Language and
Linguistics Compass

A Neural Oscillations Perspective on Phonological Development and Phonological Processing in Developmental Dyslexia

Journal:	*Language and Linguistics Compass*
Manuscript ID	LNCO-0755.R2
Wiley - Manuscript type:	Article
Keywords:	Cognitive Science of Language < Compass Section, Phonetics & Phonology < Compass Section, Language Teaching < Applied Linguistics < - Subjects, Language Acquisition < Psycholinguistics < - Subjects, Perception < Speech Science < - Subjects, child language < - Key topics, development < - Key topics

Abstract

Children’s ability to reflect upon and manipulate the sounds in words (’phonological awareness’) develops as part of natural language acquisition, supports reading acquisition, and develops further as reading and spelling are learned. Children with developmental dyslexia typically have impairments in phonological awareness. Many developmental factors contribute to individual differences in phonological development. One important source of individual differences may be the child’s sensory/neural processing of the speech signal from an amplitude modulation (~ energy or intensity variation) perspective, which may affect the quality of the sensory/neural representations (’phonological representations’) that support phonological awareness. During speech encoding, brain electrical rhythms (oscillations, rhythmic variations in neural excitability) re-calibrate their temporal activity to be in time with rhythmic energy variations in the speech signal. The accuracy of this neural alignment or ’entrainment’ process is related to speech intelligibility. Recent neural studies demonstrate atypical oscillatory function at slower rates in children with developmental dyslexia. Potential relations with the development of phonological awareness by children with dyslexia are discussed.

Keywords: dyslexia, oscillations, phonological processing

Introduction

Individual differences in children's 'phonological awareness' (their awareness of the sound structure of words as measured by behavioural tasks) are related to their progress in reading and spelling development, and this relationship has been found in all languages so far studied (Ziegler & Goswami, 2005). A range of oral tasks has been developed to measure 'phonological awareness' at different linguistic levels, for example rhyme judgement (which is the 'odd word out' from "cot" "pot" "hat"?), syllable counting (how many syllables in "caterpillar"?), and judgements about syllable stress patterns (which is correct, "SO-fa" or "so-FA"; Bradley & Bryant, 1983; Liberman et al., 1974; Wood, 2006). Awareness of these different levels of phonology is considered to be present in young children before reading is taught. These data suggest that the sensory/neural representations developed by the *preliterate* brain for processing spoken language ('phonological representations') are sufficiently well-specified to enable children to identify larger phonological units when responding in phonological awareness tasks, units such as syllables and rhymes. By contrast, children's awareness of the individual speech sounds in words (phonemes, approximately equivalent to the sound elements represented by the alphabet) develops largely as a consequence of reading instruction (Ziegler et al., 2010; Castro-Caldas et al, 1998). Before literacy is taught, pre-reading children (and illiterate adults) perform poorly on phoneme-level tasks (e.g., "What is the second sound in the word 'train'?"). However, pre-reading children and illiterate adults show good awareness of larger phonological units within words, such as syllables and rhymes. Accordingly, this review of the child's sensory/neural processing of the speech signal as related to their phonological awareness will focus on pre-literate phonology and explore the sensory/neural factors that support the identification of syllable stress, syllables and rhyme.

It is important to note that many factors other than sensory/neural processing also determine the child's development of phonological awareness, as depicted in Figure 1. Some factors, such as age of acquisition of words and vocabulary size, are likely to be language universal, while others such as phonological neighbourhood density (the number of words that are 'neighbours' of a target word because they share sounds in common) will be language specific. Nevertheless, most of these lexical factors operate in similar ways in children with and without dyslexia (Thomson et al., 2005). Importantly, learning to read and spell changes phonological awareness. Learning to read and spell is particularly important for the development of phoneme awareness. For example, when asked to choose pictures whose names began with the same sound as "truck", children who were readers chose items like "turkey", while pre-literate children frequently chose items like "chair" (Read, 1986). Read argued that this occurred because the 't' sound in "truck" is affricated and hence is phonologically closer to "ch", a phonetic distinction still heard by the pre-literate brain. Indeed, the young pre-readers studied by Read would mis-spell 'truck' as 'chrac' and 'ashtray' as 'aschray', errors that disappear as children learn conventional spelling patterns. Hence learning spelling patterns changes speech perception (see also Ehri & Wilce, 1980; readers hear more phonemes in the word PITCH than in the word RICH). While many factors will play a role in the development of a high-quality phonological system (see Figure 1), the efficiency of children's sensory/neural processing of acoustic information appears to be a key source of individual differences in phonological learning (Goswami, 2015). The nature of the sensory/neural processing that may govern individual differences in the quality of children's phonological representations is the focus of this paper.

Figure 1 about here

The Phonological Hierarchy and the Amplitude Modulation Hierarchy

The different levels of phonological awareness demonstrated in behavioural studies with children can be conceptualised as a linguistic hierarchy, in which awareness of larger phonological units, like syllables, emerges prior to awareness of smaller phonological units, like rhymes or phonemes. This phonological hierarchy can also be described in terms of hierarchically-nested levels of rhythmic organisation of speech (as proposed by linguists like Liberman & Prince, 1977). The higher organisational level of the *stress foot*, a rhythmic unit that contains a strong syllable and one or more weaker syllables (as in "PUSSycat" or "MONkey"), governs the positioning of syllables and phonemes, so that prosodic structure is determined by the positioning of larger phonological units such as stressed syllables. Children with developmental dyslexia show reduced awareness of phonology at all levels in the hierarchy, including syllable stress patterns (Goswami et al., 2013). As phonological awareness tasks measure children's awareness of the *sound structure* of language, performance in these tasks is assumed to provide an index of the quality of children's phonological representations. Here I define phonological representations as sensory/neural distributed representations in the brain that are activated as word forms (se also Port, 2007). I argue here that acoustic processing of the speech signal is likely to contribute to individual differences in children's phonological representations in important ways. In turn, this affects phonological awareness.

Our recent research suggests that an important acoustic parameter with respect to the stress foot and the organisation of the mental lexicon is change over time in intensity or *amplitude* in the speech signal (amplitude modulation, AM, see Leong et al., 2014; Leong & Goswami, 2015, 2017). Amplitude modulation has previously received little attention in the developmental language literature. Speech is a pressure wave, and the changes in amplitude

(~ signal energy) produced as the speaker opens and closes the vocal tract are experienced as variations in loudness or intensity. In natural speech, there are periodic quasi-rhythmic variations in amplitude at a number of different temporal rates simultaneously. The semi-periodic variations are caused by simultaneous movements of the vocal folds, tongue and vocal tract. These changes in amplitude are primarily experienced by the listener as speech rhythm (Greenberg, 2006). For example, in a children's nursery rhyme like "Ring-a-ring-o'-roses", regularly-spaced AMs at slower rates (~ 2Hz and ~5 Hz) can be detected in the speech signal (see top panel, Figure 2). These AM-driven "beats" create a rhythm pattern of stressed syllables like "ring" and unstressed syllables like "a", a metrical (here, trochaic) rhythm pattern. The overall shape of these amplitude changes is called the amplitude envelope (AE), plotted in red in the middle panel of Figure 2. The top panel shows the multiple AEs carried by different frequency bands in speech. These are colour-coded from low frequencies (red colours, foreground) to high frequencies (blue colours, background). The bottom panel of the figure shows the same speech information plotted as the speech spectrogram familiar from textbooks. The spectrogram primarily depicts the presence of energy across frequency (~pitch) over time, so in the spectogram changes in amplitude are depicted via increased shading. This may render their possible perceptual salience less obvious.

Figure 2 about here

The dominance of red colour AMs in Figure 2 (top panel) shows that the rhythmic changes carried by low-frequency speech information (< ~700 Hz) are particularly salient. Indeed, the AM peaks that are correlated with the occurrence of *stressed* syllables show particularly large amplitude changes in the lower frequency regions of the signal. AMs in the amplitude envelope and their phase relations (how the AMs synchronise with each other) have been shown to provide an acoustic statistical guide to the placement of stressed syllables, syllables and to the *onset-rime* division of syllables as well (Leong et al., 2014; Leong & Goswami, 2015). To divide any syllable into its constituent onset-rime units, we divide at the vowel, as in *s-eam, st-eam, str-eam*. Words with more than one syllable have more than one rime, as in "captain" and "mountain", these words share a rime for the final syllable but do not rhyme in British English.

