Dyslexia – in tune but out of time

Usha Goswami, winner of the Society's Presidents' Award, examines difficulties in 'temporal sampling'

Rhythmic timing is important in speech. Great poems with metrical rhythms illustrate this well – think of Auden's 'This is the night mail, crossing the border, Bringing the cheque and the postal order…' – the prosodic structure (the internal rhythmic patterning of the words) actually seems to convey the rhythm of the train. Children with dyslexia find it difficult to hear speech rhythm and speech timing, and also have difficulties in perceiving musical rhythms. These difficulties in timing could explain why dyslexic children struggle with phonology (the sound structure of words) across languages. But music and poetry may also help dyslexic children to improve their rhythmic abilities.

questions

Surely rhythm in speech is not temporally regular or periodic – hence speech rhythm is different to rhythm in music?

How could neuronal oscillations, which would be periodic, encode speech rhythm, which is not periodic?

resources

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One of the most interesting discoveries in the brain imaging of language is that patterns of fluctuation in speech energy (signal intensity) are important for understanding speech. This doesn't mean speaking loudly, although we do automatically raise our voices and speak more distinctly when we are talking to foreigners. Rather, research in auditory neuroscience shows that speech intelligibility is affected by the constant and ongoing energy fluctuations that are produced as we speak. These fluctuations in the energy of the speech soundwave, called amplitude modulations, are produced by the opening and closing of our jaws and by the other articulatory movements that we make (sound is a pressure wave). Amplitude modulation turns out to be critical for speech intelligibility.

My research suggests that children with dyslexia are less sensitive to slow changes in amplitude than other children. Their difficulties are particularly marked in gauging how fast an increase in intensity reaches its peak, called 'rise time'. For children with dyslexia, sensitivity to rise time is significantly worse not only in comparison to age-matched children without dyslexia, but also in comparison to younger children matched for reading level (Goswami, Huss et al., 2012). These 'reading level matched' children have a lower mental age and are developmentally less mature than the dyslexics, yet by around nine years they can discriminate changes in rise time in the range of around 50 ms. Children with dyslexia aged around 11 years need around 100 ms to perceive a change (Goswami, Huss et al., 2012). This suggests that the difficulties in perceiving amplitude rise time in dyslexia are profound, and may be one cause of this developmental learning difficulty.

AM and FM – Just like the radio?

A simple way of thinking about rise times is to think about music. In music, we can have notes of the same pitch that are made by different instruments. For example, the note G can be played on a trumpet or on a violin. The trumpet player will produce a note that starts very abruptly – it reaches its maximum intensity very quickly. A violin player draws the bow across the string, and produces a note of the same pitch, but this note takes much longer to reach its maximum intensity. The violin note has a more extended rise time. In order to play in time with each other, the two players need to begin making their notes at different times, so that peak intensity is reached at the same time. In this scenario, we perceive the players to be 'in time'. If the two sounds reach peak intensity at different times, we perceive one player to be 'coming in late'. The rise time difficulties found in dyslexia suggest that an orchestra of people with dyslexia would be poor at keeping in time, even though each individual player may have reached a high standard of skill with their own instrument.

Just as both pitch and timing (rhythm) are critical for music, both frequency modulation and amplitude modulation play critical roles in speech perception. Indeed, they play complementary roles. Both AM and FM can be used to transmit sound, as illustrated by AM radio versus FM radio. While in radio transmission AM and FM are artificial transformations, in speech these two types of modulation arise naturally and convey complementary information. Traditionally, changes in frequency were thought to be of primary importance for perceiving speech sounds, as a key aspect of speech is formant

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Kitzen, K.R. (2001). Prosodic sensitivity, morphological ability, and reading ability in young adults with and without childhood histories of

frequency structure. While frequency cues are indeed important, it turns out that speech is quite intelligible even when formant structure is largely removed, and just the AM patterns from a few frequency bands are retained. Hence amplitude modulation also plays an important role in speech perception. The AM patterns in speech are also known as the 'amplitude envelope' of speech.

