

Biological Factors Contributing to Reading Ability

Subcortical Auditory Function

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THEORIES OF DYSLLEXIA: CORE IMPAIRMENTS

An estimated 10% of children exhibit developmental dyslexia, a disorder that affects reading and spelling skills (Démonet, Taylor, & Chaix, 2004). Although these learning problems are regarded as having a neurological basis, the nature of the core neural impairment remains unclear and debated (Démonet et al., 2004; Ramus, 2001a, 2001b). A number of studies have consistently implicated poor phonological processing as one underlying basis for reading and spelling difficulties (Carroll & Snowling, 2004; Marshall, Snowling, & Bailey, 2001; Windfuhr & Snowling, 2001). Specifically, a majority of children with impairments in reading ability exhibit difficulties on an array of tasks that measure phonological processing abilities—such as decomposing words into their constituent syllables and phonemes, deciding whether a pair of words rhyme, repeating a list of digits or nonwords, or quickly retrieving information from long-term memory. Adequate phonological skills require the explicit manipulation of speech sounds and therefore adequate representation of these sounds in the brain, as well as rapid, online access to the representations during task performance. The nature of the problems underlying poor phonological skills, and ultimately poor reading, is under debate. Here, we review three such core impairments.

Core Impairment in Processing Time-Varying Acoustic Events

Some investigators argue that the phonological impairment is an outcome of an inability to perceive *time-varying acoustic signals* (Tallal, 1980; Tallal, Stark, & Curtiss, 1976). Indeed, a significant proportion of individuals with developmental dyslexia (~50%) are also afflicted with core sensory processing impairments (Ramus et al., 2003). Auditory impairments include impaired ability to judge the temporal order of rapid auditory sequences, gap detection, detection of frequency and amplitude modulations, elevated frequency discrimination, and difficulties in auditory stream segregation (Abrams, Nicol, Zecker, & Kraus, 2006; Démonet et al., 2004; Goswami et al., 2002; McAnally, Hansen, Cornelissen, & Stein, 1997; Ramus, 2003; Tallal, Stark, Kallman, & Mellits, 1980). Comparable processing impairments in infants are predictive of their

later language development (Benasich, Curtiss, & Tallal, 1993; Benasich & Tallal, 2002; Benasich, Thomas, Choudhury, & Leppänen, 2002).

Core Impairment in Excluding Background Noise

As per the noise-exclusion deficit hypothesis, the core impairment in children with learning disabilities is the inability to exclude background noise during signal processing (Sperling, Lu, Manis, & Seidenberg, 2005, 2006). Although initially proposed in the visual domain, such impairments have been shown to occur in the auditory domain as well (Ziegler, Pech-Georgel, George, & Lorenzi, 2009). According to the noise-exclusion deficit hypothesis, sensory impairments arise due to deleterious influence of background noise on sensory processing (Sperling et al., 2005).

Context-Dependent Encoding Impairment

A core impairment in context-dependent sensory processing (statistical learning) has also been identified. Children with perceptually based learning problems show reduced ability to modulate current perceptual dynamics based on prior experience. That is, children with learning problems are unable to adapt to context, resulting in poorer performance in challenging environments (Ahissar, 2007; Ahissar, Lubin, Putter-Katz, & Banai, 2006; Plante, Gómez, & Gerken, 2002).

COGNITIVE-SENSORY INTERACTION IN THE AUDITORY SYSTEM: IMPLICATION FOR DEVELOPMENTAL DYSLEXIA

The field is mired in theoretical discussions about underlying core impairments, that are nevertheless critical, because several therapeutic interventions have been devised to specifically cater to views ascribed by a certain theory (Eden & Moats, 2002; Goswami, 2006). The extant influential theories have failed to completely account for the broad cognitive, reading, and speech-in-noise perception impairments that exist in poor readers (Ramus, 2004). A critical reason why these hypotheses fail is that they are entrenched in the classic but flawed thinking that auditory processing progresses in a bottom-up manner (from sensory to cognitive processing). Consistent with mounting evidence of top-down influences, even at the lowest levels of auditory processing, there is a critical need to understand the complex-bidirectional interactions between higher-level cognitive processing and lower-level sensory encoding in poor readers. For instance, impairments in cognitive encoding can trickle down to sensory areas via a complex network of efferent feedback loops (cortico-fugal feedback). The broad impairments in developmental dyslexia can be a result of impaired cognitive-sensory interplay, and perhaps specifically be a result of deficient cortico-fugal function (Chandrasekaran, Hornickel, Skoe, Nicol, & Kraus, 2009).