For example, Leong et al. (2014) played adult listeners English nursery rhymes that had been manipulated via tone vocoding to remove phonetic information. Tone vocoding involves removing the temporal fine structure from the original signal and then applying the AMs to a sine tone carrier. The resulting acoustic patterns had clear rhythmic temporal patterning, for example sounding like morse code or flutter, but were unintelligible. Leong and her colleagues reported that participants could reliably recognise nursery rhymes solely on the basis of the phase relations between AMs at relatively slow rates (~2 Hz and ~4 Hz for these stimuli). When the AM peaks at these two rates were strongly synchronised, a stressed syllable was perceived. Leong and Goswami (2015) then developed an AM phase hierarchy model of the speech signal based on metrical speech (English nursery rhymes; the Spectral-Amplitude Modulation Phase Hierarchy model, S-AMPH). The model was created from 44 nursery rhymes of varying rhythm patterns, and then tested with a subset of nursery rhymes to see whether the model could identify phonological units. The S-AMPH model showed success rates above 90% in identifying stressed syllables, syllables and onset-rime units in the new nursery rhymes (Leong & Goswami, 2015). Again, phase relations between AMs at different temporal rates (centered respectively on ~2 Hz, ~5 Hz and ~20 Hz for these stimuli) provided the core acoustic statistics. In Leong and Goswami's model, the phase relations between the AM bands were arranged hierarchically, with the slowest rate (a band of AMs spanning 0.9 – 2.5 Hz) governing the phase relations with faster bands.

These modelling data suggest that acoustic sensitivity to patterns of AM in the amplitude envelope at what could be denoted ‘stress’ (~2 Hz) and ‘syllable’ (~5 Hz) rates (see Ghitza & Greenberg, 2009) might be important for children’s phonological development. Indeed, recent experimental studies show that the speech tasks used to measure phonological development in children contain *systematic* slow AM information. For example, Leong and Goswami (2017) modelled the individual words in the rhyme oddity task (“cot” “pot” “hat”) using the S-AMPH model. They found that judgements about phonological similarity (i.e., that “cot” and “pot” rhyme, while “pot” and “hat” do not) depended critically on phase information in the slowest band of AMs, 0.9 – 2.5 Hz. Words that shared similar AM phase in this slowest temporal band were judged to rhyme. The slow AM factors derived from the modelling were the only factors to account for significant variance in children’s errors in the rhyme oddity task. Flanagan and Goswami (2018) modelled phoneme deletion (“Say ‘hift’ without the /f/”) and plural elicitation (“wug” – “wugs”) tasks using the S-AMPH model. They found that for both of these phoneme-level tasks, the acoustic difference between items and correct responses was best described by a change in the magnitude of the phase synchronisation between the two slowest AM bands (0.9 – 2.5 Hz, and 2.5 – 12 Hz, approximately the ‘stress’ and ‘syllable’ rate bands). Children with dyslexia made more phoneme deletion errors (*hift-hit*) as the magnitude of this change increased. The greater the change in the phase synchronisation between two phonologically-similar words, the larger the similarity space of phonologically-similar words. For children with dyslexia, this increased set of possible solutions appeared to make it more difficult to work out the correct answer. This is likely to be because their neural representation of the AM structure in the amplitude envelope is poorly encoded, as discussed below.

Accordingly, acoustic sensitivity to patterns of AM in the amplitude envelope at slower rates does appear to be important for children’s phonological development. Forty years ago, Bradley and Bryant (1978) suggested that difficulties in the ‘auditory organisation’ of word forms in the mental lexicon might be a source of reading difficulties for children. Bradley and Bryant suggested that children might use parameters like rhyme and alliteration to organise words by acoustic similarity, and that this similarity-based organisation might be impaired in children with developmental dyslexia. Their landmark study was one reason for the concerted research effort across languages into the relationship between phonological awareness, learning to read, and reading difficulties (Goswami & Bryant, 1990; Ziegler & Goswami, 2005). Our new understanding of the hierarchical organisation of AMs nested in the amplitude envelope offers one way of operationalising these acoustic similarity relations. The accurate discrimination of AMs in a temporal band focused on ~2 Hz is important for recognising phonological similarity between words at the rhyme level (Leong & Goswami, 2017). The accurate discrimination of phase relations between AMs in temporal bands focused on ~2 Hz and ~5 Hz is important for perceiving strong and weak syllable patterning in sentences – for prosodic discrimination (Leong et al., 2014). The accurate discrimination of phase relations between AMs in these same relatively slow temporal bands in individual items is important for phoneme deletion, as well as for pluralisation (Flanagan & Goswami, 2018). Hence accurate discrimination of different bands of AMs and their phase relations should be important for the development of well-specified phonological representations by children. Note that AM discrimination is related to all linguistic levels measured by phonological awareness tasks – syllable stress patterns, syllables, onset-rimes and phonemes. Clearly, this AM information is only one set of potential acoustic statistics upon which ‘auditory organisation’ may be based, and an AM-description offers complementary information to the acoustic clues to phonology captured by other acoustic indices such as rapid spectral changes. Nevertheless, sensitivity to different rates of AM in speech may be a critical source of individual differences between children.

The Neural Oscillatory Hierarchy and Phase Entrainment

The AM patterns found nested in the speech signal appear to provide an important set of statistics for neural speech encoding. In fact, adult neuroimaging studies have already shown that encoding of AMs by the brain at different temporal rates is important for speech intelligibility (Giraud & Poeppel, 2012; Ghitza et al. 2012; for review). The adult studies show that the oscillations intrinsic to auditory cortex track the speech signal, and that oscillatory phase plays a key role in intelligibility (Poeppel, 2014). Accurate encoding is achieved neurally by networks of cells that oscillate (i.e., vary quasi-rhythmically between electrical excitation and inhibition, even when there is no incoming signal) at different temporal rates that match the core AM patterns in speech. The physiological basis for these oscillations comprise the synaptic potentials of pyramidal cells and their networks of inhibitory interneurons. Neuronal oscillations can be reliably measured on the scalp using EEG (electroencephalography), with millisecond accuracy. EEG most probably records the synchronization of activities reflecting neural communication processes rather than direct neuronal bursting, however the underlying physiology is not well-understood (see Edwards & Chang, 2013). The key temporal oscillatory rates for speech encoding appear to be delta (1 – 3 Hz, 1 – 3 times per second), theta (4 – 8 Hz), beta (15 – 30 Hz) and gamma (> 30 Hz, Poeppel, 2014). The cell networks use ‘rise times’ or amplitude increases (rises in amplitude, sometimes called auditory ‘edges’) as triggers to re-set or re-calibrate their quasi-rhythmic activity to synchronise temporally with the AMs in speech (Gross et al., 2013). This mechanism of phase-resetting means that more potentials are discharged to coincide with AM peaks and fewer potentials are discharged to coincide with AM troughs, thereby maximising neural excitability with the maximal points of information in the speech signal. This automatic alignment of endogenous brain rhythms and AM-driven rhythm patterns in speech is called *oscillatory phase alignment, phase locking* or *phase entrainment.* Adult studies have confirmed the importance of amplitude envelope rise times in successful phase alignment. For example, if theta-rate rise times are removed from the speech signal, theoretically thereby removing syllabic markers, the speech becomes unintelligible to adult listeners (Doelling et al., 2014). Intelligibility returns when simple clicks are inserted at the theta rate, suggesting that theta rise times help in parsing syllables from continuous speech.

The core role of amplitude rise times for neural phase re-setting is particularly interesting with respect to developmental dyslexia. A series of studies conducted over the past 15 years in a range of languages (English, French, Hungarian, Chinese, Spanish, Dutch and Finnish) have documented impaired rise time discrimination in children with developmental dyslexia (see Goswami et al., 2002; 2011a; Muneaux et al., 2004; Hämäläinen et al., 2009; Surányi et al., 2009; Poelmans et al., 2011). In these studies, individual differences in language-relevant phonological awareness tasks were typically associated with individual differences in rise time discrimination. For example, rise time discrimination was associated with tone awareness in Chinese, with phoneme awareness in Spanish, and with rhyme awareness in English (Goswami et al., 2011a). These correlations suggest that rise time discrimination may be an important sensory factor relating to the development of phonological awareness by children. The mechanistic role of rise times in the automatic phase re-setting of the ongoing cortical oscillations that encode the AMs in the speech signal, coupled with the importance of the accurate discrimination of the amplitude modulation hierarchy in the speech amplitude envelope for perceiving phonological units of different sizes, could underlie these significant relationships. Accordingly, the efficiency of children's sensory/neural processing of amplitude modulation patterns in speech is likely to have a direct effect on the quality of their phonological representations.

Figure 3 about here

Figure 3 depicts this neural oscillatory perspective in simplified terms. The neural oscillatory hierarchy is shown on the left-hand side of the figure, and reflects the endogenous oscillatory frequency bands related to speech processing found in auditory and motor cortex. The approximate temporal rates of the AM bands in the acoustic hierarchy nested in the speech amplitude envelope of child-directed rhythmic speech are depicted on the right-hand side of the figure. The figure highlights the temporal match between the AM rates in speech and the oscillatory rates in the brain, and simultaneously illustrates the sensory/neural correspondence with the phonological units that are parsed by the Spectral-Amplitude Modulation Phase Hierarchy model, depicted in the centre of the figure (for statistical analyses, see Leong & Goswami, 2015). Temporal rates for the AM bands in Figure 3 are approximate, as the statistical modelling identified broad bands of AMs centred on these rates. Further, the entire hierarchy nested in the speech signal can be expected to expand or contract depending on speaker rate. A faster rate of syllable production will compress the temporal characteristics of the hierarchy, while a slower rate of syllable production will expand these characteristics (see Leong et al., 2017, for a comparison of infant-directed speech and adult-directed speech incorporating a rate-matched comparison). Similarly, the neural oscillatory bands cover a range of frequencies, reflecting neurobiological data (Poeppel, 2014). Logically, however, the *relational structure* of the hierarchies should remain intact across speaker rate and across individual differences in preferred oscillatory phase, supporting automatic speech-to-brain mapping. Research with adults indicates that the neuronal oscillations that encode speech are also nested, forming a temporal hierarchy, with delta (~ 2 Hz, the slowest rate) at the top (Gross et al., 2013). This relatively slow oscillatory rate governs changes in phase (timing of activation) or power (strength of activation) in neuronal oscillations at faster temporal rates, such as theta and gamma.

