Educ Psychol Rev (2010) 22:323–338
DOI 10.1007/s10648-010-9137-4

Auditory Sensitivity, Speech Perception, and Reading Development and Impairment

Juan Zhang · Catherine McBride-Chang

Published online: 4 June 2010

Abstract While the importance of phonological sensitivity for understanding reading acquisition and impairment across orthographies is well documented, what underlies deficits in phonological sensitivity is not well understood. Some researchers have argued that speech perception underlies variability in phonological representations. Others have investigated the role of more general auditory sensitivity for reading development and reading difficulties, arguing that poor phonological representations may actually be due to broad underlying auditory deficits, which are not restricted to speech stimuli. We argue that these hypotheses are not necessarily mutually exclusive. In this review, we demonstrate that auditory sensitivity and speech perception can be integrated into a single developmental model, in which auditory sensitivity may have an indirect impact on reading; this impact is mediated by speech perception. In the model, we distinguish general auditory sensitivity as falling into at least two general categories: rhythmic and temporal. Correspondingly, speech perception itself can be distinguished as suprasegmental and segmental. Theoretically, the proposed model integrates a broad range of studies on general auditory and speech perception to suggest a developmental trajectory for reading acquisition that can be explored from before birth. Practically, the proposed model points to different ways of understanding and diagnosing reading difficulties and distinguishing reading difficulties across languages and orthographies.

Keywords Auditory sensitivity · Speech perception · Reading

Given the importance of reading for academic success, understanding the early origins of reading difficulties has been an overarching goal of teachers, clinicians, and researchers for decades (e.g., Adams 1990). Some researchers have targeted early speech perception as the primary developmental marker of subsequent reading delay, while others have centered on more general auditory perception as key for understanding reading development and impairment (e.g., Mody *et al*. 1997; Molfese 2000). Disentangling the associations of

J. Zhang · C. McBride-Chang (✉)
Department of Psychology, The Chinese University of Hong Kong, Shatin, NT, Hong Kong
e-mail: cmcbride@psy.cuhk.edu.hk

general auditory perception and speech perception with phonological processing skills and word reading is, therefore, important for understanding reading difficulties across languages (Wagner and Torgesen 1987). Thus, this review integrates studies of auditory sensitivity, speech perception, and reading ability in an attempt to demonstrate how reading disability might occur either via general auditory processing, speech perception, or both. We argue that speech perception and general auditory processing might both be causally associated with reading difficulties. In the first part of this review, studies on each area in relation to reading difficulties are reviewed. In "The Association between Segmental and Suprasegmental Speech Perception," the main focus is on interrelations of suprasegmental and segmental speech sensitivities in relation to reading. In the third part of this review, the debate between the issue of specific speech impairment and a general auditory deficit hypothesis is revisited. Finally, a new model on the relations among general auditory sensitivity, speech perception, and reading skills is proposed in "Discussion and Future Directions."

The Role of Auditory Sensitivity and Speech Perception in Reading Skills

Thus far, it has been widely accepted that dyslexia stems from a phonological impairment (DeBree *et al*. 2006; Goswami 2000). Phonological impairments are those that are related to speech sounds. For example, many dyslexic readers have difficulties synthesizing speech sounds together, as in knowing that, in English, the /b/ sound, when combined with a rime such as "at," makes the word "bat." To understand the origin of this phonological deficit, some researchers have turned to speech perception and general auditory processing, both of which are available to typically developing infants from before birth. Thus, the association of auditory and/or speech perception with subsequent phonological awareness can be conceptualized as a natural developmental progression (e.g., McBride-Chang 1996). However, evidence for general auditory processing as compared to more specific speech perception in relation to phonological processing has often arisen from different investigations focused on either one or the other.

Because phonemic awareness is strongly predictive of word recognition in alphabetic languages, studies of speech perception and reading development before the mid-1990s mainly focused on phonemic or segmental levels of speech, including isolated vowels and consonants, especially stop consonants. Stop consonants (e.g., /p/, /g/, /b/, /d/, /t/) were of greatest interest for at least two reasons. First, compared to other consonants (e.g., /r/, /l/), they occur faster in time. Second, they consist of transitional formants, in contrast to vowels, which are steady-state. Both of these features of stop consonants might make them particularly difficult to perceive and manipulate in tasks of phonological awareness (e.g., McBride-Chang 1995). Moreover, several studies also found that dyslexic children, as compared to typically developing children, had less sharp category boundaries for such consonants, suggesting that they not only organized these phonemes less categorically (e.g., Serniclaes *et al*. 2001) but also sometimes showed higher sensitivity to allophonic contrasts (e.g., Bogliotti *et al*. 2008). (Allophonic contrasts are variants on a given phoneme; e.g., in English, the /t/ sounds in *time* and *subtle* sound different when isolated, although they are both within the /t/ category.) This pattern of reduced accuracy and categorical perception for stop consonants has been found for Chinese children as well (e.g., Cheung *et al*. 2008; Liu *et al*. 2009). One prominent theory of such difficulties with stop consonant perceptions in children with dyslexia, termed the "temporal processing hypothesis" (Tallal 1980), is the idea that such difficulties might be due to deficient auditory perception of rapid transitional stimuli. According to this hypothesis, those with reading disabilities lack sensitivity not only to speech stimuli but also to other acoustic signals that involve a rapid change within a very short time period (tens of milliseconds). However, this theory has been criticized for at least two reasons. First, only a subgroup of poor readers also manifests speech perception difficulties with stop consonants (e.g., Manis *et al.* 1997). Second, those with reading disabilities appear to manifest such perceptual difficulties even when signals are slowed or do not involve formant transitions, so that the acoustic sensory impairment applies to a wider array of signals than do typical stop consonant perceptions or stimuli with temporal transitions only (e.g., Ahissar *et al.* 2000). Nevertheless, there are a number of studies demonstrating the difficulties of dyslexic children, particularly in manipulating and perceiving stop consonants across languages. Thus, researchers have focused particularly on phoneme-level speech perception in a number of studies on reading development and impairment.

