Mind, Brain, and Literacy: Biomarkers as Usable Knowledge for Education

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ABSTRACT—Neuroscience has the potential to make some very exciting contributions to education and pedagogy. However, it is important to ask whether the insights from neuroscience studies can provide “usable knowledge” for educators. With respect to literacy, for example, current neuroimaging methods allow us to ask research questions about how the brain develops networks of neurons specialized for the act of reading and how literacy is organized in the brain of a reader with developmental dyslexia. Yet quite how these findings can translate to the classroom remains unclear. One of the most exciting possibilities is that neuroscience could deliver “biomarkers” that could identify children with learning difficulties very early in development. In this review, I will illustrate how the field of mind, brain, and education might develop biomarkers by combining educational, cognitive, and neuroscience research paradigms. I will argue that all three kinds of research are necessary to provide usable knowledge for education.

Traditionally, the term “biomarker” (an objectively measurable biological marker) has referred to plasma or protein products, for example, in cerebral spinal fluid (e.g., high levels of tau protein in the early stages of Alzheimer’s disease). However, a biomarker can also be a neuroimaging signature, such as the underactivation of a certain neural network or a cognitive signature, such as the cognitive measures of early decline (e.g., impaired memory function) that are strongly associated with Alzheimer’s disease (Beddington et al., 2008). These developments offer a window of opportunity for the field of mind, brain, and education. The identification of biomarkers for educational skills like reading and mathematics offers the potential for the field of neuroscience to contribute usable knowledge to education. However, it is not clear that the field is sufficiently advanced to identify biomarkers based on protein products. I will argue here that, as mind and brain are intimately related, a robust cognitive marker may in fact have more utility or “usability” for the field than a cerebral marker. Nevertheless, neuroscience has a key role to play in identifying cognitive biomarkers, because neuroscience can offer unique insights into causal developmental mechanisms.

In this review, I will try to illustrate how neuroscience methods can make a critical contribution to the mind, brain, and education field by deepening our understanding of causal mechanisms. Taking the critical precursor skill for literacy of phonological awareness as an example, I will show how an integrated research program can help us to understand the developmental mechanisms that lead to a learning difficulty such as developmental dyslexia. Developmental dyslexia is usually characterized as a specific problem with reading and spelling that cannot be accounted for by low intelligence, poor educational opportunities, or obvious sensory or neurological damage. Once it becomes possible to agree on the underlying causal mechanisms that give rise to specific problems, the field of mind, brain, and education will have the tools to develop a range of biomarkers for identifying the learning difficulty in question. For developmental dyslexia, these could include biomarkers at the level of brain structure (e.g., Niogi & McCandliss, 2006), brain function (e.g., Eden & Zeffiro, 1998), genes (Dale et al., 1998), and cognition (e.g., Goswami et al., 2002). As cognitive markers are typically cheaper to administer than markers that rely on neural imaging or the extraction of protein products, the most useful “usable knowledge” for education may be better cognitive measures for identifying educational risk. My essential argument is that cognitive measures will be based on firmer foundations if the neural
basis of the learning difficulty has been thoroughly investigated and understood.

I will therefore adopt a narrow focus for this review based on phonological awareness, the child’s awareness of the sound structure of words. Phonological awareness has been found to predict reading acquisition in all languages so far studied. I will argue that if we can isolate the neural processes that underpin the development of phonological awareness, this would provide usable knowledge for education. First, it would enable the development of biomarkers to test for the risk of reading difficulties (a robust biomarker should be usable with preverbal children and should not require attention skills). Discovery of a reliable marker would enable language-focused remediation to be offered early in the developmental trajectory, long before the onset of schooling, and thus long before the child experienced reading failure (Goswami, 2008). Second, detailed information about developmental causal mechanisms at the neural level should illuminate the developmental processes that would benefit most from direct intervention. In my view, education provides the best form of intervention for learning difficulties. Increased understanding of underlying causal mechanisms should therefore enable the design of optimal interventions and optimal early reading curricula for all children. Finally, measurement of critical developmental neural processes in pre-test versus post-test designs (with appropriate control groups) should allow the unambiguous assessment of whether an intervention or a general teaching program is making a difference.