Phase Entrainment to Rhythmic Speech by Children

The fact that a neural oscillatory hierarchy matches the AM/phonological hierarchy found in child-directed rhythmic speech (Figure 3) suggests that the deliberately rhythmic registers found in the language used with young children across cultures (and in children's spontaneous language play) are important developmentally. English nursery rhymes, German 'knee riding verses', lullabies and similar metrically-patterned children's songs and poems found in many languages may have an important role in developing the language system by 'entraining the oscillators'. As discussed earlier (Figure 3), the rhythmic rate of ~2 Hz is salient in English nursery rhymes, reflecting the temporal placement of stressed syllables. Interestingly, cross-language research in linguistics (Dauer, 1983) suggests that 2 Hz is also the average rate across languages for producing stressed syllables in conversational speech. If *infant-directed speech* is analysed from an AM perspective, it turns out to have more energy in the AM band centred on 2 Hz than adult-directed speech (corresponding to the oscillatory delta band, see Leong et al., 2017). As well as having more delta band energy, infant-directed speech shows stronger phase synchronisation between ~2 Hz and ~5 Hz AMs compared to adult-directed speech, corresponding to oscillatory delta-theta phase synchronisation. Hence infant-directed speech emphasises both delta-band AM information and delta-theta AM phase synchronisation, characteristics of the speech signal that are important for extracting the phonological linguistic hierarchy (Leong & Goswami, 2015). The different temporal structure of infant-directed speech compared to adult-directed speech supports the idea that the accurate encoding of AMs at delta- and theta-rates is important for phonological learning and the quality of children's phonological representations.

Neural oscillatory entrainment to speech can be studied in infants and children using electrophysiology and the electroencephalogram (EEG). In EEG studies, variations in the brain's electrical energy patterns are recorded using sensors placed on the scalp. When analysed with advanced signal processing methods, EEG recordings can reveal the phase alignment (entrainment) of cell network activity at different rates (delta, theta) with AMs in the speech envelope. Studies using EEG have also measured oscillatory entrainment by using AM-noise, a rhythmic input which matches the complexity of the speech signal. Using AM-noise produces a simple neural signal - an auditory steady-state response (ASSR) at the same rate as the modulation (e.g., a 2 Hz input causes a 2 Hz response). For an ASSR, it is difficult to be sure that the brain response at (for example) a 'syllabic' rate like 5 Hz is identical to the brain response that would occur for real syllables embedded in the speech stream. Therefore, while the ASSR enables measurement of the time scales of cortical processing, it does not necessarily reflect the integrity of oscillatory processing for different phonological units in speech. Nevertheless, experimental work shows that German-learning infants show an ASSR to delta/theta and gamma rates of rhythmic non-speech stimulation from birth (Telkemeyer et al., 2011), suggesting that the mechanisms likely to support oscillatory entrainment to AM information in the speech signal are already 'on-line'. Indeed, the auditory system may well be set up to process speech in the womb, at least regarding low frequency voice modulations, as these are transmitted though the amniotic fluid. Accordingly, oscillatory entrainment to speech information in delta and theta bands may possibly begin in the womb. This could be studied experimentally.

Typically-developing children also show oscillatory entrainment. In the first study to measure oscillatory phase entrainment to *speech* rather than AM noise by children, Power and colleagues used a syllable repetition task to ensure a rhythmic stimulus (“ba… ba… ba”; 2 Hz rate, Power et al., 2012). The children either both saw and heard the speech (video of a ‘talking head’; auditory-visual or AV condition), or heard the speech only (auditory condition, A), or saw the speech only (visual condition, V). The visual condition was included as speech is a multi-modal stimulus. In principle, visual entrainment to speech should also be important for intelligibility (for example, visual speech information also helps to phase-reset auditory networks). Control analyses were used by Power et al. (2012) to ensure that an ongoing oscillation was being measured rather than a series of evoked potentials (see also Soltész et al., 2013, for similar control analyses with dyslexic adults). English-speaking children aged on average 13 years showed significant neural entrainment in the EEG delta band (the rate of stimulus delivery, and the ‘stressed syllable’ rate in language processing) in all three conditions (A, AV, V). They also showed significant entrainment in the theta band (‘syllable’ rate) in the A and AV conditions. Interestingly, individual differences in theta entrainment were significantly correlated with reading development for this sample.

Phase Entrainment to Rhythmic Speech in Developmental Dyslexia

The relation between theta entrainment and reading was of interest as Power et al.’s (2012) study was a precursor for studies with children with developmental dyslexia. Power et al. (2013) proposed that neural entrainment to speech may be *atypical* in children with developmental dyslexia, since these children have known phonological difficulties and also have difficulties in discriminating amplitude rise times (Goswami, 2015, for a review). Indeed, a recent study of rise time discrimination by English-learning *infants* who were at family (genetic) risk for developmental dyslexia found that impaired rise time discrimination was already measurable at 10 months, long before any print experience or reading instruction had commenced (Kalashnikova et al., 2017). Given the core role of amplitude rise times in accurate neural phase entrainment to AM patterns in speech (e.g., Doelling et al., 2014), an obvious neural mechanism relating these sensory difficulties to impaired phonological development in children with developmental dyslexia would be atypical oscillatory entrainment.

Temporal Sampling theory (TS theory, Goswami, 2011) was developed to provide a possible framework for understanding individual differences in children's phonological development from this sensory/neural perspective. The TS framework linked auditory sensory rise time impairments to atypical neural speech encoding by the brain via oscillations. The core proposal was that the automatic alignment of endogenous brain rhythms and AM-driven rhythm patterns in speech would be atypical for children with impaired rise time perception. The term 'temporal sampling' refers to the fact that our continuous perceptual experience of speech depends on the binding together of information that is recorded discontinuously by our sensory systems. The brain is sampling sequential 'snapshots' of the auditory signal at multiple rates simultaneously via the different oscillatory networks in auditory cortex, and then binding them into a single percept (Teng et al., 2017). TS theory proposed that neural encoding of the *slower rates* of AM (<10 Hz, the rates which govern rhythm perception) could be atypical in children with developmental dyslexia. As reviewed above, the accurate perception of slower AMs should be important for the development of phonological awareness across all languages, for all children.

When children with dyslexia were tested with the rhythmic syllable repetition paradigm developed by Power and his colleagues, they showed a significant difference in *preferred phase* in the delta band compared to control children. This phase difference was found in the A and AV conditions only, suggesting that entrainment to visual speech is intact in dyslexia. Indeed, in this study the visual phase-resetting mechanism for auditory cell networks referred to earlier did not differ between dyslexic and control children. Preferred phase reflects the point in time during an oscillatory cycle (from excitation to inhibition) when most neurons discharge their electrical pulses. A group difference in preferred delta phase suggests that for the children with dyslexia, the peak neural response was occurring at less informative points in the incoming speech signal. Contrary to prediction, theta entrainment across conditions did not differ between groups (Power et al., 2013). Accordingly, for English-speaking children with developmental dyslexia, the phase entrainment of networks of cells that respond to rhythmic speech input at the *delta rate* was atypical. The neural response was 'out of time' compared to the neural response of typically-developing readers. The mean phase lag for the dyslexic group could be computed and was 12.8 ms. This phase lag would also affect the fidelity of the faster oscillations governed by the delta oscillation, for example gamma oscillations, thereby affecting the accuracy of phonetic perception as well.

Figure 4 about here

This developmental perspective on preferred phase can be conceptualised as shown schematically in Figure 4. If the oscillatory delta peak of maximal neuronal excitability occurs at a temporal point at which the speech signal carries less information (i.e., the oscillation is out of phase with the AM information), speech perception would be adversely affected. As well as smearing the perception of prosodic information, the temporal alignment of faster oscillations would also be disrupted. Hence all the information in the linguistic hierarchy encoded by the listener that is carried by AM information (information about syllables, onset-rimes and phonemes), as well as prosodic linguistic information, would be of poorer quality. Subsequent to Power et al.'s rhythmic repetition studies, TS theory has been investigated further in studies using sentences and stories (Power et al., 2016; Molinaro et al., 2016). There are also relevant studies using the ASSR, described in the next section.