At the same time, although the role of speech perception at the phonemic level for subsequent reading difficulties has being widely explored, more researchers have also begun to examine the role of speech perception at the suprasegmental (e.g., syllable level, onset–rime segmentation) or speech prosody (e.g., stress, lexical tone, intonation) level in the past decade or so. One reason for this focus on suprasegmental speech perception is that, developmentally, phonological deficits might stem from an impairment at a broader level of speech processing (e.g., the syllable or onset–rime level). Children first master phonological units with large grain sizes such as the syllable or onset and rime units before literacy acquisition, only to grasp the concept of small-size units such as phonemes following literacy instruction (Goswami 2002). For example, Cutler and Carter (1987) found that, in English, about 90% of all words and approximately 85% of content words begin with strong syllables that contain full vowels, suggesting that metric stress is a good indicator of potential word boundaries. Therefore, infants likely first use such effective prosodic cues, termed “metrical segmentation strategy” (Cutler 1990), to segment the speech streams to which they are exposed before they grasp smaller units of speech. Failure to split such speech streams into syllables or onsets and rimes would likely subsequently result in a perception difficulty at the phonemic level.

Studies regarding the role of speech perception at the suprasegmental level in word recognition focus on different specific prosodic features in different languages. Table 1 shows some tasks for testing the sensitivity of speech perception at the suprasegmental level. Some of these (e.g., the metric stress task) focus on word-level processing, whereas others (e.g., the rhythmic matching task) extend to sentence-level processing.

Most of these tasks have distinguished disabled readers from typically developing readers. For example, Wood and Terrell (1998) recruited 30 poor readers from primary school and matched them with both age-matched and reading-matched controls (mean age, 8 years). They assessed participants using time-compressed speech and rhythmic matching tasks, together with a set of phonological processing and reading tasks, and found that children with reading difficulties were poorer on a rhythmic matching task, which tapped prosodic sensitivity, even after statistically controlling for vocabulary knowledge. However, no group difference was found in this study for time-compressed speech, reflecting temporal processing with vocabulary knowledge controlled. This early work showed the significant role of suprasegmental, or rhythmic, sensitivity on reading development.

Subsequently, researchers have demonstrated that tasks of metric stress are associated with word reading (e.g., Holliman *et al.* 2008) and spelling (Wood 2006) in typically developing children ages 5–7 years. Difficulties in replicating stress patterns have been shown even in children as young as 3 years old. Debree *et al.* (2006) found that those Dutch children at risk for reading difficulties (i.e., whose parent or sibling had diagnosed reading

Table 1 Tasks for Testing Speech Perception at the Suprasegmental Level

Task	Testing aim	Description and examples for task
Metric stress task (Holliman *et al*. 2008)	Word-level speech prosody (for very young children)	Children are first asked to identify objects in a picture (e.g., sofa) when they are pronounced correctly. The performance in this session is considered as baseline. Then some objects are mispronounced by changing the original metric stress (e.g., SOfa is pronounced as soFA), and children are asked to point out the objects.
DEEdee task (Whalley and Hansen 2006)	Word-level speech prosody	Children first hear a familiar phrase such as "Sleeping Beauty." Then two DEEdee phrases are presented one by one, with only one matching the stress and rhythm of the original phrase (e.g., "DEEdee DEEdee" and "dee DEEdee DEE"). Children should decide which DEEdee phrase matches the original phrase.
Compound noun task (Whalley and Hansen 2006)	Phrase-level prosody	Children are first presented a noun phrase that could represent two or three items according to prosodic cues, including stress, pause, and intonation (e.g., *football and socks* or *foot, ball, and socks*). They are then asked to choose one picture that best depicts the phrase.
Rhythmic matching task (Wood and Terrell 1998)	Sentence-level speech prosody	A sentence is filtered until no phoneme can be identified and only the intonation and rhythmic pattern of the sentence are preserved. Then two different sentences are presented, and children are asked to choose the one that has the same prosodic pattern as the original one.
Chinese lexical tone identification task (McBride-Chang, Tong *et al*. 2008)	Word-level speech prosody	Pairs of lexical tones combined with the same syllable are aurally presented, and children are asked to choose one picture that matches the meaning of the target tone. For example, children hear one of the following two words, /ji1/ (衣, clothing) or /ji2/ (椅, chair), and they are asked to choose the picture (from two choices given) that depicts the word.
Chinese lexical tone categorization task (Cheung *et al*. 2008)	Word-level speech prosody	A series of stimuli across a continuum with two end points sharing the same syllable but different lexical tones (e.g., /si 33/ and /si 55/) is used. Participants are presented all stimuli one by one and asked to decide to which category (/si 33/ or/si 55/) they belong.

difficulties) were significantly poorer at repeating irregularly stressed nonwords than controls. Given this finding for such young children, this speech prosodic insensitivity could be an inherited deficit (Debree *et al*. 2006; Wood *et al*. 2009).

One important prosodic, or suprasegmental, feature is lexical tone. Chinese is one of the most famous tonal languages in the world. For example, there are four lexical tones in Mandarin; the same syllable /fu/ can represent different meanings if it is combined with different tones. /fu1/ refers to 夫 (husband), and /fu2/, /fu3/, and /fu4/ each correspond to 浮 (float), 腐 (rot), and 富 (rich), respectively. Chinese (Cantonese-speaking) children with dyslexia (ages 8–10 years old) could be distinguished from those without dyslexia on lexical tone identification and categorical perception (e.g., Cheung *et al*. 2008) in one study. In another study of those with and without a family history of dyslexia, 5-year-olds at risk for dyslexia were significantly poorer in distinguishing lexical tones (McBride-Chang, Lam *et al*. 2008). Among typically developing preschool children (ages 4–6 years), two other studies have demonstrated that lexical tone sensitivity is uniquely associated with Chinese word reading, with a variety of other measures statistically controlled (e.g., McBride-Chang, Tong *et al*. 2008; Shu *et al*. 2008). These studies underscore the importance of different aspects of suprasegmental speech processing across cultures for understanding literacy development and impairment.

Another group of researchers has argued that the poor phonological representation of reading-disabled children was not restricted to speech prosody but extended to general rhythmic processing (Goswami 2002; Goswami *et al*. 2009; Goswami *et al*. 2002; Muneaux *et al*. 2004; Richardson *et al*. 2004; Thomson *et al*. 2006; Thomson *et al*. 2009). The perception of amplitude modulation (AM) and frequency modulation (FM) with low speed (e.g., at 2 Hz) was evidenced to be important for the perception of acoustic rhythm (e.g., Fry 1954; Goswami *et al*. 2009). Several studies have demonstrated that sensitivity to AM and FM was significantly associated with reading skills. Table 2 shows the tasks typically used to tap acoustic rhythmic sensitivity.