Rather than get bogged down by arguments related to a causal relationship between core deficits and reading impairments, let us focus on understanding the biological correlates of the various impairments in children with reading disorders. It is important to 1) understand how biologically relevant, time-varying sounds (e.g., speech sounds that can pose perceptual challenges to children with dyslexia) are represented in the brain; 2) explore how this representation varies as a function of reading ability; and 3) understand how training and experience can modulate these representations in children with developmental dyslexia.

Brainstem Representation of Speech Sounds: A Window to Examining Cognitive-Sensory Interplay in the Auditory System

Speech sounds can be thought to consist of three basic components: pitch, harmonics, and timing (see Figure 6.1). In speech, these three elements of the acoustic signal can be differentiated based on their time scales, and they carry different informational content. In English, timing and harmonic cues convey the phonetic content of speech sounds, and are mainly responsible for the verbal message (the specific consonants and vowels). Pitch conveys intent (question versus statement), emotion, and other extra linguistic cues. Timing and harmonic cues, such as the difference in timing of voicing between /d/ and /t/, or the different release burst spectra of /d/ and /g/, are especially vulnerable to masking by background noise and pose perceptual challenges for some individuals with language and reading impairments (Hornickel, Skoe, Nicol, Zecker, & Kraus, 2009; Tallal & Gaab, 2006). Our studies have led to the development of a framework that organizes the speech signal into components that are selectively enhanced or impaired in certain populations and listening conditions (Tzounopoulos & Kraus, 2009).

Neural transcription of speech acoustics has been well studied in the auditory cortex of humans and experimental animals for stop consonants, vowels, and pitch. The focus here is on subcortical (brainstem) processing of speech sounds. The auditory brainstem response (ABR) is a noninvasive measure of far-field representation of stimulus-locked, synchronous electrical activity, originating at the brainstem (Chandrasekaran & Kraus, 2010b), that reflects the temporal and spectral characteristics of complex stimuli with remarkable precision (Skoe & Kraus, 2010). Unlike the more abstract representation of sound in the cortex, speech evokes a response in the brainstem that looks and sounds (when played back) like the evoking utterance itself (Galbraith, Arbagey, Branski, Comerchi, & Rector, 1995). Responses are interpretable and meaningful in individuals. When recorded in response to a consonant or vowel syllable, the *timing* of the speech-evoked brainstem response (sABR) provides information, by fractions of milliseconds, about the onset and offset of the consonant and the vowel. The phase-locked frequency-following aspect of the response reflects spectrotemporal patterns in the evoking signal. Analysis

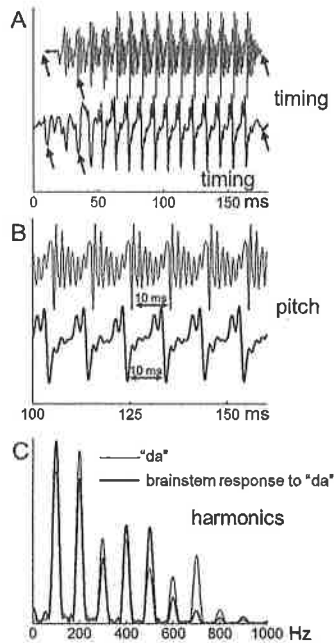


Figure 6.1. The stimulus /da/ (thin lines, upper trace in A and B) and its brainstem response (thick lines, lower trace in A and B); the brainstem response looks like the stimulus. A) The entire utterance and response with timing features indicated with arrows. B) A segment illustrating both syllable and response has a fundamental cycle of 10 ms, or 100 Hz. C) Spectral representation of the vowel portion of the stimulus. This frequency-domain representation illustrates the similarity of the harmonic structure.

of the spectral content of the response provides information about the fundamental frequency and lower harmonics, major contributors to the perceived pitch of the signal, as well as higher harmonics (including the formant structure). Several aspects of the sABR reflect language and musical experience, and short-term auditory training (Carcagno & Plack, 2011; Kraus and Chandrasekaran, 2010; Krishnan and Gandour, 2009; Russo, Hornickel, Nicol, Zecker, & Kraus, 2010; Song, Skoe, Banai, & Kraus, 2011; Strait, Hornickel, & Kraus, 2011; Tzounopoulos & Kraus, 2010), making it well suited to provide objective physiological information about speech encoding in populations with known impairments at perceptual and cognitive levels. It is important to note that higher-level cognitive processes dynamically interact with subcortical encoding of sound to shape auditory perception.