Neural Entrainment to Slower Modulations in Speech and Non-speech Inputs Appears Atypical in Developmental Dyslexia

Although studies using the speech signal are most informative with respect to the neural underpinnings of the 'phonological deficit' in dyslexia, a number of studies have used the ASSR to provide a simpler index of cortical responding. It is important to recall that while the ASSR may document entrainment, it cannot provide direct information regarding atypical responding (such as potential phase shifts) for *speech* information. Studies with both children and adults in a range of languages have reported an atypical ASSR to nonspeech stimulation in dyslexia (French: Lehongre et al., 2011; English: Hamalainen et al., 2012; Dutch: Poelmans et al., 2012, Vanvooren et al., 2014; Spanish: Lizarazu et al., 2015). The rates of AM stimulation have varied across studies, as have the group differences reported. As noted earlier, the use of speech as the input is critical to ensure that the inferences drawn in these studies concerning impaired entrainment in dyslexia at 'phonetic' or 'syllabic' rates are correct. At the current time, and given the considerable variability across studies, the field has yet to reach a consensus concerning dyslexia and the processing of AM noise.

Accordingly, the focus here will be on studies using the speech signal as input, which are likely to be more informative with respect to neural impairment and compensation. In the first such study with children, Power and his colleagues asked participants with and without dyslexia to repeat semantically unpredictable sentences presented as degraded (noise vocoded) speech. Noise vocoding is a technique that forces greater reliance on speech envelope cues, and individuals with dyslexia are typically significantly worse than controls at understanding noise vocoded speech (Megnin-Viggars & Goswami, 2013). The sentences were unpredictable to prevent children from using sentence context as a basis for guessing the words (e.g., “Arcs blew their cough”). Power et al. then used the children’s electrical brain responses to resynthesise the AMs in the input (the brain excitation response was used to re-create the envelopes in the original sentences). This provided a direct measure of the neural quality of children’s speech envelope representations. Power et al. (2016) reported that the envelopes in the 0 – 2 Hz (delta) band were encoded less accurately by the children with dyslexia compared to age-matched controls. The accuracy measure reflected the size of the correlation for each individual between the speech envelopes produced by reverse-engineering from the electrical responses in the brain (the reconstructed envelopes) and the acoustic information in the original speech envelopes, averaged across all the 200 sentences used in the experiment. Envelope encoding was also significantly less accurate for the children with dyslexia when they were compared to reading-level (RL) matched controls, children who were 2 years younger in age and who had reached the same developmental level in word reading as the children with dyslexia. The RL-match comparison seeks to control for the effects of reading experience on the brain. Reading experience is known to affect phonological awareness and speech processing, and indeed has recently been shown also to affect the amplitude modulation structure of conversational speech (illiterate adults speak differently, see Araujo et al., 2018). The significant difference in encoding accuracy compared to younger reading-level matched children found by Power and his colleagues suggests a fundamental encoding deficit for slow AM speech information in developmental dyslexia, at least for English-speaking dyslexic children. Power et al.’s (2016) study hence provides *direct evidence* for impaired neural phonological representations in dyslexia. Nevertheless, the children with dyslexia could report accurately the same number of sentences as the younger RL children. The neural data suggest that the dyslexic children were achieving this level of speech recognition differently, although they do not reveal the complementary information being used. Of course, the children with dyslexia were not as efficient in speech recognition of the degraded signal as they should have been for their age, as shown by the comparison with the chronological age-matched control group, who were significantly more accurate in the sentence report task compared to the children with dyslexia.

Regarding phonological awareness, individual differences in envelope encoding were significantly related to individual differences in lexical stress perception, supportive of impaired encoding of stress patterning in dyslexia. As will be recalled, the modelling work discussed earlier showed that the phase of AMs in the delta band between word pairs contributed to rhyme similarity judgements, while changes in the magnitude of phase synchronisation between AMs in delta and theta bands was correlated with phoneme deletion. Accordingly, impaired encoding of speech envelope information in the delta band should affect phonological awareness at the rhyme and phoneme levels as well.

A study of Spanish children using MEG (magnetoencephalography, a technique that enables the localisation of phase entrainment as well as millisecond accuracy in recording neuroelectric oscillations) and a story listening task also found atypical delta-band entrainment for children with dyslexia (Molinaro et al., 2016). This is particularly interesting theoretically, as Spanish is a syllable-timed language while English is a stress-timed language. Hence the atypical delta band oscillatory entrainment that appears to characterise children with dyslexia is not affected by linguistic rhythm type. Molinaro and colleagues reported that the reduced delta synchronisation found in dyslexia originated in right primary auditory cortex. This is interesting with respect to the original study by Gross et al. (2013), which found that the right hemisphere showed significantly stronger phase entrainment to delta-band modulations in speech than the left hemisphere. This finding of right-lateralised entrainment differences in dyslexia in Spanish is consistent with a recent fNIRs (functional near-infrared spectroscopy, a blood flow measure enabling localisation) study of English-speaking children using the ASSR. Cutini et al. (2016) played rhythmic (AM) noise at two rates, 2 Hz (delta band) and 40 Hz (gamma band), to children with dyslexia and age-matched controls in a passive listening task. Analyses of blood flow (HbO concentration, a hemodynamic response) revealed a right-lateralised region focused on the supra-marginal gyrus (an area classically considered to be active during prosodic processing, see Sammler et al., 2015) that was more active in children with dyslexia for 2 Hz stimulation. Significant differences in hemodynamic activity were also found for the left superior temporal gyrus and the left angular gyrus (areas classically considered to be active during speech processing, see Rauschecker & Scott, 2009). The hemodynamic responses were significantly related to rise time discrimination for this sample of children (these were the same children who had participated in Power et al., 2013, 2016).

The fNIRs data suggest a different balance of processing for slower versus faster AMs by hemisphere for the two groups, which is driven by atypical responses in both hemispheres. The right hemisphere loci reported by Molinaro et al. (2016) and Cutini et al. (2016) are also interesting in light of the typical finding of a left-lateralised phonological processing deficit in fMRI studies of dyslexia (functional magnetic resonance imaging, which measures blood flow in the brain and hence identifies which brain areas are most active when different functions are performed; see Richlan et al., 2013, for a meta-analysis). The superior time course information provided by EEG and MEG may explain this discrepancy. Atypical encoding of speech in dyslexia may originate in the right hemisphere and then subsequently affect left hemisphere activity (Molinaro et al., 2016), particularly once reading instruction commences and begins to affect speech processing. This possibility could be explored by studying illiterate adults as well as by studying children (see Goswami, 2015). Indeed, the conversational speech of illiterate adults has been shown to contain less tightly-synchronised AM information than the conversational speech of literate adults (Araujo et al., 2018). Accordingly, the mechanisms that are most important for speech perception by illiterates may differ as well. It is also important to study more languages than English and Spanish. Impairments at some temporal rates and compensation at other rates in different studies are likely to be found, reflecting cross-language differences in both orthographic and phonological learning (Lallier et al., 2016)

Future Directions

A sensory/neural oscillatory perspective on the mechanisms underpinning language acquisition may be very fruitful regarding how we conceptualise the language processing deficits found in children with oral developmental language disorder (DLD, previously termed Specific Language Impairment, e.g., Tallal, 2004). It may also illuminate our understanding of other developmental difficulties with an oral language component, such as autism. Regarding DLD, children with oral language impairments have also been found to show impaired rise time discrimination in experimental studies (Corriveau et al., 2007; Beattie & Manis, 2012). In children with DLD, impaired sensory discrimination of rise time is related to impaired processing of rhythm patterns in spoken language and impaired sensitivity to prosodic phrasing (Richards & Goswami, 2015, 2019; Cumming et al., 2015), mirroring results in developmental dyslexia. Nevertheless, the linguistic perceptual effects of impaired rise time discrimination may vary when comparing children with dyslexia and children with DLD. For example, one recent study compared children with DLD, children with dyslexia, and children with both DLD and impaired reading using a filtered nursery rhyme recognition task. Children with dyslexia showed perceptual impairments when the nursery rhymes were passed through a low pass filter, which retained only the slower modulation information. Children with pure DLD and intact reading showed impairments when the nursery rhymes were passed through a band pass filter, which retained only faster modulation information. Children with both DLD and poor reading showed impairments in both conditions. Studies of oscillatory entrainment to speech by children with DLD are currently absent in the literature, but could be highly informative.

Regarding new avenues for remediation for dyslexia, TS theory suggests that giving young children activities that help them to develop accurate rhythmic synchronisation between different modalities and speech might enhance their phonological development (Bhide et al., 2013; Flaugnacco et al., 2014). Speech is a multi-modal signal (auditory, visual, motor), it is both a sound and an action. Accordingly, fostering multi-modal rhythmic activities may 'entrain the oscillators' that underpin rhythm perception and rhythmic production, improving the phase alignment of delta- and theta-rate oscillatory networks in auditory and motor cortex with rhythms in speech (see Goswami & Szűcs, 2011). For example, practice in singing in time to music, or practice in drumming or marching in time to a marching song, might support phonological development by enhancing the phase alignment of oscillators in the auditory and motor domains. As rhythm is more overt in music than in speech, children with rhythmic difficulties may find it easier to perceive musical rhythm, potentially supporting rhythmically-based musical interventions for both dyslexia and DLD. Intervention studies that incorporate pre-intervention and post-intervention measures of neural entrainment could throw light on this issue.