Stimuli used in AM tasks are pure (nonlinguistic) tones, the amplitude of which increases to a constant peak (modulation depth) at different changing rates. For example, if the rate is very large or the rise time is short (e.g., 15 ms), a clear beat will be produced. In

Table 2 Tasks for Testing Auditory Rhythmic Sensitivity

Task	Description and examples for task
AM beat detection task (Goswami *et al*. 2002)	Stimuli are nonspeech sounds with AM. The modulation depth is constant, but the rates of amplitude change (rise time) vary across a continuum. Participants are first trained to become familiar with the stimuli at the end points, corresponding to different categorical labels. Then they are asked to decide to which category each stimulus across the continuum belongs.
Rise duration rove task (Goswami *et al*. 2009)	This task is similar to the above AM beat detection task, except that the duration of steady state changes randomly, with only the rise time offering a consistent cue by which to categorize stimuli.
FM detection task (Talcott *et al*. 2003)	One pair of stimuli is presented in each trial. One stimulus is a pure tone with a constant frequency, and the other contains some FM. Participants should identify which stimulus includes frequency change.
Pitch contour task (Foxton *et al*. 2003)	Several pure tones with different pitches are presented sequentially, producing a standard pitch contour. In each trial, a new sequence of tones is presented. The absolute frequencies of these tones are transposed, and participants are asked to decide if the contour is the same as the standard one.

contrast, if the rate is small or the rise time is long (e.g., 400 ms), a smooth change will be perceived. Sensitivity to the AM beat detection of the sound envelope (at 2–10 Hz) appears to be important for reading.

For example, Goswami *et al*. (2002) explored the relation between auditory sensitivity tapped by an AM beat detection task, a temporal processing task, and reading skills among 7-year-old to 11-year-old children. They found that dyslexic children were poorer than age-matched and reading-matched controls on the AM beat detection task. Similar results were also found by Richardson *et al*. (2004). Perhaps even more importantly, Goswami *et al.* found that, when groups were combined, the AM beat detection task, reflecting acoustic rhythmic sensitivity, contributed a unique 25% of variance to word reading, with children's age, nonverbal IQ, and vocabulary knowledge statistically controlled. In contrast, the temporal processing task could only uniquely explain about 10% of the variance in reading.

Insensitivity to AM was demonstrated not only in English-speaking children with dyslexia but also in English-speaking adult dyslexics (Thomson *et al*. 2006), French-speaking dyslexic children (mean age, 11.4 years) (Muneaux *et al*. 2004), and Finnish-speaking adults with dyslexia (Hämäläinen *et al*. 2005). Similar results were also found using the "rise duration task," which is a much purer measure than the AM beat detection task in 8-year-old to 15-year-old children with reading disabilities (Goswami *et al*. 2009). The abovementioned studies together indicate that the AM beat detection task, which taps acoustic rhythmic sensitivity, is a good predictor of reading across languages, whether the language is stress-timed (English) or syllable-timed (French), and whether the correspondence between phonology and orthography is relatively transparent (Finnish) or opaque (English).

The AM task has been widely shown to be related to reading skills, and its importance was explained using the framework of "P-center theory." Goswami (2002) proposed that "Stress beats (P-centers) are principally determined by the acoustic structure of amplitude modulation at relatively low rates in the signal" (p. 155) and that "P-center detection is important for the representation of onset–rime segments in syllables" (p. 155). That is, sensitivity to the rise time (envelope) of AM can influence the segmentation of onsets and rimes within syllables, which can further affect rime awareness and consequent reading. Heil (2003) argued that there is a special neuronal mechanism in the auditory cortex of human beings that can detect slopes of amplitude envelopes, similar to neurons found in the cat auditory cortex (Biermann and Heil 2000).

Apart from the AM task, there are other measures used to access acoustic rhythmic sensitivity such as the FM and pitch contour tasks. In one study, Talcott *et al*. (2003) compared nineteen 12-year-old to 15-year-old Norwegian-speaking poor readers and 22 age-matched controls on an auditory FM task (at 2 Hz) and showed that detection thresholds for FM were significantly higher in poor readers than in those with normal reading abilities, indicating that the insensitivity to acoustic rhythm of reading-disabled children even exists in more transparent orthographies such as in Norwegian.

The Association between Segmental and Suprasegmental Speech Perception

The association of speech perception at the phonemic level with phonological awareness has been argued to be strong in previous work (McBride-Chang 1995). Here, we mainly look at the relationship between speech perception at the suprasegmental level and phonological awareness in order to explore potential pathways from speech prosody to reading. Three questions are of interest. First, does sensitivity to speech prosody correlate with phonological awareness? Second, can speech sensitivity at the suprasegmental level (speech prosody) explain reading independently of phonological awareness? Third, can speech sensitivity to prosody be associated with reading independent of speech perception at the segmental level (phonemic sensitivity)?

The answers to all three questions appear to be "yes." For example, Wood and Terrell (1998) found that sensitivity to speech prosody tapped by a rhythmic matching task was significantly associated with phoneme deletion, rhyme deletion, and reading skills. Metric stress sensitivity is also significantly associated with rhyme awareness (Holliman *et al.* 2008; Wood 2006) and phoneme awareness (Holliman *et al.* 2008). Lexical tone awareness in Chinese also tends to be significantly correlated with other phonological awareness tasks (e.g., McBride-Chang *et al.* 2008; Shu *et al.* 2008). Thus, there is a moderate to strong association between various measures of suprasegmental speech perception and phonological awareness across languages.

Perhaps more interestingly, however, such suprasegmental processing can uniquely explain variance in various literacy tasks, with other phonological awareness tasks controlled in some studies (e.g., McBride-Chang *et al.* 2008; Wood 2006). For example, Holliman *et al.* (2008) found that metric stress awareness could explain unique variance in word reading even when age, vocabulary, and phonological awareness assessed by phoneme deletion and rhyme deletion were taken into account, suggesting that sensitivity to speech rhythm could explain individual differences in reading ability independently of phonological awareness.