Very slow rates of amplitude modulation (typically < 4 Hz) are experienced by listeners as speech rhythm and syllable stress patterning (prosody). Rise times in the amplitude envelope of speech correspond to syllable onsets, and stressed syllables have larger rise times. Accurate perception of prosodic patterning turns out to be crucial for word recognition. As an analogy, consider listening to a non-native speaker of English. This non-native speaker is likely to have learned all the individual speech sounds (the 'phonemes') correctly and is likely to say them in the right order (the order in which they are written). However, they may still use the stress patterning of their native language. In such cases, it can be very difficult to understand what is being said. We need listening experience to 'train our ears' to persistent mis-stressing of English words. This analogy shows that prosody (strong and weak syllable 'beats') is part of the hidden structural glue that makes individual speech sounds into recognisable words. Prosody, however, is not represented in the writing system for English.

Dyslexia and the 'phonological deficit'

Learning about the sound structure of words and learning which sound elements follow each other is a natural part of language acquisition. However, children with dyslexia, across languages, have difficulties in being able to reflect on the sound structure of words – to develop 'phonological awareness'.

Phonological awareness has classically been assessed by tasks that measure a child's ability to detect and manipulate component sounds within single words, at the different 'grain' sizes of syllable, rhyme and phoneme. For example, children with dyslexia are worse at counting the number of syllables in words (two syllables in *toffee*, three syllables in *viola*), at deciding whether two words rhyme, or at deciding that two words begin with the same sound element (phoneme). Prior to literacy

This is the night mail… poster for GPO film of Auden's poem that conveys the rhythm of the train

acquisition, phonological development across languages is very similar. All children develop awareness of syllables and rhymes (or 'onset-rime' units; to divide a syllable into onset and rime, we segment the syllable at the vowel, as in *m-ate*, *gr-eat*, *str-aight*; as this example shows, rime is a phonological category).

Learning to read is largely responsible for the development of 'phoneme awareness'. The development of phoneme awareness depends partly on the consistency with which letters symbolise phonemes in a language, and partly on the complexity of phonological syllable structure (Ziegler & Goswami, 2005). Because of this, there are large cross-language differences in the rate of

development of phonemic awareness as children learn to read, with English learners being particularly slow. This slowness in English occurs because phonemes are not actual units in the speech stream, and so children have to learn about phonemes largely via learning letters. Letters in English are not very consistent in how they map to sound. Hence children cannot learn about (most) phonemes simply by analysing their own speech.

This was shown a long time ago by the work of Charles Read on 'invented spelling' (Read, 1986). Read showed that pre-reading children think that the sounds at the beginning of 'chicken' and 'track' require representation by the same letter. In a way they are correct, as acoustically these sounds are indeed very similar. On the other hand, pre-readers think that the sounds symbolised by the letter P in *pit* and *spoon* are different – as indeed they are. Yet in English spelling we represent these sounds by the same letter. A beginning speller might well write SBN for *spoon*. Phonologically, this child is being accurate.

Most children overcome these inconsistencies in grapheme–phoneme relations and learn about phonemes relatively quickly, but children with dyslexia do not. They struggle to learn the letter–sound correspondences of English, showing deficits in 'phoneme awareness' even as university students. On the other hand, children with dyslexia in more transparent orthographies, like German or Italian, become as good at phoneme-level tasks as non-dyslexic children after a few years of learning to read. Yet these children too never attain automaticity or fluency in recoding print to sound, and so are

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functionally dyslexic. Dyslexic difficulties with phonology typically persist into adulthood even in transparent languages, but are more difficult to see in these languages (see Ziegler & Goswami, 2005). One possibility, which is only recently receiving attention, is that these phonological difficulties, and the associated difficulties in learning about phonemes, stem from an underlying difficulty with speech prosody.

