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The development of stress sensitivity and its contribution to word reading in school-aged children

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Background: This study examined the development of stress sensitivity and its relationship with word reading. Previous research has rarely measured phoneme and stress sensitivity in the same task, making a direct comparison of the contribution between the two in reading development difficult.
Methods: Participants were native English-speaking adults and children at ages of 6, 8, and 10 years ($N = 24$, 22, 22, and 24, respectively). A lexical decision task was used to measure both stress and phoneme sensitivity. Oral vocabulary, phoneme awareness, and word reading were assessed.
Results: Stress sensitivity accounted for unique variance in reading over and above vocabulary and phoneme awareness in 6-year-olds. Both adults and children had better phoneme sensitivity than stress sensitivity.
Conclusions: These findings highlight the unique contribution of stress sensitivity in reading development. The current study made a novel contribution to studying the relationship between prosody and literacy by utilising a task that is able to assess children's stress and phoneme sensitivity simultaneously.

What is already known about this topic

- Prosody plays an important role in literacy acquisition across a variety of languages with word stress.
- Phoneme awareness as measured by the phoneme deletion task is one of the strongest predictors of reading development in English.
- Stress sensitivity may contribute to reading via vocabulary development, rime awareness, phoneme awareness, and morphological awareness.

What this paper adds

- Stress sensitivity made a unique contribution to word reading over and above oral vocabulary and phoneme awareness for 6-year-old children.
- Both stress and phoneme sensitivity was measured within the same task using the same set of materials.
- Both children and adults showed better phoneme sensitivity compared to stress sensitivity.

Implications for theory, policy, or practice

- Models delineating the relationship between prosody and literacy should consider unique variance explained by stress sensitivity in reading development.
- Children learning to read in English may need longer literacy exposure to develop better stress sensitivity because of the lack of regularity in English stress.
- Stress sensitivity may contribute to word reading given that it may help children understand stress assignment and learn unfamiliar stress representation as well as orthographic stress regularities.

Suprasegmental (or prosodic) features are speech attributes that accompany consonants and vowels but which are not limited to single sounds and often extend over syllables, words, or phrases (Crystal, 2003). Multiple components of suprasegmental information have been found to play important roles in literacy development, including stress, intonation, and timing, operating at different linguistic levels (word, phrase, and sentence) (Calet, Gutiérrez-Palma, Simpson, González-Trujillo, & Defior, 2015; Holliman, Wood, & Sheehy, 2010a,b; 2012, 2014b; Wood, 2006a). Stress is prominence given to a certain syllable in a word (Kager, 2007) and lexically contrastive in languages such as English, Spanish, and Dutch. These languages include minimal pairs of words that differ only in stress location (i.e. *trusty* and *trustee*). Stress may be important for word reading because it provides cues for both identifying grammatical categories and for parsing speech. The word *record* can be a noun or verb depending on stress assignment on the syllable. Speakers of English use stress productively to infer grammatical category when introduced to novel words, and likewise use grammatical category to infer stress (Kelly & Bock, 1988; Kelly, 1988). In addition, native listeners of English often parse a stressed syllable as the initial syllable of a meaningful word (i.e. *apple*, *ladder*) (Cutler & Butterfield, 1992). Motivated by the importance of stress sensitivity in language processing and its potential contribution to reading development, we examined the relationship between stress sensitivity and literacy acquisition among children at ages of six, eight, and ten, using just one task to tap into children's implicit knowledge of stress and phonemes simultaneously. The rationale for selecting these three age groups was that children at these ages are likely to represent beginning, intermediate, and advanced readers, allowing us to examine the developmental changes of sensitivity to segmental and suprasegmental information and the contribution of this sensitivity to word reading. Such cross-sectional design is one of the unique contributions of the current study to the literature; most previous studies have only focused on one age group to examine prosodic sensitivity and its relation to reading acquisition (e.g. Anastasiou & Protopapas, 2015; Holliman, Wood, & Sheehy, 2008; Gutiérrez-Palma & Palma-Reyes, 2007; Gutiérrez-Palma, Raya-García, & Palma-Reyes, 2009; Whalley & Hansen, 2006).

Phonological awareness is generally defined as the ability to identify, analyse, and manipulate sound units of the spoken words at the syllable, onset-rime, and phoneme level (Castles & Coltheart, 2004). Phonological awareness usually requires explicit attention to phonological units as objects of identification, analysis, and manipulation. Commonly used phonological awareness tasks in the literature include matching, blending, oddity, segmentation, or deletion tasks (see Lenchner, Gerber, & Routh, 1990, for a review). In the literature on prosody and reading, researchers have used the terms of prosodic sensitivity and prosodic awareness interchangeably (e.g. Goswami et al., 2013). However, in the current study, we considered awareness and sensitivity as two separate but related cognitive abilities. We defined stress awareness as a meta-linguistic skill which involves the ability to explicitly attend to the stress features in words. On the other hand, stress sensitivity involves implicit attention to the stress features. To the best of our knowledge, the majority of previous research on prosody and reading has used tasks that measured children's implicit attention to stress information (but see Anastasiou & Protopapas, 2015). In the current study, we used a lexical decision task to tap into children's sensitivity to stress information in relation to segmental information. This task requires no explicit attention to stress patterns or segments.

The development of stress sensitivity and its role in reading development

Research has shown that sensitivity to stress develops prelexically in infants learning contrastive stress languages. Spanish-learning infants could discriminate minimal stress pairs at nine months of age (Skoruppa et al., 2009, 2013). Stress sensitivity facilitates speech segmentation by helping the identification of word boundaries in infancy, and it continues to play a role in language acquisition in young children. As children's language processing abilities become more sophisticated and children begin to learn to read and write, stress sensitivity also plays a role in literacy development (Jusczyk, Houston, & Newsome, 1999). De Bree, Wijnen, and Zonneveld (2006) found that 3-year-old Dutch-speaking children at risk of dyslexia showed more difficulty imitating nonwords with stress patterns that are irregular or not allowed in Dutch compared to normally developing children, indicating a delay in word stress acquisition in the at-risk group.