A second aim of this review is to illustrate that a narrow research focus does not preclude the building of bridges between mind–brain and education. I will therefore finish by considering how neuroscience research programs could in the future enable recommendations from a “neuroscience-enriched” educator concerning the timing, sequence, differentiation, and methods of instruction in the early teaching of reading. I will argue that important first steps are (a) neuroscientific investigation of basic auditory processing in order to understand the neural mechanisms underpinning the development of phonological awareness; (b) investing in studies that are longitudinal, beginning in infancy; (c) deepening our knowledge about brain responses to simple auditory events, with the aim of developing simple biomarkers; (d) eventually including all kinds of learners in the research, with comparisons between typically developing and atypically developing children over developmental time being particularly important; and (e) regarding methods, recognizing the need to “start small,” with (in this case) tractable research questions about sensory mechanisms that nevertheless inform basic phenomena in the learning and teaching of reading.

THE DEVELOPMENT OF PHONOLOGICAL AWARENESS ACROSS LANGUAGES

The most important precursor skill for reading acquisition across languages is called phonological awareness. Phonological awareness first emerges as a natural part of language acquisition. As children acquire language, they become aware of the sound patterning in their language, and use similarities and differences in sound patterning to organize the mental lexicon (see Ziegler & Goswami, 2003). Phonological awareness is usually defined as the child’s ability to detect and manipulate component sounds in words. According to hierarchical theories of syllable structure, there are at least three linguistic levels at which component sounds can be considered. Children can be aware that (a) words can be broken down into syllables (two syllables in wigwam, three syllables in butterfly) and (b) syllables can be broken down into onset-rime units (to divide a syllable into onset and rime, divide at the vowel, as in t-eam, dr-eam, str-eam. The term “rime” is used because words with more than one syllable have more than one rime, for example, in mountain and fountain, the rimes are “-ount” and “-ain”, respectively. Finally, (c) the child can become aware of phonemes.

Phonemes are the smallest speech sounds making up words, but phonemes are an abstract concept defined in terms of sound substitutions that change meaning. For example, pin and pit differ in terms of their final phoneme, and pin and pan differ in terms of their medial phoneme. In all languages studied to date, phonemic awareness appears to emerge as a consequence of being taught to read and write. Prereading children and illiterate adults are generally not aware of phonemes: they perform poorly in tasks requiring them to manipulate or to detect single phonemes (e.g., Goswami & Bryant, 1990; Morais, Cary, Alegria, & Bertelson, 1979). Children who are learning to read become proficient in detecting and manipulating single phonemes fairly rapidly, and this proficiency depends on the age at which reading is taught and the transparency of the orthography that they are learning (e.g., Seymour, Aro, & Erskine, 2003). Matthew effects (the reciprocal effects of reading experience on other cognitive skills like phonological awareness) then compound these differences across languages (Stanovich, 1986). The mechanism for learning about phonemes seems to be learning about letters. Letters are used to symbolize phonemes. This symbolic function requires child learners to focus on some of the phonological similarities they detect in the speech stream, and discard others. For example, words like TRAY and TRACK begin with the same sound as words like CHICKEN. However, we use different letters to represent this sound for TRAY (the letters TR) versus CHICKEN (the letters CH). Beginning spellers who have not yet learned these orthographic conventions will represent the sounds with the same letter, as in the “invented spellings” ASCHRAY for “ashtray” and
CHRIBLS for “troubles” (Read, 1986). One letter, such as P, can be used to symbolize physically quite different sounds (like the P in “pit” versus “spoon”—young children may spell the latter as SBN, and acoustically they are correct to do so). As children become expert readers and spellers, orthographic learning changes phonological judgements, and possibly even auditory processing (see Goswami, Ziegler, & Richardson, 2005). Of course, such difficulties only arise for young learners of orthographies that lack 1:1 letter-phoneme correspondence, like English. In most of the world’s alphabetic orthographies, the same letter always corresponds to the same sound (e.g., Italian, Spanish, and Finnish).