Indeed, it is interesting to note that humans' 'preferred beat rate' for music is 120 beats per minute (Moelents, 2002). This is exactly 2 Hz, a temporal rate that should benefit the remediation of phonological difficulties in children (Bhide et al., 2013). Indeed, the developmental data reviewed here show a primary role for ~2 Hz AMs in the linguistic development of pre-literate children, for example via the AM modifications that characterise IDS. Accordingly, these data may suggest that differences reported in the modulation peaks for music (~2 Hz) and language (~5 Hz) are more apparent than real (Ding et al., 2017). Ding et al. analysed a series of different musical forms such as jazz and classical music, and a range of different human languages such as Chinese and English. They found that the modulation peak for music was ~2 Hz, and for language ~5 Hz. However, all the language analysed was produced by *highly literate individuals*. Language as spoken by pre-literate and illiterate individuals may show the same ~2 Hz modulation peak as the music produced by different cultures. Again, this could be explored experimentally. If spoken language for both pre-literate and illiterate groups shows a modulation peak at ~2 Hz, matching the peak for music, then not only would human societies have converged on metrical organisation around a ~2 Hz rate for *both* speech and music, the ~5 Hz peak reported for spoken language in numerous adult studies would reflect the impact of literacy on spoken language production. Lullabies across cultures are sung at a beat rate of ~2 Hz (Trehub & Trainor, 1998). This provides tentative evidence that matching of the modulation structure of music and language may be found in preliterate cultures. Currently it is notable that almost the entire neural oscillatory literature regarding language processing depends on analysing the speech perception and production of university and college students (Araujo et al., 2018). This should be remedied in future studies, as millions of people in the world are illiterate.

Conclusion

A sensory/neural oscillatory perspective on the mechanisms underpinning phonological development in children is useful for understanding developmental dyslexia and widens inquiry from classic narrowly-focused phoneme-based analyses that dominate the literature (e.g., Hulme & Snowling, 2013). A temporal sampling perspective foregrounds the importance of children's perception of stressed syllables and metrical rhythm patterns in spoken language for their development of phonological awareness. According to the sensory/neural mechanistic framework offered by Temporal Sampling theory, atypical sensory/neural processing of amplitude rise times and of patterns of amplitude modulation may underpin the phonological 'deficit' in dyslexia, with impaired learning about phonemes in dyslexia reflecting impairments at higher levels (namely slower time scales) in the oscillatory hierarchy. As reviewed here, slow AMs carry information about rhyme similarity (Leong & Goswami, 2017) and about phoneme-level changes (Flanagan & Goswami, 2018), in addition to information about rhythmic patterning and prosodic structure. Accordingly, atypical phase entrainment of neural networks by AM information in speech at slower timescales (at delta- and theta-rates) will affect children's phonological development at all linguistic levels, and may affect the extraction of grammatical information as well (for example, concerning inflectional morphology in English, see Flanagan & Goswami, 2018). Further, recent studies with adults show that low frequency cortical oscillations (< 8 Hz) also carry phonetic information directly (Di Liberto et al., 2015). This low frequency oscillatory phonetic information is represented atypically in children with developmental dyslexia (Di Liberto et al., 2018), at right hemisphere cortical locations. This provides direct evidence that atypical oscillatory entrainment to slower modulations (< 10 Hz) has negative consequences for the development of phoneme awareness, as predicted by TS theory.

TS theory also proposed that other speech features that are less dependent on slower AMs in the speech envelope may be over-weighted in the phonological representations developed by children with dyslexia, at least prior to learning to read. For example, to compensate for the atypical processing of slower AMs, acoustic elements such as rapid spectral changes may be perceived in fine detail, which would impair generalisation (impairing phonemic learning: Serniclaes et al., 2004; Chandrasekaran et al., 2009). To date, there are insufficient data to clearly demonstrate such compensation. However, consistent with this proposal, Goswami et al. (2011b) showed that while children with dyslexia were significantly poorer at discriminating amplitude rise time changes in synthetic speech syllables than control children, they were significantly *better* at discriminating rapid rises in frequency in these syllables, able on average to discriminate a difference of 15 ms in rising frequency compared to 30 ms for control children. Meanwhile, Serniclaes and his colleagues have demonstrated maintained allophonic perception in developmental dyslexia, with dyslexic children continuing to make distinctions between allophonic variants of sounds like /d/ and /t/ that are no longer perceived by control children. Hence while typically-developing children appear to develop phonological lexical representations that are optimally organised to support the acquisition of orthographies, children with atypical temporal sampling of the speech signal do not. Nevertheless, the speaking and listening skills of affected children may appear unimpaired on certain oral measures, even though the rhythmic timing of their oral speech production may show subtle effects (see Leong & Goswami, 2014, for adult data). Indeed, impairments in syllable timing can be identified if the speech production of very young children (2 and 3 years) who are at family risk for dyslexia is analysed (Smith et al., 2008).

In closing, it is important to emphasise that the TS developmental framework predicts that the developmental trajectories characteristic of children with dyslexia in different languages may differ for each language. This may be the case even before literacy tuition begins. For example, the role of linguistic rhythm class needs further experimental exploration, and AM-based analyses of infant-directed and child-directed speech in different languages using the S-AMPH modelling approach are required. Further, as orthographic information becomes integrated into the phonological lexicon via learning to read, this may lead to differential weightings developing for the different phonological units given by rapid versus slower temporal information in speech, which could also vary with orthographic transparency. Orthographic learning may thus impact oscillatory processes differently in different languages. This proposed complex and ongoing developmental interaction between phonological and orthographic learning makes experimental investigations of TS theory challenging. Nevertheless, infants in all languages begin parsing the speech signal by using rhythm and stress patterns. Accordingly, a TS framework may offer a sensory/neural/cognitive framework within which to design theory-driven investigations of phonological difficulties in dyslexia and also within which to investigate other developmental disorders of language learning such as DLD and perhaps even autism. In each case, comparative investigations across languages are likely to be particularly informative. Accordingly, a neural oscillations perspective may enhance our understanding of language development in many areas of childhood difficulty, not just developmental dyslexia.

Bibliography

Araujo, J., Flanagan, S., Castro-Caldas, A., & Goswami, U. (2018). The temporal modulation structure of illiterate versus literate adult speech. *PLoS One, 13 (10*), e0205224.

Beattie, R. L.,Manis, F. R., (2012). Rise Time Perception in Children With Reading and Combined Reading and Language Difficulties. *Journal of Learning Disabilities. 46 (3),* 200–209. DOI: 10.1177/0022219412449421

Bhide, A., Power, A.J., & Goswami, U. (2013). A rhythmic musical intervention for poor readers: A comparison of efficacy with a letter-based intervention. *Mind Brain & Education,* 7 (2), 113-123. DOI: 10.1111/mbe.12016

Bradley, L., & Bryant, P. E. (1978). Difficulties in auditory organisation as a possible cause of reading backwardness. *Nature, 271*, 746-747. doi:10.1038/271746a0

Bradley, L. & Bryant, P.E. (1983). Categorising sounds and learning to read: A causal connection. *Nature, 310*, 419-421. DOI: 10.1038/301419a0

Castro-Caldas A., Petersson, K.M., Reis, A., Stone-Elander, S., & Ingvar, M. (1998). The illiterate brain: Learning to read and write during childhood influences the functional organization of the adult brain. *Brain, 121,* 1053-1063

Chandrasekaran, B., Hornickel, J., Skoe, E., Nicol, T.G. & Kraus, N. (2009). Context-dependent encoding in the human auditory brainstem relates to hearing speech in noise: implications for developmental dyslexia. *Neuron, 64*, 311–319. https://doi.org/10.1016/j.neuron.2009.10.006

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. doi:10.1044/1092-4388(2007/046)

Cumming, R., Wilson, A., & Goswami, U. (2015). Basic auditory processing and sensitivity to prosodic structure in children with specific language impairments: A new look at a perceptual hypothesis. *Frontiers in Psychology: 6*, 972. doi: 10.3389/fpsyg.2015.00972

Cutini, S., Szűcs, D., Mead, N., Huss, M., & Goswami, U. (2016). Atypical right hemisphere response to slow temporal modulations in children with developmental dyslexia. *Neuroimage*, 143, 40-49. doi: 10.1016/j.neuroimage.2016.08.012

Dauer, R. (1983). Stress-timing and syllable timing revisited. *Journal of Phonetics, 11*, 51-62.