Wood (2006a) tested English-speaking children's abilities to cope with stress errors in spoken words in a mispronunciation task. Children heard disyllabic words with initial stress and vowel reduction in the unstressed syllable, such as ‘sofa’ /ˈsoʊfə/, and saw the picture of a house containing multiple items and one of them was a sofa. A toy character mispronounced the word in four different ways: /soʊˈfaː/, /səˈfaː/, /ˈsiːfə/, and /ˈsiːfaː/. Children were asked to point to the item in the picture despite the mispronunciation. At ages 4–5, children's performance was most affected by the change of stress patterns (e.g. /ˈsoʊfə➔səˈfaː/) than by the other manipulations (e.g. /ˈsiːfə/, /oʊ➔iː/ or /ˈsiːfaː/, /oʊ➔iː/ and /ə➔aː/) (Study 1). At ages 5–7, children's performance accounted for significant variance in spelling abilities after controlling for phonological awareness and vocabulary (Study 2). To succeed at the mispronunciation task, children had to recover the correct stress pattern in order to match the stored representation of the target word in their lexicon (Holliman et al., 2012). The strength of this task is that it measures children's sensitivity to stress location and vowel change associated with stress. The use of toy characters and visual aids also make the task child-friendly. One limitation is that segments that are not associated with stress were not manipulated. Children did not hear mispronounced words such as /ˈsoʊpə/ (/f➔p/). Wood (2006a) measured sensitivity to segmental phonology using a separate task, making direct comparison between phoneme and stress sensitivity difficult.

The influence of stress sensitivity in literacy development is also observed in children learning to read a more transparent orthography such as Spanish. In a sequence recall task, children aged 7–8 years learned a pair of phoneme contrast (/ˈkupi-ˈkuti/) and a pair of stress contrast (/ˈmipa-miˈpa/). Children learned to associate the words with number keys on the computer (e.g. 1 for /ˈkupi/ and 2 for /ˈkuti/). In the test phase, children heard groups of 2, 3, or 4 nonwords and recalled the sequence by pressing the keys in the corresponding order (e.g. press 12 for /ˈkupi-ˈkuti/). Spanish-speaking children's stress sensitivity predicted nonword reading (Gutiérrez-Palma & Reyes, 2007) and accounted for a significant amount of variance in text reading (Gutiérrez-Palma et al., 2009). The sequence recall task is an online measure, and it uses nonwords; thus, children do not need to have large vocabulary size to perform well. This measure could tease apart the influence of lexical knowledge on stress sensitivity and tap into children's abstract representation of stress patterns. However, one limitation is that it places a high demand on short-term memory, as children have to store up to four nonwords in memory.

The relative importance of segmental and stress information in reading development

In beginning readers, it is well established that sensitivity to segmental phonology (i.e. phonemes, syllables, onsets, and rimes) is a strong predictor of reading ability (Blachman, 2000; Castles & Coltheart, 2004; Goswami & Bryant, 1990). According to the Psycholinguistic Grain Size Theory (Ziegler & Goswami, 2005), gaining access to phoneme-sized units is a crucial step for beginning readers of an alphabetic language because such access is necessary for the establishment of a complete mapping between phonemes and graphemes. It should be noted that the contribution of segmental phonology to literacy acquisition may be developmentally limited as children grow from phonologically mediated word recognition at early reading stages toward direct, non-mediated visual access at more advanced stages (Stanovich, 1986). In a longitudinal study in which 5 to 6-year-old children learning to read in English, Spanish, or Czech were tested for six time points at roughly 6 month interval, researchers found that phoneme awareness only predicted variation in reading growth between Time 1 and Time 4 (i.e. first 16 months of the study) but not between Time 4 and Time 6 (the final 12 months of the study) (Caravolas, Lervåg, Defior, Málková, & Hulme, 2013), suggesting that the role of segmental phonology in literacy acquisition in more advanced readers is much reduced.

Given the importance of segmental awareness in reading acquisition, it is necessary to take into account segmental awareness when addressing the influence of stress sensitivity on literacy acquisition. Some researchers observed that prosodic sensitivity is a significant predictor of reading development over and above what is already accounted for by phoneme awareness (English: Holliman et al., 2012; Wood, 2006a; Spanish: Calet, Flores, Jiménez-Fernández, & Defior, 2016; Gutiérrez-Palma et al., 2009) whereas others reported that sensitivity to speech prosody was no longer a significant predictor once awareness to segments was controlled for (David, Wade-Woolley, Kirby, & Smithrim, 2007; Goodman, Libenson, & Wade-Woolley, 2010). David et al. (2007) measured prosodic sensitivity using the Rhythmic Competency Analysis test in which children in Grades 1–5 were asked to use their hands or legs to produce beats in unison with the underlying beat of the music. In a series of hierarchical regression analyses, the researchers found that when the shared variance with phonological awareness was removed, rhythm accounted for nearly 9% of the variance in pseudoword reading in Grade 5 only. However, rhythm did not account for unique variance in real word reading in all grade levels after controlling for the contribution of phonological awareness. Goodman et al. (2010) used the mispronunciation task to examine 5-year-old children's stress sensitivity and found that after controlling for nonverbal IQ and vocabulary, stress sensitivity accounted for 15.2% of the unique variance in real word reading; however, when phonological awareness was entered in the hierarchical regression analysis before stress sensitivity, stress sensitivity was no longer a significant predictor of reading. It appears that whether the contribution of stress sensitivity to reading development is over and above that of phonological awareness is both task and age dependent.