The emergence of syllable and onset-rime awareness is developmentally comparable across languages and appears to be part of how the brain acquires language. Preschool children in all languages so far tested are aware of syllables, onsets, and rimes. The development of phonemic awareness varies with language. Children learning transparent orthographies with 1:1 correspondences between letters and phonemes, such as Greek, Finnish, German, and Italian, rapidly acquire phonemic awareness. Children who are learning to read in languages where morphology highlights phonetic contrasts, such as Turkish, also acquire phonemic awareness more rapidly (e.g., Durgunoglu, 2006; see also Frost, Katz, & Bentin, 1987, for an explanation of the orthographic depth hypothesis). Children learning nontransparent orthographies like English, Danish, and French are slower to acquire phonemic awareness (see Ziegler & Goswami, 2003). Children learning nonalphabetic orthographies, like Chinese children, appear to acquire syllable, onset, and rime awareness in a manner similar to children who speak languages with alphabetic orthographies. The acquisition of phonemic awareness then varies dramatically as a function of whether the Chinese characters (Chinese does not use an alphabetic script) are taught via early immersion in a phonetic script representing the sounds of the characters (Pin-Yin in mainland China, Zhu-Yin-Fu-Hao in Taiwan) or are taught by rote. Children in mainland China and in Taiwan both acquire phonemic awareness (Huang & Hanley, 1995; Siok & Fletcher, 2001). Children in Hong Kong, who begin learning the Chinese characters by rote rather than via a phonetic script, do not appear to develop phonemic awareness (Huang & Hanley, 1995).

THE BASIC AUDITORY PROCESSES YIELDING PHONOLOGICAL AWARENESS

To use the sound patterning of one’s language to organize the mental lexicon, similarities and differences between the sounds of words must be distinguished with relative precision. Basic auditory processing skills are the key to this precision. Recent research in child phonology suggests that early phonological representations for words are essentially “phonotactic templates” or “prosodic templates”, namely auditory patterns varying in intensity, duration, frequency, and rhythm (Pierrehumbert, 2003; Vihman & Croft, 2007). The dominant template in spoken English is bisyllabic, with stronger stress on the first syllable (e.g., “mummy”, “daddy”, “baby”). This prosodic template is so prevalent that we tend to alter the words that we use with babies to fit the pattern (“millie”, “dolly”, “doggie”). It is also the first template that young children produce (e.g., “nana” for “banana”). To distinguish these prosodic templates in the stream of sound that is spoken language, auditory cues to rhythm and stress are important.

A long time ago, it was proposed that basic auditory processing difficulties might characterize both children with specific language impairment (SLI), who have problems in the basic acquisition of language, and children with developmental dyslexia, who have problems in acquiring written but not in acquiring spoken language (Tallal & Piercy, 1973, 1974; Tallal, 1980). Tallal’s focus on the importance of the accurate perception of auditory temporal structure for developing a phonological system was very insightful. However, she characterized the key temporal parameters for phonological development as being rapidly changing or transient acoustic events. This was presumably because in the 1970s, it was believed that phonemes were the key to language learning, and that phonemes corresponded to acoustic features called formants—rapid changes in frequency and intensity (Blumstein & Stevens, 1981). Tallal (1980) argued that children with deficits in processing rapid and transient temporal information would have consequent difficulties in phoneme perception, and would thus have difficulty in acquiring literacy (as phoneme awareness was necessary for reading, see also Tallal, 2004).

In practice, however, rapid temporal information is only necessary for distinguishing between phonemes such as /b/ or /d/ when they are heard without context. Speech sounds are seldom heard without context by young infants, and in fact, the new template models of phonological development are not based on phonemes. They are based on prosodic patterns that correspond to the speech envelope or amplitude envelope. Speech as an acoustic signal can be modeled by factoring it mathematically into the product of a slowly varying envelope (also called amplitude modulation) and a rapidly varying fine time structure (see Smith, Delgutte, & Oxenham, 2002). Experiments using “chimeric” sentences created from the envelope of one sentence and the fine time structure of another have shown that the brain relies mainly on envelope cues for understanding speech (Smith et al., 2002). Babies who are deaf and who are given cochlear implants that transmit only envelope information and no rapid fine structure can develop language, and show the typical hierarchical sequence (syllable, rhyme, phoneme).
in developing phonological awareness (James et al., 2005). Clearly, basic auditory cues to the amplitude envelope, which include the auditory cues that yield prosodic patterning and speech rhythm, must be important for phonological development (see also Foxton et al., 2003).