Di Liberto, G.M., O'Sullivan, J.A., & Lalor, E.C. (2015). Low-frequency cortical entrainment to speech reflects phoneme-level processing. *Current Biology, 25*, 2457-65. https://doi.org/10.1016/j.cub.2015.08.030

Di Liberto, G., Peter, V., Kalashnikova, M., Goswami, U., Burnham, D. & Lalor, E. (2018). Atypical cortical entrainment to speech in the right hemisphere underpins phonemic deficits in dyslexia. *Neuroimage, 175*, 70-79. https://doi.org/10.1016/j.neuroimage.2018.03.072

Ding, N., Patel, A. D., Chen, L., Butler, H., Luo, C., & Poeppel, D. (2017). Temporal modulations in speech and music. *Neuroscience & Biobehavioral Reviews, 81 (B*), 181-187. https://doi.org/10.1016/j.neubiorev.2017.02.011

Doelling, K.B., Arnal, L.H., Ghitza, O., & Poeppel, D. (2014) Acoustic landmarks drive delta–theta oscillations to enable speech comprehension by facilitating perceptual parsing. *Neuroimage. 85*, 761–768. DOI: 10.1016/j.neuroimage.2013.06.035

Edwards, E., Chang, E. F. (2013). Syllabic (~2–5 Hz) and fluctuation (~1–10 Hz) ranges in speech and auditory processing. *Hearing Research, 305*, 113-134. https://doi.org/10.1016/j.heares.2013.08.017

Ehri, L.C. & Wilce, L.S. (1980). The influence of orthography on readers' conceptualisation of the phonemic structure of words. *Applied Psycholinguistics, 1,* 371-385. https://doi.org/10.1017/S0142716400009802

Flanagan, S.A. & Goswami, U. (2018). The role of phase synchronisation between low frequency amplitude modulations in child phonology and morphology speech tasks. *Journal of the Acoustical Society of America.* 143(3), 1366 – 1375.doi: 10.1121/1.5026239

Flaugnacco, E., Lopez, L., Terribili, C., Zoia, S., Buda, S., Tilli, S., Monasta, L., Montico, M., Sila, A., Ronfani, L., Schön, D. (2014). Rhythm perception and production predict reading abilities in developmental dyslexia. *Frontiers in Human Neuroscience*, *8*, 392. https://doi.org/10.3389/fnhum.2014.00392

Ghitza O., Giraud A.-L., & Poeppel D. (2012). Neuronal oscillations and speech perception: critical-band temporal envelopes are the essence. *Frontiers in Human Neuroscience, 6*, 340. doi: 10.3389/fnhum.2012.00340

Ghitza, O, and Greenberg, S. (2009). On the possible role of brain rhythms in speech perception: Intelligibility of time-compressed speech with periodic and aperiodic insertions of silence. *Phonetica.* 66, 113-126. doi: 10.1159/000208934

Giraud, A.L., and Poeppel, D. (2012). Cortical oscillations and speech processing: emerging computational principles and operations. *Nature Neuroscience, 15***,** 511-517. DOI: 10.1038/nn.3063

Goswami, U., Thomson, J., Richardson, U., Stainthorp, R., Hughes, D, Rosen, S. & Scott, S.K. (2002). Amplitude envelope onsets and developmental dyslexia: A new hypothesis. *Proceedings of the National Academy of Sciences, 99 (16*), 10911-10916.

Goswami, U. (2011). A temporal sampling framework for developmental dyslexia. *Trends in Cognitive Science, 15*, 3-10. https://doi.org/10.1016/j.tics.2010.10.001

Goswami, U. (2015). Sensory theories of developmental dyslexia: three challenges for research. *Nature Reviews Neuroscience, 16*, 43-54. doi: 10.1038/nrn3836

Goswami, U., and Bryant, P.E. (1990). *Phonological skills and learning to read*. Hove: Psychology Press. Reissued in 2016 as a 'Psychology Classic'.

Goswami, U., and Szűcs, D. (2011). Educational Neuroscience: Developmental Mechanisms; Towards a conceptual framework. *Neuroimage, 57*, 651-8. DOI: 10.1016/j.neuroimage.2010.08.072

Goswami, U., Wang, H-L., Cruz, A., Fosker, T., Mead, N., & Huss, M. (2011a). Language-universal sensory deficits in developmenta dyslexia: English, Spanish and Chinese. *Journal of Cognitive Neuroscience, 23,* 325-337. https://doi.org/10.1162/jocn.2010.21453

Goswami, U., Fosker, T., Huss, M., Mead, N., & Szücs, D. (2011b). Rise time and formant transition duration in the discrimination of speech sounds: The Ba-Wa distinction in developmental dyslexia. *Developmental Science, 14,* 34-43. DOI:10.1111/j.1467-7687.2010.00955.x

Goswami, U., Mead, N., Fosker, T., Huss, M., Barnes, L., and Leong, V. (2013). Impaired perception of syllable stress in children with dyslexia: a longitudinal study. *Journal of Memory and Language, 69(1),* 1-17. https://doi.org/10.1016/j.jml.2013.03.001

Greenberg, S. (2006). A multi-tier framework for understanding spoken language. In S Greenberg and W Ainsworth (Eds.), *Understanding Speech – An Auditory Perspective*. Mahweh, NJ: LEA; 2006: pp. 411-434.

Gross J., Hoogenboom N., Thut G., Schyns P., Panzeri S., Belin P., & Garrod, S. (2013). Speech rhythms and multiplexed oscillatory sensory coding in the human brain. *PLoS Biology*, *11 (12),* e1001752. https://doi.org/10.1371/journal.pbio.1001752

Hämäläinen, J, Leppänen, P, Eklund K, Guttorm, T, Thomson, J, Goswami U & Lyytinen, H (2009). Perception of amplitude envelope onsets in Finnish children with dyslexia - Behavioural and brain event-related potential findings. *Applied Psycholinguistics, 30 (3*), 511-530. https://doi.org/10.1017/S0124716409090250

Hämäläinen, J.A., Rupp, A., Soltész, F., Szücs, D., & Goswami, U. (2012). Reduced phase locking to slow AM in adults with dyslexia: An MEG Study. *Neuroimage*, *59*, 2952-2961. DOI: 10.1016/j.neuroimage.2011.09.075

Hickok, G., and Poeppel, D. (2007). The cortical organization of speech processing. *Nature Reviews Neuroscience, 8,* 393-402. Doi:10.1038/nrn2113

Hulme, C, and Snowling, M. (2013). Learning to Read: What we know and what we need to understand better. *Child Development Perspectives, 7 (1*), 1-5. DOI: 10.1111/cdep.12005

Kalashnikova, M., Goswami, U., & Burnham, D. (2017). Mothers speak differently to infants at risk for dyslexia. *Developmental Science,21 (1),* e12487. DOI: 10.1111/desc. 12487.

Lallier, M., Molinaro, N., Lizarazu1, M., Bourguignon, M., Carreiras, M. (2017). Amodal atypical neural oscillatory activity in dyslexia: A cross-linguistic perspective. *Clinical Psychological Science*, 5 (2), 379-401. DOI: 10.1177/2167702616670119

Lehongre, K., Ramus, F., Villiermet, N., Schwartz, D., & Giraud, A-L. (2011). Altered low-gamma sampling in auditory cortex accounts for the three main facets of dyslexia. *Neuron, 72*, 1080-1090. DOI: 10.1016/j.neuron.2011.11.002

Leong, V., Stone, M., Turner, R.E., & Goswami, U. (2014). A role for amplitude modulation phase relationships in speech rhythm perception. *Journal of the Acoustical Society of America, 136*, 366-81. https://doi.org/10.1121/1.4883366

Leong ,V. and Goswami, U. (2014). Assessment of rhythmic entrainment at multiple timescales in dyslexia: Evidence for disruption to syllable timing. *Hearing Research, 308*, 141-161. https://doi.org/10.1016/j.heares.2013.07.015

Leong ,V., and Goswami, U. (2015). Acoustic-emergent phonology in the amplitude envelope of child-directed speech. *PLoS One, 10 (12),* e0144411. https:// doi.org/10.1371/journal.pone.0144411

Leong, V., and Goswami, U. (2017). Difficulties in auditory organization as a cause of reading backwardness? An auditory neuroscience perspective. *Developmental Science*, *20* (6), e12457. DOI: 10.1111/desc.12457

Leong, V., Kalashnikova, M., Burnham, D. & Goswami, U. (2017). The temporal modulation structure of infant-directed speech. *Open Mind*, *1*, (2), p.78-90. DOI: 10.1162/OPMI_a_00008

Liberman, M., and Prince, A. (1977). On stress and linguistic rhythm. *Linguist Inquirer, 8*, 249-336.

Liberman, I. Y., Shankweiler, D., Fischer, F.W. & Carter, B. (1974). Explicit syllable and phoneme segmentation in the young child. *Journal of Experimental Child Psychology*, *18*, 201-212. doi:10.1016/0022-0965(74)90101-5

Lizarazu, M., Lallier, M., Molinaro, N., Bourguignon, M., Paz-Alonso, P.M., Lerma-Usabiaga, G., & Carreiras, M. (2015). Developmental evaluation of atypical auditory sampling in dyslexia: Functional and structural evidence. *Human Brain Mapping 36*, 4986-5002. DOI: 10.1002/hbm.22986

Luo, H., and Poeppel, D. (2007). Phase patterns of neuronal responses reliably discriminate speech in human auditory cortex. *Neuron, 54*, 1001-10. https://doi.org/10.1016/j.neuron.2007.06.004

Megnin-Viggars, O. and Goswami, U. (2013). Audiovisual perception of noise vocoded speech in dyslexic and non-dyslexic adults: The role of low-frequency visual modulations. *Brain & Language, 124 (2),* 165-73. https://doi.org/10.1016/j.bandl.2012.12.002

Moelents, D. (2002). *Preferred tempo reconsidered*. In Proceedings of the 7th International Conference on Music Perception and Cognition, Sydney, (Eds. C Stevens, D Burnham, G McPherson, E Schubert, J Renwick), pp. 580-583. Adelaide: Causal Productions, 2002.