Wood, Wade-Woolley and Holliman (2009) proposed a model with four pathways to explain the relationship between stress sensitivity and reading development. In all four pathways, stress sensitivity develops as a result of periodicity bias, an innate bias that predisposes children to tune in to the rhythmic characteristics of their native language. Stress may be the base for rhythm perception in stress-based languages, such as English and Dutch, which exhibit a strong contrast between strong and weak syllables and strong syllables have longer duration than weak syllables. In contrast, in syllable-based languages such as French and Spanish, the duration of each syllable is approximately equal (see Arvaniti, 2009 and Dauer, 1983 for further discussion about rhythmic categorisation). One of the pathways suggests that stress sensitivity facilitates children's spoken word recognition. Because stressed syllables often signal the beginning of a content word in English, rhythmic information may bootstrap the identification of word boundaries, which in turn helps the learning of new words. Vocabulary growth is associated with better phonological awareness, which then promotes the development of reading and spelling abilities (Ouellette, 2006; Walley, Metsala, & Garlock, 2003). Another pathway suggests that stress sensitivity is associated with phoneme awareness. Previous research with dyslexic children has found that phoneme identification is easier in stressed syllables than in unstressed syllables (Chiat, 1983). Wood (2006b) has reported that stress sensitivity was a significant predictor for phoneme awareness, which in turn is one of the strongest predictors of reading achievement (Hulme et al., 2002). In addition to vocabulary and phoneme awareness, the other pathways also suggest that the relationship between stress sensitivity and literacy can be explained via its link with rime or morphological awareness. More recently, Holliman et al. (2014a) found that the four pathways proposed by Wood et al. (2009) were too simplistic. Instead, there are interrelations among these variables in which vocabulary is related to morphology, rime is related to phoneme, and both rime and phoneme are related to morphology.

The mechanism underlying the contribution of stress sensitivity to word reading can be explained as follows. First, stress sensitivity is likely to be related to stress assignment, which is essential for reading words in a language with lexically contrastive stress and unpredictable stress location such as English. Stress assignment is important for distinguishing minimal pairs such as *forbear* /fɔːˈbɛə/ and /ˈfɔːˌbɛə/. When stress falls on the initial syllable, *forbear* is a noun and means ‘an ancestor’. When stress falls on the final syllable, *forbear* is a verb and means ‘to refrain from.’ Stress sensitivity may facilitate the access of the lexical and semantic representation of the target word and help children assign stress to the correct syllable. Gutiérrez-Palma et al. (2009) found that stress sensitivity accounted for a significant and unique amount of variance in stress assignment after controlling for working memory, phonological awareness, and phoneme sensitivity. Furthermore, Gutiérrez-Palma and Reyes (2007) showed that stress assignment was significantly correlated with both real word and nonword reading.

Second, stress sensitivity may also help children acquire stress representations of unfamiliar words. In English, the predominant stress pattern is initial stress as 90% of the content words begin with a stressed syllable (Cutler & Carter, 1987). Thus, trochee, a strong-weak pattern in disyllabic word (e.g. *table*), is the predominant stress pattern while iamb (e.g. *today*), a weak-strong pattern, is the non-predominant stress pattern. There is evidence suggesting that both school-aged children with normal reading development and children with dyslexia prefer the trochaic pattern to iambic (Anderson, Lin, & Wang, 2013). It is likely that children with higher stress sensitivity may read an unfamiliar polysyllabic word by stressing the first syllable.

Third, stress sensitivity may also help children learn orthographic stress regularities. Although there is no stress diacritic marking stress location in English, there are other orthographic cues to indicate stress. Two generalisations can be made about the orthographic cues for stress in disyllabic words (Kelly, 2004; Kelly, Morris, & Verrekia, 1998). First, the presence of more letters than necessary to represent a word's final phoneme indicates iambic stress. For example, the last letter in *discuss* is not necessary for pronouncing the phoneme /s/. Second, the number of words with trochaic stress increased significantly with the number of consonants in word onset position. Corpus analysis showed that when there is only one onset consonant, the proportion of trochaic words is 69%. When there are three onset consonants, the proportion of trochaic words increases to 98%. English speakers named and made lexical judgments faster for iambic words marked for stress than those unmarked for stress (Kelly et al., 2004). English speakers were also more likely to assign trochaic stress to disyllabic pseudowords when they begin with two consonants than when they begin with one consonant (Kelly, 1988). These results demonstrated that adults are aware of and could take advantage of the orthographic stress cues to facilitate lexical access. Although such results may not be generalisable to beginning readers, it is possible that children who are more sensitive to orthographic stress regularities may become better readers.

The current study

Previous research suggests that both awareness to segmental phonology and stress are significant predictors of reading development. The present study examined the development of stress sensitivity in comparison to phoneme sensitivity and the relative importance of segmental and stress sensitivity in reading development. In previous studies, phoneme awareness was often measured using a separate task. Differences in task design and demand may undermine the comparison of the respective contribution to reading by segmental and suprasegmental phonology. The current study adapted the Lexical Decision Task (LDT), which has been used previously to measure adult listeners' implicit awareness of stress patterns (Dupoux, Sebastián-Gallés, & Peperkamp, 2008; Lin, Wang, Idsardi, & Xu, 2014), for use with children. The LDT requires listeners to make an explicit judgment regarding the lexicality of the auditory stimulus. For example, the participant would need to indicate that 'table' is a real word, but that 'mable' and 'tuhBULL' are not. Because listeners' attention was not explicitly drawn to stress, the task could tap into the encoding of stress pattern in listeners' phonological representation of individual words. In addition, this task is less demanding to children's short-term memory because children only judge one word at a time. Another advantage of the LDT is that the nonwords used to measure stress and phoneme sensitivity were created from the same real word stimuli. As a result, stress and phoneme sensitivity measured by the LDT forms a more direct, precise comparison than that between phoneme awareness measured by, for example, the phoneme deletion task and stress sensitivity measured by another task, for example, mispronunciation or sequence recall.