When mothers talk to their babies, they adopt a lilting rhythmic speech pattern called "Motherese". This is observed across languages. Motherese (or infant-directed speech [IDS]) is characterized in particular by higher pitch, greater pitch, and volume variability and the use of a small set of highly distinctive melodic contours (e.g., Fernald et al., 1989). The prosodic patterning provided by Motherese is thought to be very important for infants acquiring language, who can use speech rhythm and stress patterns as cues to potential word boundaries (e.g., Cutler & Mehler, 1993; Echols, 1996). Infants show sensitivity to the speech rhythms characteristic of different languages very early indeed, at a few days old (e.g., Mehler et al., 1988). Rhythm is a complex acoustic percept. The auditory cues that yield rhythmic information include the duration of sounds, their intensity (loudness), rise time (the rate of change of the amplitude modulation and the depth of amplitude modulation), and changes in frequency (pitch changes). These auditory cues in combination in effect describe the amplitude envelope (see Figure 1). In recent research, we have been exploring the role of auditory cues such as rise time and duration in the development of phonological awareness and literacy skills by children across languages.

RISE TIME, THE AMPLITUDE ENVELOPE, AND PHONOLOGICAL AWARENESS

Rise time refers to the rate of change of the onset of the amplitude envelope of a particular auditory signal (speech or nonspeech). Rise time at syllable onset is thought to be particularly important in the perception and production of rhythmic speech (Bregman, 1993; Scott, 1998). As the maximal change in amplitude as a syllable is produced coincides with the production of the vowel, rise time is also a cue to vowel onset. The production of vowels in stressed syllables is accompanied by particularly large amplitude changes and salient rise times, whereas unstressed syllables have smaller amplitude changes and smaller rise times. This can be seen in Figure 1. The sharp rise time at the beginning of the first stressed syllable of "quickly" is much stronger than at the beginning of the second unstressed syllable, although both are associated with the same phoneme /k/. Rise time together with amplitude change is thus one auditory cue that is important for identifying the prosodic templates that are integral to phonological development in English, and rise time may also help with segmenting the syllable into onset-rime units (t-eam, dr-eam, str-eam).

We have been studying rise time processing extensively in children with developmental dyslexia, as these children have well-documented problems with phonological awareness, across languages. We have investigated whether children with developmental dyslexia have particular problems in discriminating rise time and other auditory cues related to amplitude envelope structure, such as duration and intensity. Children with developmental dyslexia are indeed significantly less sensitive to rise time than typically developing children (Goswami et al., 2002; Richardson, Thomson, Scott, & Goswami, 2004; Thomson & Goswami, 2008; see Pasquini, Corriveau, & Goswami, 2007, for similar data with adults). Further, individual differences in rise time discrimination are predictive of phonological awareness, even when factors such as age, verbal and nonverbal IQ, and vocabulary are controlled. Precocious readers, who usually have exceptional phonological skills, appear to be significantly more sensitive to rise time than typically developing controls (Goswami et al., 2002, study 2). This relative insensitivity to rise time in developmental dyslexia is also found for French children (Muneaux, Ziegler, Truc, Thomson, & Goswami, 2004) and for Hungarian children (Surányi et al., 2009), and Finnish dyslexic children show a relationship between rise time perception and literacy development (Hämäläinen et al., 2009). As French and Hungarian are syllable-timed languages, whereas English is a stress-timed language (i.e., the languages represent different rhythm types), these findings suggest that amplitude envelope cues are critical for phonological development at a level of auditory structure that is more basic than rhythm type. Therefore, rise time discrimination is likely to play an important role in the development of the phonological system, and subsequently the acquisition of literacy, across languages.

EXPLORING AMPLITUDE ENVELOPE PERCEPTION USING NEUROSCIENCE METHODS

So far, the data suggest that (a) phonological development is important for reading acquisition across languages;
(b) phonological development prior to reading across languages essentially comprises awareness of syllables, onsets, and rimes; (c) an important auditory cue to syllabic structure (and possibly the onset-rime division of the syllable) across languages is rise time; (d) phonological awareness is related to the basic auditory processing of cues like rise time; and (e) children with developmental dyslexia in a number of languages have specific difficulties in discriminating rise time. Given that we appear to have identified a basic auditory cue that contributes to phonological development and reading acquisition across languages, we can now explore the neural correlates of rise time representation.