Therefore, there may be other pathways from speech prosody to reading skills beyond phonological awareness. Whalley and Hansen (2006) found that sensitivity to speech prosody at the word level tapped by a compound noun task could account for word reading, but not nonword reading, in typically developing children (ages 8–10 years), indicating that speech prosody may facilitate reading by enhancing lexicon access. In the same study, they also found that speech prosodic sensitivity at the phrase level tapped by the DEEdee task could explain the 30.3% unique variance in passage-level reading comprehension, with phonological awareness and nonspeech rhythm controlled. Even when word reading was further controlled, it still uniquely accounted for 24.7% variance in this reading measure. The authors argued that perhaps children use such prosodic sensitivity to facilitate the chunking of syntactic and semantic units in short-term memory and consequent comprehension. Similarly, Xu (1991) found that cues of Mandarin lexical tones could be activated and used to facilitate the storage of information in short-term memory. Therefore, prosody sensitivity may influence reading through short-term memory. Besides the pathways of lexical access and short-term verbal memory, another potential mechanism for the influence of suprasegmental speech on later reading might be through the pathway of morphological awareness. In some languages, the pronunciation of a given word or morpheme can change when it becomes part of a compound word or is altered with the addition of a suffix or a prefix. For example, *i* in *wide* is pronounced differently from the way it is pronounced in *width*. As a different example, given the root word *active* in which the first syllable is stressed in pronunciation, a change occurs when the word is changed to make it a noun, with the second syllable now stressed (*activity*). Such prosodic, especially stress-related, changes could provide morphological or grammatical cues for reading (e.g., Clin *et al.* 2009; Wood *et al.* 2009). Clin *et al.* (2009) found evidence for this association. In their study, after controlling for age, nonverbal IQ, general language ability, working memory, and phonological awareness, they found that stress-shifting morphological awareness significantly accounted for unique variance in reading, while stress-neutral morphological awareness could not. This study has important implications for Chinese because more than 70% of Chinese words are compound words, and Chinese lexical tones tend to change when morphemes are pronounced alone as compared to when they are combined with other morphemes or words (Fang 1990). Sensitivity to such lexical tone cues might thus facilitate morphological awareness, an important correlate of Chinese reading (McBride-Chang *et al.* 2005).

The last question of interest concerns the relationship between speech perception at the segmental level and speech perception at the suprasegmental level in reading. We argue that suprasegmental speech may be associated with reading independent of segmental speech sensitivity for the following reasons. First, although the path from segmental or phonemic level speech sensitivity has been related to reading through the paths of phonological processing, especially phonological awareness, as shown in previous work (e.g., McBride-Chang 1996), suprasegmental speech could also impact reading through other potential pathways, such as morphological awareness as mentioned above. Second and more importantly, speech prosody may partly reflect the origin of segmental speech sensitivity. Developmentally, infants grasp prosodic patterns in native language earlier than phonemic information (Jusczyk 1992), and they use both prosodic and statistical cues to form phonemic categories in their native languages (Kuhl 2004). Therefore, suprasegmental sensitivity might facilitate the identification of certain phonemes (e.g., stress sensitivity could enhance the recognition of stressed phonemes) and enhance segmental sensitivity, thereby accelerating subsequent phonemic awareness and reading (Wood *et al.* 2009).

Reading Disability: Speech Deficit or General Auditory Impairment?

From the review above, it is clear that numerous studies have so far demonstrated that auditory sensitivity and speech perception are related to reading. However, some researchers have argued that reading disability is related to insensitivity to speech perception only, supporting the speech-specific hypothesis (e.g., Mody *et al.* 1997). Others have proposed that children and adults with reading disabilities tend to have poor sensitivity not only in perceiving speech sounds but also in perceiving general auditory signals, supporting the auditory deficit hypothesis (e.g., Moisescu-Yiflach & Pratt 2005). The above debates have persisted for many years (Mody *et al.* 1997). The typical paradigm addressing the debates includes both speech perception and auditory tasks simultaneously in the same study.

There are a number of studies in support of the speech-specific hypothesis. For example, research demonstrating that children with dyslexia actually show even better discrimination between stimuli within a phonemic category than controls and a worse performance only when discriminating stimuli across phonemic boundaries suggests that their impairment is at the linguistic or speech level rather than at the level of general auditory processing (e.g., Bogliotti *et al.* 2008; Manis and Keating 2005; Serniclaes *et al.* 2001).

In addition, some researchers have explicitly compared the discrimination of nonspeech pairs analogous to speech pairs to test the auditory hypothesis and found no evidence for it. For example, Mody *et al.* (1997) used /ba/ and /da/ speech stimuli, as well as nonspeech stimuli, which were sine-wave analogs of the second and third formants of the above two speech syllables. They found that second-grade poor readers only performed worse than grade-matched good readers in discriminating speech stimuli, but not in nonspeech stimuli.

This language-specific hypothesis was also supported by some event-related potential (ERP) studies. For example, Schulte-Körne *et al.* (1998) recruited 19 dyslexic children in grades 5 and 6 and matched them on age and IQ with 15 controls. A passive oddball paradigm was used to compare mismatch negativity elicitation on both speech syllables (/ba/ and /da/) and nonspeech tones (1,000 and 1,050 Hz). They found no significant group differences on the pure tone task, but the amplitude for dyslexic adolescents was significantly smaller than that of controls on the syllable task, suggesting a phonological, rather than a domain-general, deficit.

However, other studies have demonstrated that dyslexics have a more general auditory deficit. For example, one study of college students with dyslexia found that patterns of auditory perception were delayed, as compared to those for nondyslexic students, across language-related and non-language-related categories (Moisescu-Yiflach and Pratt 2005). At the other end of the age spectrum, Molfese (2000) recorded the ERPs within 36 h of birth for 17 children whose reading skills were subsequently analyzed at the age of 8 years. He found that ERP responses to both auditory and nonauditory stimuli were highly predictive of subsequent reading skill. In another study, 109 typically developing children were recruited, and their brain responses (ERPs) to speech and nonspeech acoustic sounds were annually recorded from ages 1 to 8. When they were 8 years old, the children were then tested on word-level reading skills. Results showed that N1 components for both speech and nonspeech stimuli from ages 1 to 4 years were significantly related to decoding skills at the age of 8 years (Molfese *et al*. 2004). Similar results have been demonstrated for children learning both alphabetic languages (e.g., Maurer *et al*. 2003) and Chinese (e.g., Meng *et al*. 2005) using ERP methodologies.

One overarching problem in resolving the speech-specific versus general auditory impairment debate is that of measurement. A typical method used in previous studies supporting the speech-specific deficit hypothesis was as follows. First, reading-disabled and control participants were recruited and completed particular auditory processing tasks. Then, the performances of both groups were compared to draw conclusions. However, this method is potentially problematic because it does not preclude the possibility that auditory sensitivity might be developmentally related to reading even though no group difference could be found at the current testing time point. As Kuhl (2004) has argued, infants are born with different auditory sensitivities, based on which they learn statistical cues in their native language environment and sharpen their sensitivities to certain acoustic features that frequently occur in their native speech. Those with reading disabilities might have somewhat delayed auditory sensitivity at the very beginning, potentially hindering the establishment of later speech sensitivity (speech perception) and subsequent reading, but they might catch up with normal children on certain auditory processing skills later. That is, the apparent speech deficit may originate from early auditory insensitivity.