We hypothesised that children's sensitivity to both phonemes and stress would improve with age. In a cross-sectional study, Wood (2006a) found that 7-year-old English-speaking children performed better than their 5-year-old counterparts in the mispronunciation task, suggesting increased sensitivity to stress errors with maturation and more literacy exposure. Gutiérrez-Palma and Reyes (2007) found that 7 to 8-year-old children were significantly more accurate with the phoneme contrast (e.g. /ˈkupi-ˈkuti) than the stress contrast (e.g. /ˈmipa-miˈpa/) in the sequence recall task; we therefore hypothesised that children will show better phoneme sensitivity than stress sensitivity in the LDT in the current study. In addition, based on previous studies (e.g. Holliman et al., 2012; Wood, 2006a), we hypothesised that both phoneme and stress sensitivity would be significant, but distinct, predictors of word reading. We sought to examine carefully the relationship between stress sensitivity and reading development that is beyond vocabulary and phoneme awareness. If stress sensitivity remains a significant predictor of reading after controlling for vocabulary and phoneme awareness, this would be considered strong evidence supporting the unique relationship between stress and literacy acquisition.

Methods

Participants

Twenty-four 6-year-olds (M_{age} = 6.17, male = 9), 22 8-year-olds (M_{age} = 8.21, male = 5), 22 10-year-olds, (M_{age} = 10.25, male = 7), and 24 adults (M_{age} = 23.8, male = 8) were tested. Children participants were from mid-sized cities in the tri-state area of the mid-Atlantic region in the U.S. Adult participants were from the student population in a mid-Atlantic university. They were all native English speakers. Information about children's health and development and language background was collected from a parental demographic questionnaire. Two 6-year-olds and five 10-year-olds were excluded from data analyses because of mental or learning disabilities (i.e. dyslexia, autism, and anxiety) or behavioral problems (i.e. ADHD). Also, two 8-year-olds were excluded because their primary language spoken at home was not English. None of the adult participants reported having any vision or hearing impairment.

Materials

Lexical decision task. Forty disyllabic words and 44 trisyllabic words were chosen from *The American Heritage Frequency* book (Carroll, Davies, & Richman, 1971), which provided frequency of occurrence in reading materials for children in Grades 3–5. These words were specifically selected to ensure that stimuli in the phoneme and stress conditions were perfectly matched in terms of the number and types of sounds. Half of the 40 disyllabic words were initial-stressed while the other half were final-stressed. The mean whole word frequency of disyllabic words with initial-stress and final-stress was 510.35 (per million, $SD = 935.64$) and 315.05 ($SD = 464.75$), respectively. This difference was not significant, $t(38) = .682$, $p = .501$. The difference in number of phonemes also did not reach significance (initial stress: 4.7, final-stress: 5.1; $t(38) = -1.744$, $p = .089$). Half of the 44 trisyllabic words had initial-stress while the other half had medial-stress. The mean whole word frequency of trisyllabic words with initial-stress and medial-stress was 107.63 and 112.18, respectively. This difference was not significant, $t(42) = -.086$, $p = .932$. The trisyllabic words also did not differ significantly in terms of number of phonemes (initial-stress: 6.6, medial-stress: 6.9; $t(42) = -1.05$, $p = .298$).

Stress-changed nonwords were created by changing the stress location of the real words. We only modified initial and medial stress positions for trisyllabic words because in English there are a greater number of words with initial- and medial-stress than final stress (Lin et al., 2014). Phoneme-changed nonwords were created by changing one phoneme in the disyllabic words and two phonemes in the trisyllabic words. The rationale for changing two phonemes in the trisyllabic words was to make the difference between a real word and its corresponding nonword more distinct, resulting in an easier lexicality judgment for participants. For example, for the disyllabic word *cabin* /ˈkæbɪn/, the stress-changed nonword was /kæˈbɪn/ and the phoneme-changed nonword was *calin* /ˈkælɪn/. For the trisyllabic word *accident* /ˈæksɪdənt/, the stress-changed nonword was /ækˈsɪdənt/ and the phoneme-changed nonword was *acpivent* /ˈækpɪvənt/ (i.e. /s➔p/ and /d➔v/). The stimuli used in this task are listed in Supporting Information.

The auditory stimuli were recorded by a female native English speaker in a sound-reduced booth using a Shure SM51 microphone and Syntrillium Cool Edit at 44.1 kHz and 16 bits precision. The speaker recorded the stress-changed nonwords by changing the vowel quality accordingly. In other words, a schwa in the real word was pronounced as a full vowel in the stress-changed nonword, while a full vowel in the real word was reduced in the stress-changed nonword (i.e. *family* /ˈfæməli➔fəˈmili/). To ensure this manipulation was successful, acoustic correlates of the stressed and unstressed syllables in the stress-changed nonwords were measured using Praat (Boersma & Weenink, 2010). A series of t-tests showed that stressed syllables have higher pitch (*Mean Difference* = −57.54 Hz, $t(90) = -7.45$, $p < .001$), longer duration (*Mean Difference* = −106.78 ms, $t(90) = -5.61$, $p < .001$), and stronger intensity (*Mean Difference* = −3.30db, $t(90) = -5.53$, $p < .001$) than unstressed syllables. These results suggest that the stress-changed nonwords maintain the stress characteristics of real words.

Each stimulus was manually cut using Praat to ensure there was no silence at the onset or offset of the word. Intensity was normalised for all stimuli at 70 db. Acoustic measurements of pitch and duration were taken for the real words and nonwords. One-way ANOVAs showed that for both disyllabic and trisyllabic words, there was no significant difference in pitch and duration (ms) among the three conditions (all ps $> .1$). The stimuli were divided into three lists. For example, if the real word *cabin* was assigned to List 1, the phoneme-changed version was assigned to List 2, and the stress-changed version was assigned to List 3. Each participant was randomly assigned to one of the three lists so that he/she only heard one version of each word.