In my own research group, we have been exploring the neural correlates of rise time processing using event-related potentials (ERPs). ERPs are particularly suitable neuroscience tools for questions about the development of auditory processing skills, as auditory information comes in over time, and millisecond differences in the arrival of information can have important consequences (e.g., for sound localization). ERPs enable the timing rather than localization of neural events to be studied, and are time-locked to specific events designed to study cognitive function. The most usual outcome measures are (a) the latency of the potentials, (b) the amplitude (magnitude) of the various positive and negative changes in neural response, and (c) the distribution of the activity. The sequence of observed potentials and their amplitude and duration are then used to understand the underlying cognitive processes.

In our research, we have been focusing on the mismatch negativity response (MMN). The MMN is a preattentive measure of the automatic detection of auditory change, and in adults there is a clear MMN to rise time (Thomson et al., 2004). To date, however, we have had difficulty in finding a clear MMN to rise time in children aged from 7 to 10 years. So far, we have suggestive data for the N100 and late discriminative negativity (LDN) responses, but no clear data for the MMN response. The N100 is an early auditory component signifying the detection of auditory events. The LDN is a later component also related to sound discrimination (in particular, to the detection of deviance in linguistic sounds, see Hommet et al., 2009). In a pilot study run by Thomson et al. (2004), we asked children to listen to rise times of either 15 ms (a very sharp or abrupt rise time) versus 90 ms (a more gradual rise time) through headphones as they watched a silent video. Behavioral data from other studies (Richardson et al., 2004) had suggested that the difference between these rise times was usually perceived by control children but not by children with developmental dyslexia. Thomson et al. (2004) found relatively clear patterns of N100 responding. For the 15 ms rise time stimuli, both children with developmental dyslexia and chronological age (CA) controls showed a large N1 at the temporal (over temporal cortex) and mastoid (over temporal bone) electrode sites (approximately $-2.5 \mu V$). For the 90 ms rise time stimuli, in contrast, the groups diverged. The CA controls showed a significantly reduced N1 amplitude for 90 ms rise times compared with 15 ms rise times, whereas the dyslexic children did not. Hence neurally, the dyslexic brain was responding to the presence of auditory events, as shown by the N1. However, the amplitude of its response did not differentiate the relatively long rise time of 90 ms from the much shorter rise time of 15 ms. Yet this 75 ms difference in rise time is important for the accurate perception of syllable onsets. The amplitude of the N100 was also significantly correlated with the behavioral measures. For example, behavioral performance on a rise time discrimination task was significantly correlated with N1 amplitude ($r = -0.77$, temporal electrode LM, p < .01; a nose reference was used), as were the phonological and literacy measures (e.g., for electrode LM, learning novel phonological strings, $r = 0.68$; performance on a standardized spelling test, $r = 0.74$; performance on a phonological awareness task [oddiy task], $r = 0.80$; p’s < .01). The data showed that there was a relationship between the amplitude of the neural response to simple auditory rise time events and the child’s behavior in tasks measuring literacy and phonological awareness.

In a more recent study seeking MMNs to rise time, Fosker et al. (2009) reported a difference in the LDN component of the electroencephalographic (EEG) response to rise time changes in children with developmental dyslexia compared to age-matched control children who were typically developing readers. Using a paradigm based on Thomson (2004), in which the discrimination of tones with rise times of 15 ms was compared to that of tones with rise times of 90 ms in a passive oddball paradigm, it was found that the children with developmental dyslexia showed a significantly smaller LDN response to the rise time change. Behaviorally, the children with developmental dyslexia were significantly impaired in discriminating the rise times of simple tones, but not their intensity. No difference in MMNs was found between the two groups for either rise time or for intensity. Hence one possible biomarker for phonological difficulties and developmental dyslexia could be rise time ERPs (N100 or LDN responses). However, whether the MMN will prove to be a useful ERP marker for developmental dyslexia must be questioned (see also Bishop, 2007, for a discussion of the inconsistent findings from studies using MMNs to identify auditory processing difficulties in SLI children).