In addition, the auditory tasks used in previous studies can also substantially influence obtained results. Thus far, most studies addressing the debate on speech-specific versus general auditory processing have focused on the examination of temporal processing. However, both acoustic rhythmic sensitivity, as tapped by the AM beat detection task, and temporal processing, as assessed by the temporal order judgment task or the rapid frequency discrimination task, were significantly associated with phonological awareness (rhyme awareness), and each of them could uniquely explain reading when the other was statistically controlled (e.g., Goswami *et al*. 2002; Muneaux *et al*. 2004), suggesting that these two components can explain reading skills independently of the other. Some researchers have further argued that these two types of auditory processing might be different in nature from each other. For example, Hämäläinen *et al*. (2008) used the passive oddball paradigm and ERP technique to test both temporal sensitivity and rise time perception (rhythmic sensitivity) in Finnish-speaking children (reading-disabled, $N=23$; controls, $N=30$; 8–10 years old). In each trial, paired pure tones were aurally presented under two conditions with a constant interstimulus interval of 610 ms. Under the first condition, the within-pair interval was 10 ms, whereas under the other condition, it was 255 ms. Under each condition, there were two types of deviants. Under one condition, the rise time of the second sound was different from the second tone of the standard pair. Under the other condition, the pitch of the second sound was different from the second tone of the standard pair. Results showed that reading-disabled children had larger mismatched negativity and smaller late discriminative negativity when the deviant stimulus was rise time change and the within-pair interval was long (255 ms). However, when this interval was short (10 ms) and pitch change occurred in the deviant stimuli, the attention orientation to novel stimuli tended to be smaller in the reading-disabled group as compared to controls.

These results indicate that temporal processing may be related to attention allocation, while rhythmic processing may reflect stimulus detection without attention. These two kinds of auditory processing markers may be different in nature. Dyslexic children thus might be poor at either temporal processing, slow rhythmic processing (e.g., AM at 4 Hz and FM at 2 Hz), or both. Since different reading-disabled children might manifest different types of auditory deficits (Amitay *et al*. 2002), the speech-specific hypothesis cannot be fully supported unless a broader range of auditory tasks is used and no group differences emerge.

Finally, the difficulty levels of stimuli may also matter. Lyytinen *et al*. (2005) proposed that the difference in mismatch negativity elicitations between controls and reading-disabled children might depend on the complexity and demands of tasks rather than on whether the stimuli were speech or nonspeech. This proposition was supported by the study by Kujala *et al*. (2003), in which eight adults with dyslexia and eight controls were investigated. In the study, they used a three-tone oddball paradigm. Three stimuli with different frequencies (500, 750, and 625 Hz) were used to produce two conditions. Under the first condition, the 625-Hz stimuli appeared later than the other two and served as a backward mask. The other two stimuli were presented with different orders, which corresponded to the standard and deviant stimuli. Under the second condition, the 625-Hz stimuli were presented before the other two, so that they involved an earlier detection of the order difference. They found that under condition 1, the amplitude of dyslexic groups was significantly smaller than that of controls. However, under condition 2, there were no group differences. Meng *et al*. (2005) found similar group-level differences only under conditions in which the nonspeech stimuli presented were more difficult overall.

Discussion and Future Directions

Given these concerns, we argue that the domain-general hypothesis and the language-specific proposition are not mutually exclusive, and that phonological deficits may stem from either the general auditory level, the language-specific level, or both. To begin with, poor phonological representations in reading-disabled children may originally arise from auditory deficits. According to the native language neural commitment hypothesis (Kuhl 2004), infants are born with different auditory sensitivities to all acoustic stimuli. Based on these sensitivities, infants gradually build neural networks that are only sensitive to speech patterns in their native languages; such patterns impact later language development (Kuhl 2004). In this conceptualization, poor general auditory perception could hinder the establishment of later speech sensitivity and subsequent reading, one possible explanation for the findings that later-onset dyslexics were shown to manifest deficient auditory perception as newborns in some studies (e.g., Molfese 2000). In addition, reading-disabled children with severe auditory impairments consistently demonstrate difficulties in phonological tasks and reading (Amitay *et al*. 2002).

At the same time, however, reading disability may also stem directly from speech perception deficits. The development of speech sensitivity is actually a categorical learning process, implying that environment also matters. Sufficient native language exposure is necessary to provide enough speech examples so that one can grasp the most relevant acoustic cues and statistical information by which to form phonemic or speech prosodic categories. Otherwise, if one develops either hypersensitivity or insensitivity to relative dimensions of speech, prototypes of speech categories cannot be easily mastered, one potential reason that some dyslexics show a lower resistance to noise (Ahissar 2007; Ahissar *et al*. 2006) and sometimes perceive speech stimuli in an allophonic way (Bogliotti *et al*. 2008). That is, good auditory perception does not necessarily guarantee normal speech sensitivity (e.g., Mody *et al*. 1997).

We propose a new model for the integration of auditory sensitivity, speech perception, and reading in Fig. 1. Developmentally, auditory sensitivity, including both temporal and rhythmic processing, impacts speech perception at both segmental/phonemic and suprasegmental/prosodic levels, respectively. These, in turn, can influence literacy acquisition through the pathways of phonological processing and morphological awareness.

The first part of the model shows the two types of auditory sensitivity, temporal sensitivity and rhythmic processing, both of which are partly determined by genes and show individual differences at birth. In the second part, temporal processing impacts phonemic speech perception according to the temporal processing hypothesis (Farmer and Klein 1995; Tallal 1980). Meanwhile, rhythmic sensitivity has an influence on suprasegmental perception or speech prosody. This association is supported by one recent study demonstrating that the rise duration rove task could account for 14% unique variance in speech prosody, even with age and IQ (Wechsler Intelligence Scale for Children) controlled for in the combined sample of dyslexics and age-matched controls (8–15 years old) (Goswami *et al*. 2009). In addition, speech prosody may also influence speech perception at the segmental level. Sensitivity to speech prosody such as stress may facilitate spoken word recognition and accelerate vocabulary recognition, which will