Prosody and the 'phonological deficit'

Tasks to measure prosodic awareness in dyslexia have been developed relatively recently. In a ground-breaking study, Kitzen (2001) converted film and story titles into 'DeeDees', so that (for example) *Casablanca* became DEEdeeDEEdee. Participants with dyslexia heard a tape-recorded DeeDee sequence while viewing three alternative (written) choices, for example *Casablanca*, *Omega Man* and *The Godfather*. Kitzen found that her dyslexic participants were significantly poorer in the DeeDee task than age-matched controls. However, interpretation of the group difference was complicated by the reading demands of the task.

More recently, we created a version of the DeeDee task for children with dyslexia. Our task relied on recognising pictures of 'famous names'. For example, Harry Potter was DEEdeeDEEdee. We found that 12-year-old children with dyslexia were significantly worse in matching the DeeDee sequences to the pictures than non-dyslexic 12-year-olds (Goswami et al., 2010), and recently we found that nine-year-old children with dyslexia were significantly worse in the DeeDee task compared with seven-year-old reading level controls (Goswami, Mead et al., 2012). Individual differences in DeeDee performance are related to auditory sensitivity to rise time, pitch, duration and sound intensity.

We also developed a more direct measure of syllable stress perception. Using four-syllable English words, we asked participants to make same–different judgements when one of the words was mis-stressed (Leong et al., 2011). For example, they might hear a word pair like *DIFFiculty–diffICulty*. Both highly compensated dyslexic undergraduates and dyslexic children aged 13 years showed significantly less sensitivity in this task compared with age-matched controls. Individual differences in stress sensitivity for adults were uniquely related to individual differences in auditory sensitivity to rise time. For children, the auditory predictors of stress sensitivity were rise time and duration.

These marked difficulties with syllable stress made us wonder whether beat perception in music might also be impaired in dyslexia. As noted, rise time is critical to the perception of rhythmic timing, and the beat structure in music depends partly on some notes having greater accentuation than others, a bit like strong and weak (stressed and unstressed) syllables. To test musical perception, we devised a musical measure of beat perception for children. Children listened to short 'tunes' made by a chime bar, with strong and weak beats, and were asked to make same–different judgements. For example, they might hear 'DING ding ding DING ding ding DING ding ding', repeated twice, but the second time with a longer delay between the accented and unaccented notes. This delay disrupted the overall beat structure, so that the tunes sounded rhythmically different. The children with dyslexia were significantly worse in making these judgements than both age-matched controls (Huss et al., 2011) and reading-level matched controls (Goswami, Huss et al., 2012). Musical beat perception was associated with auditory sensitivity to rise time, pitch and duration. In Huss et al.'s study, individual differences in the musical beat perception task accounted for 42 per cent of unique variance in single-word reading, after controlling for age and IQ. In Goswami, Huss et al.'s (2012) study, musical beat perception predicted 43 per cent of unique longitudinal variance in reading comprehension. Hence individual differences in perceiving patterns of beat distribution, in both language and music, are intimately connected with reading development and dyslexia.

'Temporal sampling' and syllable structure

Interestingly, the underlying beat structure in the music task was 2 Hz, (beats occurring every 500 ms or two beats a second). This temporal rate was chosen because we had other evidence that 'rhythmic entrainment', or following rhythmic patterns, was impaired at this rate in developmental dyslexia. Children and adults with dyslexia were much more erratic than controls in tapping in time with a metronome at 2 Hz (Thomson et al., 2006; Thomson & Goswami, 2008). Across languages, speakers produce stressed syllables at the rate of approximately 2 per second, or 2 Hz. Hence one logical possibility is that the dyslexic brain finds it difficult to 'entrain' to rhythmic input at this temporal rate, accounting in part for the syllable stress and prosodic difficulties that characterise

Coordinating rhythmic movement in time with speech and music may also be beneficial

dyslexia. Recently, we tested this idea in a brain-imaging study using amplitude-modulated noise (Hämäläinen et al., 2012).