Procedure

Task instructions were displayed on PowerPoint slides and read to the participants by the experimenter. The participants were told to press the √ key if they decided what they heard was a real word and press × if they decided what they heard was a silly made-up word. The experimenter played six auditory stimuli, three real words and three nonwords, and asked the participant 'what would you do?' The experimenter provided oral feedback. Finally, the experimenter told the participant to try more examples and answer as quickly and correctly as possible. Afterwards, the experimenter initiated the task implemented via the E-prime software (Psychology Software Inc., Pittsburgh, PA). Each trial began with a fixation sign '+' written in Courier New font displayed in the center of the screen for 500 ms, followed by the auditory stimulus. The trial terminated as soon as the participant made a response or after 5000 ms. The task was divided into two blocks with a break in between. The first block consisted of 40 disyllabic items while the second block consisted of 46 trisyllabic items. Participants received six practice trials with visual feedback at the beginning of each block. E-prime randomised the order of the test trials and automatically recorded participants' response accuracy and latency.

Other measures

Word reading. Children's English word reading skills were assessed using the Letter–Word Identification subtest from the Woodcock–Johnson III Tests of Achievement (WJ-III; Woodcock, McGrew & Mather, 2001). The test was slightly modified so that the first 14 items were skipped. The first 14 items were all individual letters, and we assumed that children with normal reading development at first grade and beyond should be able to read the entire alphabet. The remaining 62 items were visually presented on PowerPoint slides, with two words on each slide. Children were instructed to read aloud the words one at a time. The experimenter recorded the accuracy of children's response, giving 1 point for a correct response and 0 points for an incorrect response; hence, the maximum score is 62 points. The experimenter terminated the test if the child made six consecutive incorrect responses (Cronbach's α = .751).

Receptive vocabulary. Children's receptive vocabulary skills were assessed using the Peabody Picture Vocabulary Test, Fourth Edition (PPVT-4, Dunn & Dunn, 2007). The test was administered based on standardised procedures and scored based on national norms (Cronbach's α = .94). The maximum raw score is 204, although the maximum standardised score varies based on age norms.

Phoneme awareness. Children's phoneme awareness was assessed using the phoneme deletion task that has been successfully used in previous studies (i.e. Anderson & Wang, 2012; Anderson et al., 2013). Children first heard a nonword presented via headphones and were asked to repeat it. Then they were instructed to produce a new word after removing a sound in the nonword. For example, children heard 'say *mab*, now say it again but don't say the /b/' (the correct response is /ab/). Only nonwords were used in this task to control for the effects of lexical knowledge on phoneme awareness. There were four practice items and 20 test items. The targeted phoneme for deletion varies in position (see Anderson et al. 2013 for details). Children's responses were recorded via a microphone. One point was given for a correct response and 0 points were given for an incorrect response; hence, the maximum score is 20 points (Cronbach's α = .886).

All children received the LDT, followed by the non-computer tasks. The order of the non-computer tasks was counterbalanced. All adults received the LDT first, followed by a screening survey.

Results

Table 1 shows children's performance in the phoneme deletion task, PPVT (both raw and standard scores), and WJ-III. One-way ANOVAs revealed a significant age effect in phoneme deletion accuracy, $F(2, 46) = 8.856$, $p = .001$, PPVT standard scores, $F(2, 55) = 5.822$, $p = .005$, and reading scores, $F(2, 50) = 30.234$, $p < .001$. In the phoneme deletion task, 10-year-olds were significantly more accurate than both six-, $t(35) = -4.083$, $p = .001$, and 8-year-olds, $t(26) = -2.432$, $p = .002$, although there was no significant difference in accuracy between six and 8-year-olds, $t(31) = -1.050$, $p = .302$. Six-year-olds had higher PPVT scores than 8-year-olds, $t(39) = 2.032$, $p = .049$, and 10-year-olds, $t(37) = 3.300$, $p = .002$, although there was no significant difference between 8 and 10-year-olds, $t(34) = 1.381$, $p = .176$. It should be noted that only standard PPVT scores were used in analysis; hence, the age effect had been supposedly accounted for. Eight-year-olds had significantly higher word reading scores than 6-year-olds, $t(35) = -4.855$, $p < .001$. Ten-year-olds had significantly higher reading scores than 6 and 8-year-olds, $t(35) = -7.619$, $p < .001$ and $t(30) = -2.405$, $p = .023$, respectively.

LDT

Tables 2 and 3 show children and adults' accuracy rates and response times (RT) in the LDT, respectively. Disyllabic and trisyllabic items were combined to simplify the presentation of results. Only RT data of correct responses were included in the analysis, resulting in the loss of 11% of data. Furthermore, RTs less than 500 ms (all auditory stimuli were longer than 600 ms) or greater than 4000 ms were excluded (additional 0.7% loss of data). Given the large amount of RT data loss, subsequent analyses were focused on accuracy data only. Because two thirds of the items in the LDT were nonwords, there were an unequal amount of 'Yes' and 'No' responses, resulting in higher accuracy scores for participants that were biased to press 'No'. To take into account this potential bias, we calculated D-prime scores in the phoneme-changed and stress-changed condition, respectively (Figure 1).

Table 1. Children's performance in the phoneme deletion Task, PPVT, and WJ-III.

Age group	Phoneme deletion (numbers correct)	PPVT (raw scores)	PPVT (standardised scores)	WJ-III (numbers correct)
6	4.190 (3.234)	134.045 (13.768)	124.818 (10.738)	19.095 (11.202)
8	5.500 (3.802)	151.947 (12.559)	118.000 (10.687)	35.375 (8.421)
10	9.625 (4.856)	168.882 (13.665)	112.882 (11.548)	41.937 (6.942)

Note. Numbers in parenthesis are standard deviations. Maximum score for Phoneme Deletion is 20. Maximum raw score for PPVT is 204, and the maximum standardised score varies based on age norms. Maximum score for WJ-III is 62.

Table 2. Accuracy rates and D-prime scores in the lexical decision task.