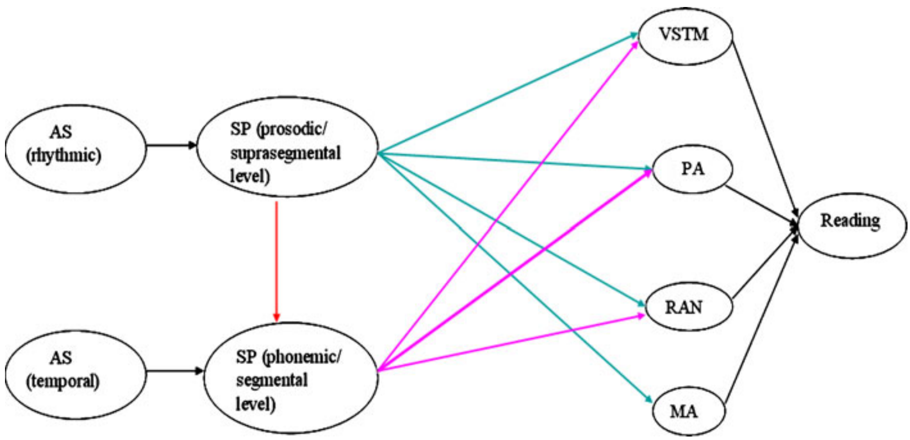

Fig. 1 Four-stage model showing the pathways from auditory and speech perception to reading. *AS* auditory sensitivity, *SP* speech perception, *VSTM* verbal short-term memory, *PA* phonological awareness, *RAN* rapid automatized naming, *MA* morphological awareness

enhance the perception of phonemes according to the lexical restructuring hypothesis (Metsala and Walley 1998), as argued by Wood *et al.* (2009). Also, as mentioned before, stressed speech segments are better perceived and grasped. In the third part of this model, segmental sensitivity can have an impact on reading through the pathway of at least three components of phonological processing (i.e., the main pathways of phonological awareness, lexical access via rapid naming of common objects/symbols, and verbal short-term memory as argued by McBride-Chang 1996). At the same time, as aforementioned, speech perception at the suprasegmental level may influence reading through both phonological processing and morphological awareness, both of which have been evidenced to be important for reading development.

There may be some potential critiques to the proposed model. First, it may be argued that rhythmic processing and temporal sensitivity may be combined into one single latent factor of auditory sensitivity. As mentioned in the third part in this review, both types of auditory processing could be related to phonological awareness and reading skills independently of each other and may be of different natures. In addition, it is possible for reading-disabled children to be impaired on one aspect but not on the other, as shown in some previous studies (Amitay *et al*. 2002; Muneaux *et al*. 2004), showing the dissociation of the two factors. Therefore, rhythmic processing and temporal sensitivity reflect different aspects of auditory processing and should be treated as two separate factors.

Another critique may be that segmental and suprasegmental processing should not be considered as two different factors. However, we view speech prosody and phonemic sensitivity as being associated with reading independently through different pathways. For example, speech prosody is more closely related to morphological awareness as it can provide important cues of morphological changes. In addition, phonemic sensitivity, especially processing of stop consonants, is more related to temporal processing, while speech prosody concerns are more related to auditory rhythmic processing, which corresponds to slow changes in sound. In addition, developmentally, sensitivity to speech prosody is achieved earlier than and even facilitates phonemic sensitivity (Jusczyk 1992; Kuhl 2004). Therefore, although segmental processing and suprasegmental processing are related, they should not be considered as representing the same speech perception aspect.

A third concern is the relationship between auditory sensitivity and speech perception in reading: Some may argue that auditory sensitivity may influence reading coincidentally with speech perception. That is, auditory and speech perception should be treated as of the same level rather than looking at auditory sensitivity as emerging earlier and impacting reading via speech perception. However, developmentally, auditory perception does emerge earlier and also underlies the foundation of speech perception (Kuhl 2004). In addition, it is rare for those with severe impairments in various auditory perception measurements to show normal speech sensitivity (Amitay *et al*. 2002). Thus, it is reasonable to propose that auditory sensitivity causally influences speech perception and subsequent reading.

Although the proposed model focuses on reading development, it is consistent with some findings and emerging models by speech pathologists and linguists who focus particularly on oral language development. For example, the pathway from speech perception to phonological awareness in our model was also demonstrated in children with speech–sound disorders in the study by Rvachew and Grawburg (2006). Moreover, the role of sensitivity to suprasegmental speech rhythm in the acquisition of grammatical morphology and vocabulary was also shown in children with specific language impairments (Beckman *et al*. 2007; Corriveau *et al*. 2007).

The proposed model is of theoretical significance. First, it provides a new perspective by which to look at the debate on auditory general impairment and speech specific deficits. It argues that both kinds of processing are not exclusive of one another and, more importantly, they can be integrated into a coherent model. This idea may also be important for understanding bilingual phonological transfer. In one study, Wang *et al*. (2005) found that Chinese tone matching skill could uniquely account for the 8% variance of English pseudoword reading even after statistically controlling for English phoneme deletion skill, with the whole regression explaining 57% of the variance for immigrant children whose first language was Mandarin and second language was English (mean age, 8 years). This result was initially surprising because lexical tone is not a speech feature in English; it should only be important in Chinese for these children. However, sensitivity to L1 (Chinese) lexical tone might actually reflect, in part, underlying auditory rhythmic sensitivity, which could influence L2 (English) speech perception at the suprasegmental level, just as stress can uniquely predict English reading beyond phonemic awareness. The new model is also significant for investigating the universal factors impacting reading across languages. Large grain size, such as rime awareness, has been evidenced to be important for reading development across many orthographies (Goswami *et al*. 2002). Therefore, acoustic perception, such as AM sensitivity, which is crucial for the segmenting of onsets and rimes, is likely to be essential across languages. Finally, this hypothesized model covers multiple aspects of auditory processing (both temporal and rhythmic processing) and speech perception (both segmental and suprasegmental) simultaneously, encompassing a broader picture of the origins of poor phonological processing in reading-disabled individuals than has been offered previously.

Apart from the universal factors across orthographies, the model also highlights some unique speech features within each language. For example, the best predictor of reading in English is phonemic awareness, implying that speech perception at the segmental level may be particularly salient when investigating English reading skills. In contrast, phonemic awareness has been shown to be less correlated, and lexical tone awareness has been shown to be relatively more strongly associated with Chinese reading (McBride-Chang *et al*. 2008), suggesting that suprasegmental perception may be particularly important in exploring Chinese reading development and impairment.

Apart from its theoretical importance, the model is also potentially practically useful, especially for intervention programs. The model argues that phonological deficits may stem from many potential origins. They may arise from the speech perception level or even a deeper underlying auditory level. At the level of speech, there may be one or more deficits in temporal processing, rhythmic processing, segmental speech sensitivity, or perception of speech prosody. Different individuals may differ in difficulties, according to which more effective training programs might be suggested. Meanwhile, new training programs can test causal relations proposed in the model, perhaps also taking into account children's ages when such programs are introduced. For example, auditory processing programs would seem to be particularly useful for the youngest children.