Alternatively, it may be that devising a very accurate psychoacoustic measure of rise time sensitivity, which would not require brain imaging technology, could be a more usable biomarker. This is suggested by data from another research group, who have been examining the neural response to the amplitude envelope in typically developing children (Abrams et al., 2008). Kraus and her colleagues used EEG in a different way to explore how well the brain of a child
could “phase lock” to the speech envelope. Their interest was in whether the slower temporal features that characterize the speech envelope would be processed preferentially by the right hemisphere. This is because studies using nonspeech acoustic stimuli have shown that slower component rates (timescales commensurate with processing syllabicity and intonation contours) lateralize to the right hemisphere, whereas rapid component rates (timescales commensurate with processing formant transitions) lateralize to the left hemisphere (Poeppel, 2003). Abrams et al. used EEG to measure whether auditory neurons would be activated in phase with the changes in acoustic energy that occur with the production of different syllables, that is as the amplitude envelope of speech rises and falls. In essence, they measured whether the child’s brain could track the speech envelope in real time, which they called “phase locking”. In their paradigm, children listened to thousands of repetitions of someone saying “The young boy left home” while EEG recordings were made. The waveform of the cortical response was compared to the stimulus waveform to see whether peaks in neural firing corresponded to rise times in the speech envelope. The 12 children in the study (aged 9–13 years) tracked the speech envelope remarkably accurately, showing a series of positive peaks of neural activity which closely followed the temporal envelope of the speech, at least when right hemisphere responses were considered. In fact, the right hemisphere was 100% more accurate than the left in following the contours (rise times) of the speech envelope.

This is a very promising technique for studying the causal mechanisms that underpin poor phonological development in children with developmental dyslexia. Given the psychoacoustic rise time data discussed earlier, one plausible hypothesis is that the dyslexic brain is impaired at phase locking to the rhythmic structure of the speech. A child with developmental dyslexia would be expected to show an impaired right hemisphere contour-following response. If this were to be the case, then we would have a plausible neural causal mechanism for impaired phonological development in developmental dyslexia. If further studies showed that the accuracy of a child’s cortical tracking of the speech envelope and their behavioral rise time thresholds were measuring the same underlying neural weakness, then we would have a cognitive task that could be a useful biomarker for developmental dyslexia.

If the scenario that I outline were to be fulfilled, then the neuroscience paradigm developed by Kraus and her group will generate previously absent evidence with respect to the causal mechanisms involved in developing good phonological awareness. The behavioral data outlined earlier support the utility of developing neural measures of amplitude envelope processing, as the psychoacoustic studies pinpointed rise time as an important auditory parameter. Meanwhile, the cognitive studies highlighted the importance of prosodic and rhythmic structure for language acquisition and for the development of the phonological system. Hence all the different research paradigms were important in different ways. Both cognitive and educational studies of developmental dyslexia identified phonological processing as the key factor in explaining individual differences in reading attainment, and suggested that phonological awareness provided the optimal focus for remediation. The psychoacoustic studies of rise time processing showed that impaired rise time sensitivity seems to be ubiquitous in developmental dyslexia, across languages. This in turn suggested that a more detailed neural investigation of how the brain tracks amplitude envelope onsets might be helpful in understanding phonological development. The method developed by Kraus and her colleagues yields a potentially more fruitful way of tackling this than measuring MMNs to rise time. This EEG paradigm also demonstrated a potential neural mechanism, phase locking to the speech envelope, that may be atypical in the dyslexic brain. This now offers a way forward in terms of developing biomarkers for developmental dyslexia.

If this hypothetical elucidation of developmental mechanisms is supported by future studies, the implications for education are clear. First, we would need to develop a simple listening measure that taps rise time sensitivity in very young children (see Corriveau, Thomson, & Goswami, in press, for one possibility). We might then decide to use EEG measures, such as phase locking to the speech envelope, to confirm cortical processing difficulties with speech in children with poor rise time sensitivity (see Molfese, 2000, for an alternative use of EEG based on syllables). And ideally, we would develop useful remediation and language enrichment programs that can target the deficiencies in rhythmic timing that appear to characterize the dyslexic brain. The rise time research suggests that preschool activities based around rhythm and language (including music and singing) could be particularly beneficial (see Goswami, in press).