Molinaro N, Lizarazu M, Lallier M, Bourguignon M, & Carreiras M. (2016). Out-of-synchrony speech entrainment in developmental dyslexia. *Human Brain Mapping*; *37*, 2767-2783. DOI: 10.1002/hbm.23206

Muneaux, M., Ziegler, J.C., Truc, C., Thomson, J., & Goswami, U. (2004). Deficits in beat perception and dyslexia: Evidence from French. *Neuroreport*, *15 (7*),1-5. doi: 10.1097/01.wnr.0000127459.31232.c4

Poelmans, H., Luts, H., Vandermosten, M., Boets, B., Ghesquière, P., & Wouters, J. (2011). Reduced sensitivity to slow-rate dynamic auditory information in children with dyslexia. *Research in Developmental Disabilities, 32*, 2810-2819. https://doi.org/10.1016/j.ridd.2011.05.025

Poelmans, H., Luts, H., Vandermosten, M., Boets, B., Ghesquière, P., & Wouters, J. (2012). Auditory steady state cortical responses indicate deviant phonemic-rate processing in adults with dyslexia. *Ear and Hearing, 33*, 134-143. doi: 10.1097/AUD.0b013e31822c26b9

Poeppel, D. (2014). The neuroanatomic and neurophysiological infrastructure for speech and language. *Current Opinion in Neurobiology, 28c*, 142-149. https://doi.org/10.1016/j.conb.2014.07.005

Port, R. (2007). How are words stored in memory? Beyond phones and phonemes. *New Ideas in Psychology, 25*, 143-70. https://doi.org/10.1016/j.newideaspsych.2007.02.001

Power, A.J., Mead, N., Barnes, L., & Goswami, U. (2012). Neural entrainment to rhythmically-presented auditory, visual and audio-visual speech in children. *Frontiers in Psychology, 3*, 216. https://doi.org/10.3389/fpsyg.2012.00216

Power, A.J., Mead, N., Barnes, L. & Goswami, U. (2013). Neural entrainment to rhythmic speech in children with developmental dyslexia. *Frontiers in Human Neuroscience,* 7, 777. https://doi.org/10.3389/fnhum.2013.00777

Power, A.J., Colling, L.C., Mead, N., Barnes, L., & Goswami, U. (2016). Neural encoding of the speech envelope by children with developmental dyslexia. *Brain & Language, 160,* 1-10. https://doi.org/10.1016/j.bandl.2016.06.006

Rauschecker, J.P., and Scott, S.K., 2009. Maps and streams in the auditory cortex: nonhuman primates illuminate human speech processing. *Nature Neuroscience, 12*, 718–724. doi:10.1038/nn.2331

Read, C. (1986). *Children's creative spelling*. London, UK: Routledge Kegan Paul.

Richards, S. and Goswami, U. (2015). Auditory processing in Specific Language Impairment (SLI): Relations with the perception of lexical and phrasal stress. *Journal of Speech, Language & Hearing Research, 58*, 1292-1305. doi: 10.1044/2015_JSLHR-L-13-0306

Richards, S., & Goswami, U. (2019). Impaired recognition of metrical and syntactic boundaries in children with developmental language disorders. *Brain Sciences, 9,* 33. doi:10.3390/brainsci9020033

Richlan, F., Kronbichler, M., & Wimmer, H., (2013). Structural abnormalities in the dyslexic brain: a meta-analysis of voxel-based morphometry studies. *Human Brain Mapping, 34*, 3055–3065. https://doi.org/10.1002/hbm.22127

Sammler, D., Grosbras, M.-H., Anwander, A., Bestelmeyer, P.E.G., & Belin, P., (2015). Dorsal and ventral pathways for prosody. *Current Biology, 25*, 3079–3085. https://doi.org/10.1016/j.cub.2015.10.009

Serniclaes, W., Van Heghe, S., Mousty, P., Carre, R., & Sprenger-Charolles, L. (2004). Allophonic mode of speech perception in dyslexia. *Journal of Experimental Child Psychology*, *87* (4), 336-61. https://doi.org/10.1016/j.jecp.2004.02.001

Smith, A. B., Lambrecht Smith, S., Locke, J. L., & Bennett, J. (2008). A longitudinal study of speech timing in young children later found to have reading disability, *Journal of Speech, Language, and Hearing Research, 51*, 1300–1314. doi:10.1044/1092-4388(2008/06-0193)

Soltész, F., Szűcs, D., Leong, V., White, S. & Goswami, U. (2013) Differential entrainment of neuroelectric delta oscillations in developmental dyslexia. *PLoS ONE 8 (10*): e76608. doi:10.1371/journal.pone.0076608

Surányi, Z., Csépe, V., Richardson, U., Thomson, J.M., Honbolygó, F., & Goswami, U. (2009). Sensitivity to Rhythmic Parameters in Dyslexic Children: A Comparison of Hungarian and English. *Reading & Writing, 22*, 41-56. DOI 10.1007/s11145-007-9102-x

Tallal, P. (2004). Improving language and literacy is a matter of time. *Nature Reviews Neuroscience, 5*, 721-728. doi:10.1038/nrn1499

Telkemeyer, S., Rossi, S., Nierhaus, T., Steinbrink, J., Obrig, H., & Wartenburger, I. (2011). Acoustic processing of temporally-modulated sounds in infants: Evidence from a combined NIRS and EEG study. *Frontiers in Psychology, 2*, 62. https://doi.org/10.3389/fpsyg.2011.00062

Teng X, Tiang, X., Rowland, J., & Poeppel, D. (2017). Concurrent temporal channels for auditory processing: Oscillatory neural entrainment reveals segregation of function at different scales. *PLoS Biology*, *15* (11): e2000812. https://doi.org/10.1371/journal.pbio.2000812

Thomson, J., Richardson, U., & Goswami, U. (2005). Phonological similarity neighbourhoods and children's short-term memory: Typical development and dyslexia. *Memory and Cognition, 33* (7), 1210-1219. doi:10.3758/BF03193223

Trehub, S.E., and Trainor, L. (1998). Singing to infants: Lullabies and play songs. In C. Rovee-Collier, L. Lipsitt, & H. Hayne (Eds.) *Advances in infancy research* (Vol. 12, pp. 43–77). Stamford, CT: Ablex.

Vanvooren, S., Poelmans, H., Hofmann, M., Ghesquire, P., & Wouters, J. (2014). Hemispheric asymmetry in auditory processing of speech envelope modulations in prereading children, *Journal of Neuroscience*, *34* (4), 1523–1529. https://doi.org/10.1523/JNEUROSCI.3209-13.2014

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. DOI: 10.1111/j.1467-9817.2006.00308.x

Ziegler, J. C., Bertrand, D., Tóth, D., Csépe, V., Reis, A., Faísca, L., et al. (2010). Orthographic depth and its impact on universal predictors of reading : A cross-language investigation. *Psychological Science, 21*, 551–559. https://doi.org/10.1177/0956797610363406

Ziegler, J.C., and Goswami, U. (2005). Reading acquisition, developmental dyslexia, and skilled reading across languages: A psycholinguistic grain size theory. *Psychological Bulletin, 131*, 3-29. doi:10.1037/0033-2909.131.1.3

Figure Captions

1. **Schematic depiction of some of the factors that contribute to the development of phonological representations by children**. The figure shows some of the major factors that will affect the development of accurate phonological representations for words by children across languages and from birth. The factors likely to operate in similar ways across languages are noted. The "Reading and Spelling Acquisition" factor will not be operating from birth, hence it is denoted by a dashed line. AM = amplitude modulation.
2. **The amplitude envelope and speech spectrogram for the English nursery rhyme phrase "Ring a' ring o' roses".** The speech signal is depicted over time in all panels. The middle panel shows the raw speech signal with the amplitude envelope (the power-weighted averaged amplitude) in red. The conventional depiction of speech as a spectrogram is shown in the bottom panel of the figure, and the top panel shows the novel and complementary depiction enabled by the S-AMPH model. The colours for the top panel depict spectral frequency bands, with relative amplitude on the Y axis. Figure by Sheila Flanagan.
3. **Schematic depiction of the linguistic hierarchy, the amplitude modulation (AM) hierarchy nested in children's nursery rhymes, and the oscillatory hierarchy**. The linguistic hierarchy depicted in the centre of the panel shows the phonological units of different grain sizes that are reliably recognised prior to literacy; note that for languages with simple syllables (comprising single consonants and vowels), the onset and rime units will correspond to single phonemes. The frequencies of the electrophysiological oscillations measurable in the brain and thought to be relevant to perceiving these phonological units are depicted to the left-hand side of the figure (delta, 1 – 3 Hz; theta, 4 – 8 Hz, beta, 15 – 30 Hz). The centre frequencies of the

amplitude modulations as extracted by the S-AMPH modelling are depicted to the right-hand side of the figure. The figure shows that the temporal rates for the AMs in speech and for the neuronal oscillations are approximately matched.