In our study, we asked well-compensated adults with dyslexia to listen passively to five-minute streams of amplitude-modulated noise (a kind of rhythmically beating white noise) at four different temporal rates, 2 Hz, 4 Hz, 10 Hz and 20 Hz. We then measured how accurately electrical fluctuations in cell assemblies (neuronal oscillations) in the auditory cortex aligned their fluctuations with the stimulation rate. We expected entrainment difficulties at both 2 Hz and 4 Hz. While stressed syllables are produced approximately twice a second across languages, speakers produce between four and seven syllables a second in different languages, depending on what they are saying and how fast they are saying it. Studies in auditory neuroscience have identified entrainment at the theta rate (4–8 Hz) as particularly important for syllable-level processing of speech. In our study, however, the dyslexics only showed impairment in neural entrainment at the slower rate of 2 Hz. Intriguingly, they also showed better entrainment than controls at the faster rate of 10 Hz.

Most recently, we have begun to study neural entrainment in children. In one study, we used a rhythmic speech design, in which children listened to a speaker saying 'ba… ba… ba…' at a rate of 2 Hz, and we measured auditory neural entrainment (Power et al., 2012). We found significant entrainment of both delta and theta neuronal oscillations in these typically developing children by rhythmic speech input. Furthermore, individual differences in theta entrainment were related to individual differences in reading.

The brain-imaging studies suggest that individual differences in oscillatory mechanisms at both the stressed syllable rate (2 Hz) and the syllable rate (4 Hz) are related to the development of word reading. Theoretically, I have developed a 'temporal sampling' framework to try to explain why poor rhythmic entrainment,

poor perception of acoustic rhythm, and poor perception of rise time are all associated with developmental dyslexia and with prosodic and sub-lexical phonological difficulties.

Temporal sampling theory

Temporal sampling theory builds on the idea that the brain 'samples' sensory information at different temporal rates, effectively taking multiple 'looks' at the speech signal using temporal windows of multiple lengths simultaneously (Poeppel, 2003). To help to encode the speech signal, the auditory system appears to synchronise endogenous ongoing oscillations (fluctuations in neuronal excitability that are occurring anyway) to the modulation rates in the stimulus, realigning the phase of neural activity so that peaks in excitability co-occur with peaks in amplitude modulation (Zion-Golumbic et al., 2012). As dyslexia involves rise time perception difficulties, it might be more difficult for the dyslexic brain to detect these peaks in amplitude modulation, or to align endogenous ongoing fluctuations in neuronal excitability to the modulation rate, as the different modulation rates would be less

well-detected. If neuronal entrainment at the syllable and stressed syllable rates is impaired in dyslexia, then this would provide a plausible explanation for the phonological difficulties found in developmental dyslexia across languages (Goswami, 2011). Difficulties in basic auditory processing of rise time, amplitude modulation and beat structure would lead naturally to difficulties in processing the sound structure of words, and to prosodic difficulties. In turn, these prosodic difficulties would be linked to difficulties in judging phonemic similarity across different words – just like listening to a non-native speaker of English.

Conclusion

Temporal sampling theory proposes that an underlying neural problem with rhythmic entrainment accounts in part for the 'phonological deficit' that characterises children with developmental dyslexia across languages. One obvious implication is that remediation with music might be very effective for improving phonology in dyslexia. Rhythm is more overt in music than in language, and so a focus on musical rhythm along with activities that

explicitly link musical beat structure to the beat structure of language may help to improve rhythmic entrainment (Bhide et al., in press). Coordinating rhythmic movement in time with speech and music may also be beneficial. Many playground games of course provide such activities, such as clapping games, skipping games, nursery rhymes and chants. Interestingly, research with adults who have specific musical difficulties (termed 'amusia', or tone deafness) suggests that these adults are 'in time but out of tune', able to organise rhythm cues but not pitch cues (Hyde & Peretz, 2004). This pattern of difficulty appears to be the mirror image of our findings with developmental dyslexia. Our data suggest that children with developmental dyslexia are 'in tune but out of time'. Rhythmic entrainment difficulties may be at the heart of developmental dyslexia.

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