auditory processing, language and literacy skills. **(a)** The influence of training on various tasks that require auditory or language processing. The mechanisms underlying these relationships and the causal direction (do inherent auditory processing skills or brain differences lead to enhanced musical aptitude or, conversely, does musical training leads to improved auditory processing ability and brain alteration?) remain unclear. **(b)** A modified version of the model by Overy *et al.* [72] of the possible relationship between musical training and literacy skills. Results from a recent study are incorporated [75], and factors such as improved attention following musical training or improvement of general sequencing skills are added.

and reading skills using pre-post-training designs [71,72]. These results demonstrated a strong relationship between musical ability (or training) and language and literacy skills. However, neither the underlying neural mechanisms supporting these connections or an understanding of how musical training might influence language skills is known. Furthermore, because no control groups exposed to other types of intervention were used, the specificity of this effect to musical training remains to be established.

Given the suggested link between auditory rapid spectrotemporal processing and language abilities, and that between musical training and language and reading skills, we hypothesized that musical training might specifically enhance the ability to process rapid spectrotemporal acoustic cues and also alter the underlying functional anatomy. In a recent fMRI study [75], 20 musicians and nonmusicians listened to three-tone sequences with varying ISIs and were asked to reproduce the order of the tones manually. Results demonstrated that musical training alters the functional anatomy underlying rapid spectrotemporal processing of nonlinguistic stimuli, resulting in improved behavioral performance along with a more efficient functional neural network primarily involving traditional language regions (Figure 5). Furthermore, performance on trials with the fastest ISI correlated significantly with the age of commencement of playing a musical instrument. In addition to their theoretical interest, these findings might have important implications for improving language and reading skills, especially in children struggling with LLI, a hypothesis originally posed by Overy [72] and modified here (Figure 4b).

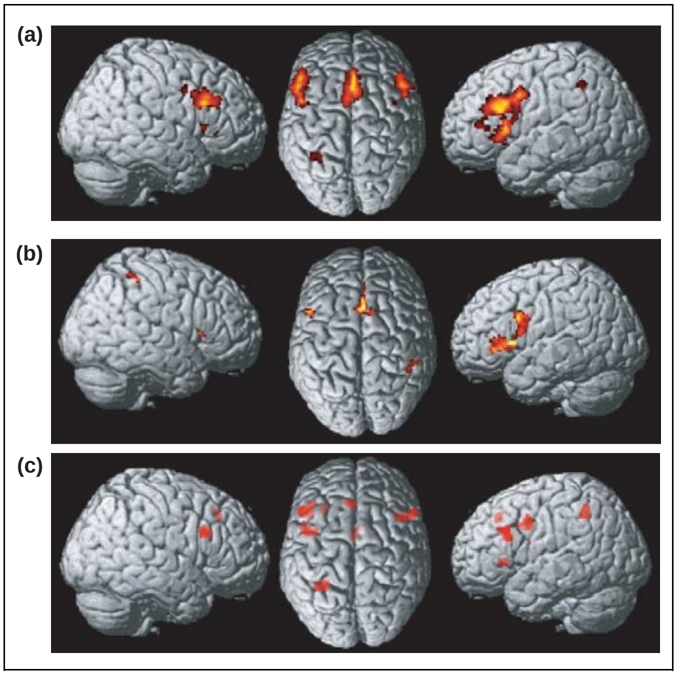

Figure 5. Imaging results for the rapid spectrotemporal processing effect in musicians and nonmusicians (18–33 years old). Metabolic activation patterns for parametric analysis in nonmusicians **(a)** and musicians **(b)**. (The results reflect areas more activated during the processing of rapid versus slow spectrotemporal cues.) **(c)** Areas that are more activated within the nonmusician group compared with the musician group. Overall, results suggest a more efficient functional network in musicians, primarily involving left hemispheric inferior frontal regions for the processing of rapid spectrotemporal cues, regions traditionally associated with language. Reprinted, with permission, from Ref. [75].

Musicians spend many years practicing and acoustically training themselves, and therefore it is not surprising to see an increase in auditory processing abilities with musical training. However, the causal direction of this relationship is still unclear. Do inherent auditory processing skills or brain differences lead to enhanced musical aptitude or, conversely, does musical training lead to improved auditory processing ability and brain alteration? Furthermore, the roles of motor sequencing training and its interaction with auditory sequencing training, which both accompany musical training, remain unclear. A recent study examining pre-existing markers for musical ability found no neural, cognitive, motor or musical differences between a group of children beginning musical training and a control group [76]. These results suggest that musical training itself (and not necessarily inherent factors) leads to improved nonmusical skills.

Although this new trend in research is exciting, current results on the potential influence of musical training on language and literacy skills must be interpreted cautiously, pending further research. Methodological weaknesses and potentially incorrect causality assumptions should both be taken into account [77]. Future studies are needed to assess prospectively and longitudinally the role of musical training in normally developing children, in addition to children and adults with LLI, to determine whether musical training leads to improved language and literacy skills. Furthermore, future studies are needed to address whether, in addition to improved rapid spectrotemporal processing of non-linguistic acoustic stimuli, musical training also leads to improved phonological processing. Finally, it remains unclear why and how musical training might improve language and literacy skills. The role of additional factors such as improved attention, non-auditory sequencing skills and pre-existing structural and functional brain differences needs to be examined to determine precisely how musical training, other types of auditory training, and language and reading development are linked.

Concluding remarks

The role of dynamic processing in developmental language and reading impairments has become a central focus of research. This research offers new insights into the possible role of dynamic temporal processing in the development and maintenance of language. We have made strides in developing novel theories pertaining to the role of auditory neuroplasticity in language development, but we still have a long way to go before we understand the dynamic, neurobiological processes involved. The advent of more sophisticated neuroimaging procedures, specifically those that can track real-time dynamic neural processing in the time range of speech, should lead to significant advances in understanding the neurobiological basis of language development and disorders. Attention to differences across studies, specifically to subject age, subject characteristics and types of measurement used (behavioral, electrophysiological or neuroimaging) might help resolve contradictory results. Additional research aimed at understanding better the potential role that auditory and/or musical training might have in improving language and reading skills is also needed. Besides sharing a similar developmental time course, music and speech represent the most cognitively complex uses of acoustic information by humans and both take advantage of dynamic modulation of acoustic parameters [78]. Utilizing one to improve the other seems to be an auspicious and promising approach and might also further our understanding of how the brain learns language, how oral and written language are linked through common neural systems, and how this information can be used to develop neuroscience-informed intervention strategies to improve the language and reading outcomes of children.

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