Age group	Real word	Phoneme-changed		Stress-changed	
	Accuracy	Accuracy	D-prime	Accuracy	D-prime
6	.835 (.371)	.873 (.333)	2.774 (1.325)	.819 (.385)	2.200 (.917)
8	.892 (.310)	.885 (.319)	2.874 (1.152)	.848 (.359)	2.469 (.780)
10	.971 (.167)	.930 (.255)	4.180 (1.334)	.814 (.389)	3.528 (1.374)
Adults	.977 (.151)	.958 (.201)	4.936 (1.207)	.884 (.321)	4.373 (1.434)

Note. Numbers in parenthesis are standard deviations.

Table 3. Response times (ms) in the lexical decision task.

Age group	Real word	Phoneme-changed	Stress-changed
6	1658 (537)	1673 (598)	1603 (616)
8	1531 (498)	1582 (583)	1627 (601)
10	1379 (422)	1586 (589)	1602 (623)
Adults	1045 (232)	1165 (302)	1192 (371)

Note. Numbers in parenthesis are standard deviations.

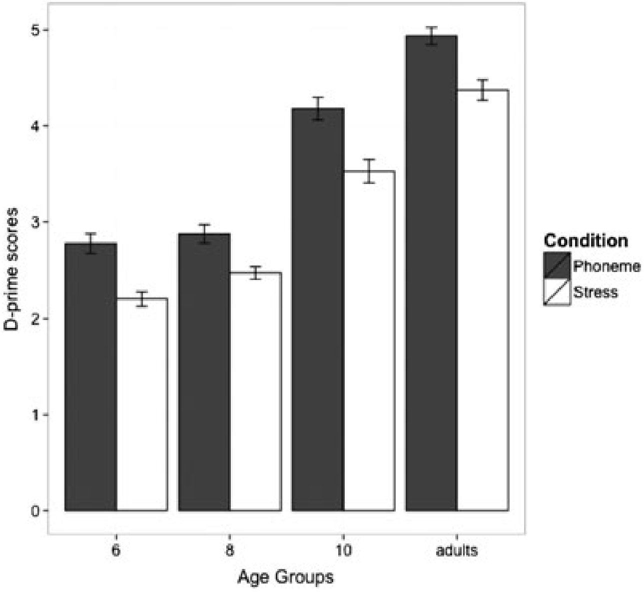

Figure 1. Results of the lexical decision task (error bars represent standard errors).

Phoneme versus stress-changed conditions. A 2 (condition: phoneme vs. stress) × 4 (age group: 6, 8, 10, and adults) × 3 (list: 1, 2, and 3) repeated-measure ANOVA was conducted to compare the developmental trends between phoneme and stress sensitivity. Condition was a within-subject factor, while age group and list were between-subject factors.

Post-hoc multiple comparisons were conducted with Tukey contrasts and adjusted p-values. Given that D-prime scores were based on individual participants' sensitivity, taking into account both real word and nonword items, we only presented results from subject analysis. The main effect of condition was significant, $F(1, 70) = 28.648$, $p < .001$. All participants had significantly higher phoneme sensitivity than stress sensitivity. The main effect of age group was significant, $F(3, 70) = 18.991$, $p < .001$. The main effect of list was significant, $F(2, 70) = 4.761$, $p = .011$, and the only significant pairwise comparison was that participants in List 2 showed higher sensitivity than those in List 1, $t(95) = -2.690$, $p = .023$. All other main effects and interactions were not significant (all ps $> .1$). Planned pairwise comparisons were conducted to compare the developmental trajectory of phoneme and stress sensitivity. For phoneme sensitivity, 10-year-olds were significantly better than 6-year-olds ($p = .008$) and 8-year-olds ($p = .039$), adults were better than 6-year-olds ($p < .001$) and 8-year-olds ($p < .001$). For stress sensitivity, adults were significantly better than 6 and 8-year-olds ($p < .001$ and $p = .002$, respectively). There was no significant age difference found between 6 and 8-year-olds or between 10-year-olds and adults for both types of sensitivity (all ps $> .1$).

Predicting word reading in children

Correlation was conducted using the polycor package (Fox, 2010) in R studio (R Development Core Team, 2008). Age group was treated as an ordinal variable with a hidden normal distribution while other variables were treated as continuous. Therefore, the analysis between age group and other variables was conducted using polyserial correlation, while the analysis among continuous variables was conducted using Pearson correlation. D-prime scores for phoneme sensitivity were positively correlated with age group, phoneme deletion, and word reading while RTs in the phoneme-changed condition were negatively correlated with reading. D-prime scores for stress sensitivity were positively correlated with age group, word reading, and D-prime scores for phoneme sensitivity. RTs in the stress-changed condition were positively correlated with RTs in the phoneme-changed condition. Because the D-prime scores and RTs were not significantly correlated, there should be minimal trade-off between speed and accuracy (Table 4).

To examine the relationship between sensitivity to segmental and suprasegmental phonology and reading development, a series of hierarchical regression analyses were conducted for each age group. The rationale for separating the age groups was twofold. First, the age span between 6 and 10 was relatively large. Previous studies examining the relative contribution of phoneme awareness and stress sensitivity to literacy acquisition have only combined ages within two-three years such as 5–7 (Wood, 2006a) or 7–8 (Gutiérrez-Palma & Reyes, 2007). Second, the contribution of phonological awareness to literacy may be developmentally limited (e.g. Stanovich, 1986). Hence, dividing up the age groups would allow us to examine the relative contribution of phoneme and stress sensitivity to literacy at more fine-grained reading levels. In each hierarchical regression, PPVT standard scores were always entered in the first step to control for oral vocabulary; D-prime scores for stress and phoneme sensitivity were entered in the second or third step. In another set of analysis, D-prime scores for phoneme sensitivity were replaced with scores from the phoneme deletion task because phoneme awareness assessed by this task has been shown to be a robust predictor of reading abilities in previous research (e.g. Anderson et al., 2013).

Table 4. Correlation among age, phoneme deletion scores, oral vocabulary, word reading scores, and performance in the lexical decision task (LDT).