**CONCLUSIONS**

Neural imaging of the brain’s responses to auditory phenomena is an exciting avenue to explore with respect to providing usable knowledge for education. As illustrated here, neuroscientific investigations of basic auditory processing can help us to understand the causal mechanisms underpinning the development of phonological awareness, across languages. Having identified promising mechanisms, we need to carry out longitudinal studies, beginning in infancy, to track and understand developmental relationships between sensory processes and cognitive outcomes like language acquisition. By deepening our understanding of brain responses to simple auditory events, we can begin to develop biomarkers for language difficulties and developmental dyslexia. Similarly, as our understanding of causal mechanisms improves, our
educational interventions and remedial teaching can also be improved. Ideally, we will gain sufficient understanding to enable the creation of optimal learning environments for all children, whether they are at risk of a learning difficulty or not. Obviously, while biomarkers can help in the identification of learning difficulties such as developmental dyslexia, the optimal learning environments for literacy will need to be language tailored.

Clearly, the research findings discussed here are only a first step for a systematic program of neuroeducation. The rise time/speech envelope findings are insufficient at present to allow a “neuroscience-enriched” educator to make any recommendations concerning the timing, sequence, differentiation, and methods of instruction in the early teaching of reading. However, such an educator could argue that rhythm perception appears to have an important connection with phonological awareness across languages, and could suggest that an early focus on rhythm in preschool (e.g., playing a chime bar at different rhythmic rates to nursery rhymes and jingles, learning to clap out syllables in words or to clap on stressed syllables, experience with percussion matched to poetry or song, learning to recite poems with clear metrical structure) might help to lay a solid foundation for literacy. On the other hand, this could have been concluded without the neuroscience component of the research. What is added by the neuroscience is a deeper understanding of causal mechanisms. The rise time data alone did not provide this. If the hypothesis that the dyslexic brain is inefficient in phase locking to rhythmic information in speech is supported by further studies, we can begin to think about how to facilitate children’s ability to phase lock to any kind of rhythmic information. For example, rhythm is usually more overt in music than in speech. So perhaps the neuroscience-enriched educator would begin with tapping or dancing in time with music.

As for the “pedagogically enriched” neuroscientist’s answers to the educator’s questions about the “what” of brain research, the next steps are clear. We need neuroscientific investigation of the basic auditory parameters that contribute to the experience of rhythm and timing across languages (i.e., rise time, duration, pitch, and intensity) and ideally across different neurodevelopmental disorders. We need these investigations to be longitudinal, either beginning in infancy or at least commencing long before the child begins learning to read. The lowest level of impairment should be identified neurally as early as possible, and developmental effects on higher-level cognition examined in longitudinal studies (see Goswami, 2003). This research strategy would not only provide insights relevant to improving the functioning of the impaired system, it would also reveal alternative developmental pathways to the same end state, enabling the identification of alternative interventions (see Karmiloff-Smith & Thomas, 2003). Cross-syndrome comparisons could disentangle specific from general developmental effects, and would eventually enable the effective design of robust biomarkers for specific disorders such as developmental dyslexia. Cross-language studies would establish whether a single biomarker is relevant across languages. We need to study all kinds of learners, however, not only children with neurodevelopmental disorders. Children whose literacy development is typical, children whose literacy development is atypical, children for whom other aspects of development are atypical although reading may be apparently normal (to rule out as well as rule in variables of interest), and adults who learn to read in later life, are all important. Here cross-sectional studies, particularly across languages, provide a useful first step.

The new field of mind, brain, and education is an exciting one, with great future promise. In applying neuroscience to education, however, both “neuroscience-enriched” educators and “pedagogically-enriched” neuroscientists must proceed with caution. We cannot afford to ignore the nature of what is (and is not) possible to measure using current neuroscience techniques when framing our research questions about the brain. It is crucial to “start small”, using the outcome measures that are actually possible given the current state of the art, and then to adapt educational questions to variables that we can meaningfully measure. In the case of producing usable knowledge about literacy, I would argue that we need to begin with auditory sensory processing. As illustrated here, even simple auditory stimuli such as tones varying in rise time have the potential to yield novel and helpful information concerning the development of the skills central to the learning and teaching of reading.

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