In summary, reading difficulties may arise from multiple levels (auditory or speech) and factors (temporal or rhythmic, segmental or suprasegmental) through different potential paths (phonological awareness, lexical access, verbal short-term memory, and morphological awareness), all of which can be covered in an integrative model. Future longitudinal studies and additional experimental studies will be important for testing these associations.

Acknowledgement We are grateful to Dr. Benjamin Munson for his suggestions on an earlier version of this manuscript.

References

Adams, M. J. (1990). *Beginning to read: Thinking and learning about print*. Cambridge, MA: MIT.

Ahissar, M. (2007). Dyslexia and the anchoring-deficit hypothesis. *Trends in Cognitive Science, 11*, 458–465.

Ahissar, M., Protopapas, A., Reid, M., & Merzenich, M. M. (2000). Auditory processing parallels reading abilities in adults. *Proceedings of the National Academy of Sciences, 97*, 6832–6837.

Ahissar, M., Lubin, Y., Putter-Katz, H., & Banai, K. (2006). Dyslexia and the failure to form a perceptual anchor. *Nature Neuroscience, 9*, 1558–1564.

Amitay, S., Ahissar, M., & Nelken, I. (2002). Auditory processing deficits in reading disabled adults. *Journal of the Association for Research in Otolaryngology, 3*, 302–320.

Beckman, M. E., Munson, B., & Edwards, J. (2007). Vocabulary growth and the developmental expansion of types of phonological knowledge. In J. Cole & J. Hualde (Eds.), *Laboratory phonology 9* (pp. 242–264). Berlin: Mouton de Gruyter.

Biermann, S., & Heil, P. (2000). Parallels between timing of onset responses of single neurons in cat and of evoked magnetic Welds in human auditory cortex. *Journal of Neurophysiology, 84*, 2426–2439.

Bogliotti, C., Serniclaes, W., Messaoud-Galusi, S., & Sprenger-Charolles, L. (2008). Discrimination of speech sounds by children with dyslexia: Comparisons with chronological age and reading level controls. *Journal of Experimental Child Psychology, 101*, 137–155.

Cheung, H., Chung, K. K. H., Wong, S. W. L., McBride-Chang, C., Penney, T. B., & Ho, C.-S. H. (2008). Perception of tone and aspiration contrasts in Chinese children with dyslexia. *Journal of Child Psychology and Psychiatry, 50*, 726–733.

Clin, E., Wade-Woolley, L., & Heggie, L. (2009). Prosodic sensitivity and morphological awareness in children's reading. *Journal of Experimental Child Psychology, 104*, 197–123.

Corriveau, K., Pasquini, E., & Goswami, U. (2007). Basic auditory processing skills and specific language impairment: A new look at an old hypothesis. *Journal of Speech, Language, and Hearing Research, 50*, 647–666.

Cutler, A. (1990). Exploiting prosodic probabilities in speech segmentation. In G. Altmann (Ed.), *Cognitive models of speech processing: Psycholinguistic and computational perspectives* (pp. 105–121). Cambridge, MA: MIT.

Cutler, A., & Carter, D. M. (1987). The predominance of strong initial syllables in the English vocabulary. *Computer Speech & Language, 2*, 133–142.

DeBree, E., Wijnen, F., & Zonneveld, W. (2006). Word stress production in three-year-old children at risk of dyslexia. *Journal of Research in Reading, 29*, 304–317.

Fang, Z. (1990). Tone sandhi and tone perception. *Acta Psychologica Sinica, 22*, 255–259.

Farmer, M. E., & Klein, R. M. (1995). The evidence for a temporal processing deficit linked to dyslexia: A review. *Psychonomic Bulletin and Review, 2*, 460–493.

Foxton, J. M., Talcott, J. B., & Witton, J. B. (2003). Reading skills are related to global, but not local, acoustic pattern perception. *Nature Neuroscience, 6*, 343–344.

Fry, D. B. (1954). Duration and intensity as physical correlates of linguistic stress. *Journal of the Acoustical Society of America, 26*, 138.

Goswami, U. (2000). Phonological representations, reading development and dyslexia: Towards a cross linguistic theoretical framework. *Dyslexia, 6*, 133–151.

Goswami, U. (2002). Phonology, reading development, and dyslexia: A cross-linguistic perspective. *Annals of Dyslexia, 52*, 141–163.

Goswami, U., Thomson, J. M., Richardson, U., Stainthorp, R., Hughes, D., Rosen, S., et al. (2002). Amplitude envelope onsets and developmental dyslexia: A new hypothesis. *Proceedings of the National Academy of Sciences, 99*, 10911–10916.

Goswami, U., Gerson, D., & Astru, L. (2009). Amplitude envelope perception, phonology and prosodic sensitivity in children with developmental dyslexia. *Reading and Writing: An Interdisciplinary Journal*. http://www.springerlink.com/content/eqk2318618670m36/. Accessed May 10, 2010.

Hämäläinen, J., Leppänen, P. H. T., Torppa, M., Müller, K., & Lyytinen, H. (2005). Detection of sound rise time by adults with dyslexia. *Brain and Language, 94*, 32–42.

Hämäläinen, J. A., Leppänen, P. H., Guttorm, T. K., & Lyytinen, H. (2008). Event-related potentials to pitch and rise time change in children with reading disabilities and typically reading children. *Clinical Neurophysiology, 119*, 100–115.

Heil, P. (2003). Coding of temporal onset envelope in the auditory system. *Speech Communication, 41*, 123–134.

Holliman, A. J., Wood, C., & Sheehy, K. (2008). Sensitivity to speech rhythm explains individual differences in reading ability independently of phonological awareness. *British Journal of Developmental Psychology, 26*, 357–367.

Jusczyk, P. W. (1992). Developing phonological categories from the speech signal. In C. A. Ferguson, L. Menn, & C. Stoel-Gammon (Eds.), *Phonological development: Models, research, implications*. Timonium, MD: York.

Kuhl, P. (2004). Early language acquisition: Cracking the speech code. *Nature Reviews Neuroscience, 5*, 831–843.

Kujala, T., Belitz, S., Tervaniemi, M., & Näätänen, R. (2003). Auditory sensory memory disorder in dyslexic adults as indexed by the mismatch negativity. *European Journal of Neuroscience, 17*, 1323–1327.

Liu, W., Shu, H., & Yang, Y. (2009). Speech perception deficits by Chinese children with phonological dyslexia. *Journal of Experimental Child Psychology, 103*, 338–354.