	Age group	Pho Del	Vocab	WJ	LDT _ RT2	LDT _ Dprime2	LDT _ RT3	LDT _ Dprime3
Age group	1							
PhoDel	.544***	1						
Vocab	-.346**	.093	1					
WJ	.864***	.635**	-.021	1				
LDT _RT2	-.205	-.160	-.041	-.360**	1			
LDT_Dprime2	.343**	.393*	-.105	.441**	-.079	1		
LDT _RT3	-.041	-.028	-.049	-.161	.835**	.037	1	
LDT_Dprime3	.472**	.286	-.231	.470**	-.140	.763**	.012	1

Note. PhoDel = Phoneme Deletion, Vocab = Vocabulary (i.e. PPVT standard scores), WJ = reading scores. Dprime = D-prime scores, 2 = phoneme-changed condition, and 3 = stress-changed condition.
$^{***}p < .001$.
$^{**}p < .01$.
$^{*}p < .05$.

Results (see Table 5) showed that for 6-year-old children, stress sensitivity remained a unique and significant predictor of word reading after controlling for oral vocabulary and phoneme sensitivity ($p = .043$). Similarly, stress sensitivity accounted for unique variance in reading after taken into account vocabulary and phoneme awareness ($p = .030$). Neither phoneme sensitivity nor phoneme awareness was a significant predictor of reading after controlling for vocabulary and stress sensitivity (both ps $> .1$). For 8-year-olds, neither phoneme nor stress sensitivity was a significant predictor of reading regardless of its order of entry. For 10-year-old children, phoneme awareness accounted for significant amount of unique variance in word reading after controlling for oral vocabulary and stress sensitivity ($p < .001$).

Discussion

The current study examined the development of stress sensitivity and the relative importance of phoneme and stress sensitivity in reading development. Phoneme awareness, measured by the phoneme deletion task in our study, was a unique predictor of word reading for 10-year-old children, independent of oral vocabulary and stress sensitivity. This finding suggests that phoneme awareness remains an important contributor of literacy acquisition for more advanced readers. However, phoneme sensitivity, operationally defined as the D-prime scores calculated from the real word and phoneme-changed conditions of the LDT, did not account for unique variance in reading in any of the age groups after controlling for oral vocabulary and stress sensitivity. Unlike phoneme deletion, the lexical judgment of phoneme-changed nonwords does not necessarily require the ability to explicitly manipulate individual sounds in the auditory stimulus, which is an essential ability needed for word reading. Our results showed that stress sensitivity accounted for unique variance in 6-year-old children's word reading over and above oral vocabulary, phoneme sensitivity or phonemic awareness. This finding adds to a growing body of research showing the unique importance of prosodic sensitivity in reading development over and above

Table 5. Results from the hierarchical regression analysis predicting word reading in each age group.

	Step	Predictor	β	β Sig.	ΔR^2	ΔF	ΔF Sig.
Age 6	1	PPVT	−.005	.980	.051	1.018	.326
	2	Dstress	.449	.043	.311	8.771	.008
	3	Dphoneme	.189	.436	.023	.637	.436
	2	Dphoneme	.189	.436	.160	3.652	.072
	3	Dstress	.499	.043	.174	4.807	.043
	1	PPVT	.036	.852	.051	1.018	.326
	2	Dstress	.485	.030	.311	8.771	.008
	3	PhoDel	.285	.165	.070	2.107	.165
	2	PhoDel	.285	.165	.14	4.614	.046
	3	Dstress	.485	.030	.188	5.619	.030
Age 8	1	PPVT	.734	.003	.485	13.161	.003
	2	Dstress	−.257	.439	.012	.318	.582
	3	Dphoneme	.456	.179	.073	2.037	.179
	2	Dphoneme	.456	.179	.062	1.788	.204
	3	Dstress	−.257	.439	.023	.642	.439
	1	PPVT	.559	.087	.439	7.815	.019
	2	Dstress	−.078	.823	.006	.101	.758
	3	PhoDel	.269	.488	.034	.528	.488
	2	PhoDel	.269	.488	.037	.637	.445
	3	Dstress	−.078	.823	.003	.053	.823
Age 10	1	PPVT	.807	.001	.622	23.003	.000
	2	Dstress	.170	.645	.002	.071	.794
	3	Dphoneme	−.251	.493	.015	.501	.493
	2	Dphoneme	−.251	.493	.010	.367	.555
	3	Dstress	.170	.645	.007	.224	.645
	1	PPVT	.557	.001	.622	23.003	.000
	2	Dstress	−.015	.893	.002	.071	.794
	3	PhoDel	.554	.000	.250	23.660	.000
	2	PhoDel	.554	.000	.252	25.781	.000
	3	Dstress	−.015	.893	.000	.019	.893

Note. PhoDel = Phoneme Deletion, Dphoneme = D-prime scores for phoneme sensitivity, Dstress = D-prime scores for stress sensitivity.

sensitivity to segmental phonology (e.g. Holliman et al. 2010a,b, 2012; Wood, 2006a). Stress sensitivity appears to be an important predictor of reading across languages with lexically contrastive stress including Spanish (Calet et al., 2015; Gutiérrez-Palma, et al., 2009), Greek (Anastasiou & Protopapas, 2015), and Dutch (Goetry, Wade-Woolley, Kolinsky, & Mousty, 2006). With regards to Wood et al.'s (2009) model, our findings with 6-year-old children suggest that in addition to the pathways where stress sensitivity facilitates word reading via vocabulary growth or via phoneme awareness, there may be a direct pathway where stress sensitivity contributes to reading over and above oral vocabulary as well as phoneme awareness for beginning readers.