4. **Schematic depiction of oscillatory phase entrainment**. The figure shows a 2 Hz oscillation that is either in phase (solid line) versus out of phase (dashed line) with important information in the speech signal ("Jack and Jill went up the hill"). The phase lag is exaggerated for explanatory purposes. Figure by Sheila Flanagan.

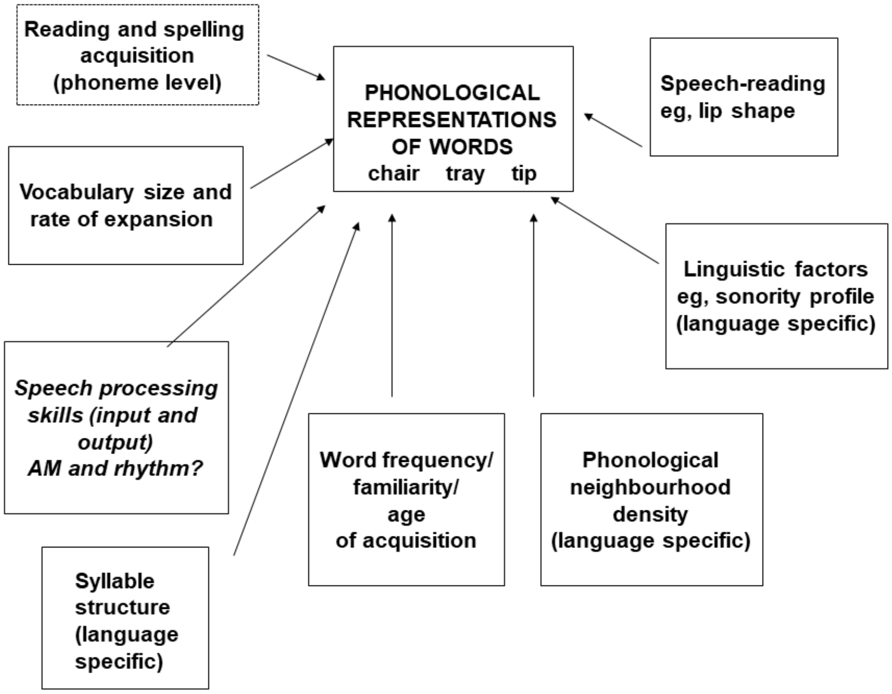

Figure 1 Schematic depiction of some of the factors that contribute to the development of phonological representations by children. The figure shows some of the major factors that will affect the development of accurate phonological representations for words by children across languages and from birth. The factors likely to operate in similar ways across languages are noted. The "Reading and Spelling Acquisition" factor will not be operating from birth, hence it is denoted by a dashed line.

254x190mm (96 x 96 DPI)

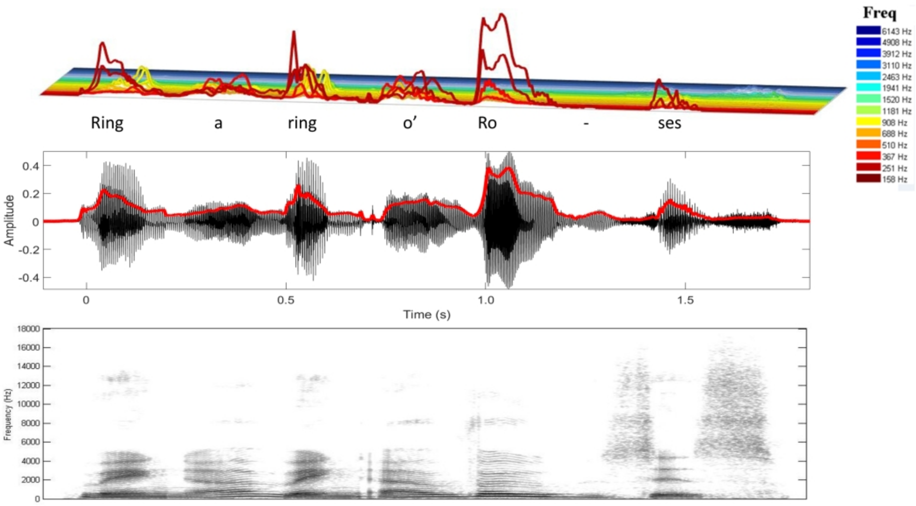

Figure 2 The amplitude envelope and speech spectrogram for the English nursery rhyme phrase “Ring a’ ring o’ roses”. The speech signal is depicted over time in all panels. The middle panel shows the raw speech signal with the amplitude envelope (the power-weighted averaged amplitude) in red. The conventional depiction of speech as a spectrogram is shown in the bottom panel of the figure, and the top panel shows the novel and complementary depiction enabled by the S-AMPH model. The colours for the top panel depict spectral frequency bands, with relative amplitude on the Y axis. Figure by Sheila Flanagan.

338x190mm (300 x 300 DPI)

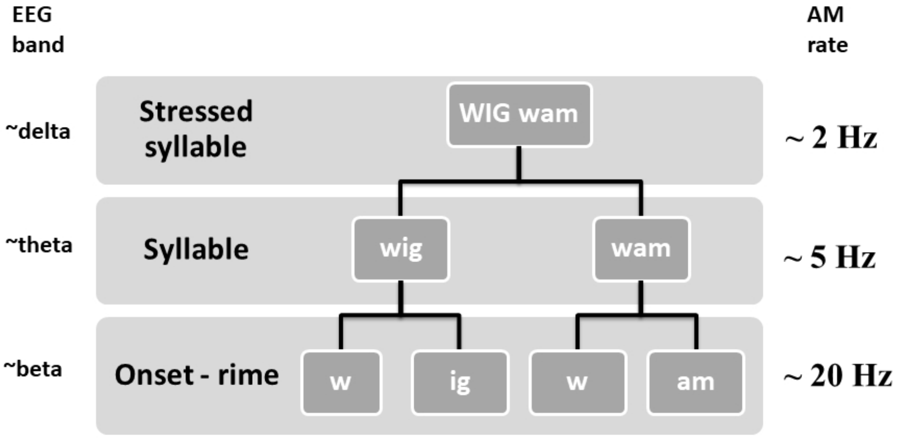

Figure 3 Schematic depiction of the linguistic hierarchy, the amplitude modulation (AM) hierarchy nested in children's nursery rhymes, and the oscillatory hierarchy. The linguistic hierarchy depicted in the centre of the panel shows the phonological units of different grain sizes that are reliably recognised prior to literacy; note that for languages with simple syllables (comprising single consonants and vowels), the onset and rime units will correspond to single phonemes. The frequencies of the electrophysiological oscillations measurable in the brain and thought to be relevant to perceiving these phonological units are depicted to the left-hand side of the figure (delta, 1 – 3 Hz; theta, 4 – 8 Hz, beta, 15 – 30 Hz). The centre frequencies of the amplitude modulations as extracted by the S-AMPH modelling are depicted to the right-hand side of the figure. The figure shows that the temporal rates for the AMs in speech and for the neuronal oscillations are approximately matched.

254x190mm (96 x 96 DPI)

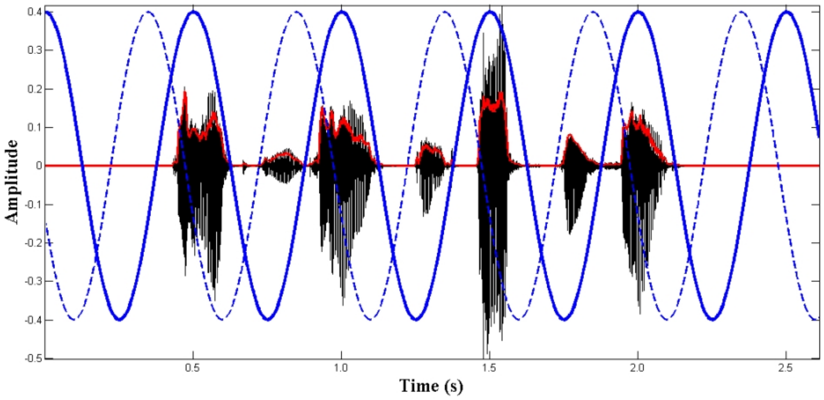

Figure 4 Schematic depiction of oscillatory phase entrainment. The figure shows a 2 Hz oscillation that is either in phase (solid line) versus out of phase (dashed line) with important information in the speech signal ("Jack and Jill went up the hill"). The phase lag is exaggerated for explanatory purposes. Figure by Sheila Flanagan.

338x147mm (96 x 96 DPI)