Lyytinen, H., Guttorm, T. K., Huttunen, T., Hämäläinen, J., Leppänen, P. H. T., & Vesterinen, M. (2005). Psychophysiology of developmental dyslexia: A review of findings including studies of children at risk for dyslexia. *Journal of Neurolinguistics, 18*, 167–195.

Manis, F. R., & Keating, P. (2005). Speech perception in dyslexic children with and without language impairments. In H. W. Catts & A. G. Kamhi (Eds.), *The connections between language and reading disabilities* (pp. 77–99). Mahwah, NJ: Erlbaum.

Manis, F. R., McBride-Chang, C., Seidenberg, M. S., Keating, P., Doi, L. M., Munson, B., et al. (1997). Are speech perception deficits associated with developmental dyslexia? *Journal of Experimental Child Psychology, 66*, 211–235.

Maurer, U., Bucher, K., Brem, S., & Brandeis, D. (2003). Altered responses to tone and phoneme mismatch in kindergartners at familial dyslexia risk. *NeuroReport, 14*, 2245–2250.

McBride-Chang, C. (1995). Phonological processing, speech perception and reading disability: An integrative review. *Educational Psychologist, 30*, 109–121.

McBride-Chang, C. (1996). Models of speech perception and phonological processing in reading. *Child Development, 67*, 1836–1856.

McBride-Chang, C., Cho, J., Liu, H., Wagner, R. K., Shu, H., Zhou, A., et al. (2005). Changing models across cultures: Associations of phonological awareness and morphological structure awareness with vocabulary and word recognition in second graders from Beijing, Hong Kong, Korea, and the United States. *Journal of Experimental Child Psychology, 92*, 140–160.

McBride-Chang, C., Lam, F., Lam, C., Doo, S., Wong, S. W. L., & Chow, Y. Y. Y. (2008). Word recognition and cognitive profiles of Chinese pre-school children at risk for dyslexia through language delay or familial history of dyslexia. *Journal of Child Psychology and Psychiatry, 49*, 211–218.

McBride-Chang, C., Tong, X., Shu, H., Wong, A. M.-Y., Leung, K., & Tardif, T. (2008). Syllable, phonemes, and tone: Psycholinguistic units in early Chinese and English word recognition. *Scientific Studies of Reading, 12*, 171–194.

Meng, X., Sai, X., Wang, C., Wang, J., Sha, S., & Zhou, X. (2005). Auditory and speech processing and reading development in Chinese school children: Behavioural and ERP evidence. *Dyslexia, 11*, 292–310.

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

Mody, M., Studdert-Kennedy, M., & Brady, S. (1997). Speech perception deficits in poor readers: Auditory processing or phonological coding? *Journal of Experimental Child Psychology, 64*, 199–231.

Moisescu-Yiflach, T., & Pratt, H. (2005). Auditory event related potentials and source current density estimation in phonologic/auditory dyslexics. *Clinical Neurophysiology, 116*, 2632–2647.

Molfese, D. L. (2000). Predicting dyslexia at 8 years of age using neonatal brain responses. *Brain and Language, 72*, 238–245.

Molfese, D. L., Molfese, V. J., & Modglin, A. (2004). Development of auditory event-related potentials in young children and relations to word-level reading abilities at age 8 years. *Annals of Dyslexia, 54*, 9–38.

Muneaux, M., Ziegler, J. C., Truc, C., Thomson, J., & Goswami, U. (2004). Deficits in beat perception and dyslexia: Evidence from French. *NeuroReport, 15*, 1–5.

Richardson, U., Thomson, J., Scott, S. K., & Goswami, U. (2004). Supra-segmental auditory processing skills and phonological representation in dyslexic children. *Dyslexia, 10*, 215–233.

Rvachew, S., & Grawburg, M. (2006). Correlates of phonological awareness in preschoolers with speech sound disorders. *Journal of Speech, Language, and Hearing Research, 49*, 74–87.

Schulte-Körne, G., Deimel, W., Bartling, J., & Remschmidt, H. (1998). Auditory processing and dyslexia: Evidence for a specific speech processing deficit. *NeuroReport, 9*, 337–340.

Serniclaes, W., Sprenger-Charolles, L., Carre, R., & Demonet, J.-F. (2001). Perceptual discrimination of speech sounds in developmental dyslexia. *Journal of Speech, Language, and Hearing Research, 44*, 384–399.

Shu, H., Peng, H., & McBride-Chang, C. (2008). Phonological awareness in young Chinese children. *Developmental Science, 11*, 171–181.

Talcott, J. B., Gram, A., van Ingelhem, M., Witton, C., Stein, J. F., & Toennessen, F. E. (2003). Impaired sensitivity to dynamic stimuli in poor readers of a regular orthography. *Brain and Language, 87*, 259–266.

Tallal, P. (1980). Auditory temporal perception, phonics, and reading disabilities in children. *Brain and Language, 9*, 182–198.
Thomson, J. M., Fryer, B., Maltby, J., & Goswami, U. (2006). Auditory and motor rhythm awareness in adults with dyslexia. *Journal of Research in Reading, 29*, 334–344.
Thomson, J. M., Goswami, U., & Baldeweg, T. (2009). The ERP signature of sound rise time changes. *Brain Research, 1254*, 74–83.
Wagner, R. K., & Torgesen, J. (1987). The nature of phonological processing and its causal role in the acquisition of reading skills. *Psychological Bulletin, 101*, 192–212.
Wang, M., Perfetti, C. A., & Liu, Y. (2005). Chinese-English biliteracy acquisition: Cross language and writing system transfer. *Cognition, 97*, 67–88.
Whalley, K., & Hansen, J. (2006). The role of prosodic sensitivity in children's reading development. *Journal of Research in Reading, 29*, 288–303.
Wood, C. (2006). Metrical stress sensitivity in young children and its relationship to phonological awareness and reading. *Journal of Research in Reading, 29*, 270–287.
Wood, C., & Terrell, C. (1998). Poor readers' ability to detect speech rhythm and perceive rapid speech. *British Journal of Developmental Psychology, 16*, 397–413.
Wood, C., Wade-Woolley, L., & Holliman, A. J. (2009). Prosodic awareness: Beyond phonemes. In C. Wood & V. Connelly (Eds.), *Contemporary perspectives on reading and spelling* (pp. 9–23). London: Routledge.
Xu, Y. (1991). Depth of phonological recording in short-term memory. *Memory & Cognition, 19*, 263–273.