Stress sensitivity did not account for significant unique variance in reading for both 8 and 10-year-olds. It is possible that children at the beginning stage of learning to read tend to take advantage of all available resources during the learning process and these resources include their awareness of segmental phonology, letter knowledge, vocabulary size, rapid automatic naming (RAN), working memory, as well as sensitivity to suprasegmental phonology. Longitudinal studies following children from kindergarten to elementary school have shown that the influences of vocabulary, RAN, and letter knowledge on word reading faded with development (De Jong & van der Leij, 1999; Torgesen, Wagner, Rashotte, Burgess, & Hecht, 1997; Wagner et al., 1997). As children become more advanced readers, they may have established a hierarchy in which phoneme awareness outweighs stress sensitivity in terms of its importance to literacy. Previous research with adults also showed that segmental information plays a stronger role than suprasegmental information in both spoken word recognition (e.g. Tong, Francis & Gandour, 2008) and visual word recognition (e.g. Li, Lin, Wang & Jiang, 2013).

One of the unique contributions of the current study to the growing body of literature on prosody and literacy was using the LDT that assessed phoneme and stress sensitivity within the same measurement. It seems that children's stress sensitivity generally develops at a slower pace than their phoneme sensitivity. For phoneme sensitivity, children showed steady improvement between ages 6 and 10, and ages 8 and 10. Similarly for phoneme awareness, there was consistent growth between ages 6 and 10 and ages 8 and 10. These results suggest that children's sensitivity to segmental information improves with age and literacy exposure. This similar pattern of better performance across age groups in both the phoneme-changed condition of the LDT and phoneme deletion task highlights the development of phonemic skills under different task demands. Better performance in the phoneme deletion task suggests that older children have improved metalinguistic awareness, verbal short-term memory, and speech perception skills (see McBride-Chang, 1995 for a review). Judging the lexicality of phoneme-changed nonwords in the LDT involves correctly perceiving and matching the incoming auditory information to the stored representation of real words in children's mental lexicon (Rubenstein, Lewis, & Rubenstein, 1971). Better phoneme sensitivity by 10-year-olds compared to 6 or 8-year-olds suggests that older children have a larger lexicon and the phonological representation of words in their mental lexicon is more fine-grained. Children was unlikely to reject the nonword *calin* if the lexical representation of *cabin* is absent or the stored representation is not as detailed and precise as individual phonemes /k-æ-b-ɪ-n/. Overall, the current study demonstrated that children's sensitivity to speech segments, in the form of metalinguistic awareness of sounds as well as the fine-grained phonological representation in lexical access, continues to develop beyond the early years of schooling.

All three age groups of children had significantly higher phoneme sensitivity than stress sensitivity. Moreover, our results showed that stress sensitivity did not improve steadily from ages 6–10. Instead, significant age difference was only observed between age 6 and adults and between age 8 and adults. It appears that increased exposure to written words in early school years does not benefit the development of stress sensitivity to the same extent as it does to the development of phoneme sensitivity. Because stress is not explicitly marked in English orthography, it is likely to be less salient in the process of word reading compared to segmental information, which are represented visually by letters (although the phoneme-grapheme mapping is less transparent in English orthography than other alphabetic scripts). We speculate that more years of reading experiences may be necessary in order for the benefit provided by print exposure to have an effect on the efficiency of activating stress representation of words in the mental lexicon. It is likely that older children may demonstrate a faster growth of stress sensitivity when entering middle schools. In addition, our finding that significant difference in D-prime scores was absent when comparing between younger and older children but present when comparing adults and children suggests that children continue to develop processing efficiency of stress beyond elementary school years.

Adults in the current study also had more difficulty with stress-changed nonwords compared to phoneme-changed nonwords and this finding is consistent with Lin et al. (2014, Experiment 2). In their LDT, native English-speaking adults' mean accuracy was 88.6% in the phoneme-changed condition but only 77.8% in the stress-changed conditions for nonwords with vowel change. English speakers also scored lower accuracy in the stress condition compared to the phoneme condition in a sequence recall task (Lin et al. 2014, Experiment 1). This inherent difficulty with stress in comparison to phoneme judgment has also been shown in Spanish, a language that does not use vowel reduction to signal stress, with native Spanish-speaking children (Gutiérrez-Palma & Palma-Reyes, 2007). Taken together, it appears that stress processing is inherently more difficult than phoneme processing in tasks that measure implicit sensitivity and this difficulty is likely not a language- or reading-level specific phenomenon.

It is important to note that English may not be the ideal language to examine the relative importance of segmental phonology versus stress in reading development. The principle auditory cues that correlate with word stress in English include suprasegmental components (i.e. pitch, duration, and intensity) as well as segmental components (i.e. vowel quality) (Fry, 1958). Given that both suprasegmental and segmental cues were changed in the nonwords, it is difficult to tease apart which phonological component plays a more important role in spoken word recognition. This question may be better answered by replicating the LDT in languages without vowel reduction such as Spanish or systematically manipulating the presence or absence of vowel change in the stress-changed nonwords as the LDT designed in Lin et al. (2014). Future research also needs to draw further attention to the 8-year-old children as this age group did not show the prediction from either stress sensitivity or phoneme awareness as did the 6-year-olds or 10-year-olds. Eight-year-olds may be in the transitional stage when their reliance on both segmental and stress information in lexical access is not stabilised.

To conclude, the current study employed a LDT in which nonwords were created by changing the phonemes or stress location in real words to assess children's implicit sensitivity of phonemes and stress patterns. Significant improvement in performance from ages 6 to 10 was observed for phoneme sensitivity but not for stress sensitivity. Stress sensitivity was a significant predictor of word reading for 6-year-old children after controlling for oral vocabulary and phoneme awareness. These findings point to the potential importance of stress sensitivity in literacy acquisition for beginning readers. There is significant implication for educational practices. Instructional activities that can strengthen young children's implicit and explicit sensitivity of stress may result in important gains on improving reading abilities. Furthermore, if stress sensitivity is indeed associated with beginning reading (e.g. de Bree et al. 2006), there is potential for researchers to incorporate assessments of stress sensitivity for diagnosis or intervention of reading disabilities.

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