Subcortical Representation of Speech and Reading Ability

Brainstem encoding of children with language-based learning disorders reveals deficiencies in timing and harmonic shaping consistent with the phonological processing problems inherent in reading disorders (Banai et al., 2009; Hornickel et al., 2009; Hornickel, Anderson, Skoe, Yi, & Kraus,

in press; Hornickel, Chandrasekaran, Zecker, & Kraus, 2011; Hornickel & Kraus, 2011; Tzounopoulos & Kraus, 2009). In evaluations of good and poor readers, it is evident that there is a relationship between the brainstem representation of speech features (timing, and harmonic structure) and reading ability, how manipulations of listening “challenge” the reader, and how contextual information affects neural encoding of speech. Together, the data show a strong association between subcortical auditory function and reading ability, and this lends credence to each of the various core impairment theories reviewed previously.

Brainstem Timing and Harmonic Encoding Is Associated with Reading Skills

A strong relationship has been observed between particular features of the speech ABR to the syllable /da/ and measures of reading skills. Significant correlations are observed between reading and subcortical timing and harmonic encoding, but not pitch encoding (see Figure 6.2). Correlational analysis between brainstem and reading indices demonstrates that reading and some phonological skills (phonological awareness and

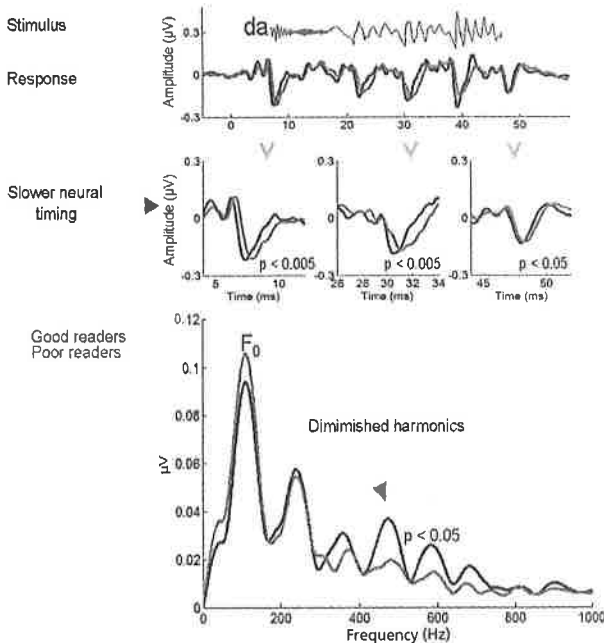


Figure 6.2. Top: Brainstem response to stimulus /da/ from good readers (black) and poor readers (grey). Middle: Key timing events in the stimulus. Poor readers show delayed-neural timing of these events. Bottom: Relative to good readers, poor readers show diminished higher-harmonic representation. (Adapted from Banai, K., Hornickel, J., Skoe, E., Zecker, S., & Kraus, N. Reading and Subcortical Auditory Function, *Cerebral Cortex*, 2009, 19, 11, pp. 2699–2707, by permission of Oxford University Press.)

phonological memory) are significantly related to subcortical timing and harmonic encoding (Banai, Nicol, Zecker, & Kraus, 2005; Banai et al., 2009; Hornickel et al., 2011; Hornickel, Anderson, Skoe, Yi, & Kraus, in press).

Consonant Differentiation

Stop consonants (e.g., in the syllables /ba/, /da/, /ga/) are especially vulnerable to misperception in poor readers (Hornickel et al., 2009; Serniclaes & Sprenger-Charolles, 2003; Serniclaes, Sprenger-Charolles, Carre, & Démonet, 2001). Timing cues evoked by acoustic differences in these syllables are present in the sABR (Johnson et al., 2008; Skoe, Nicol, & Kraus, 2011). Formant trajectories that differentiate the syllables translate into timing differences, an aspect well captured by sABRs. This is important because subcortical differentiation of stop consonants is associated with reading ability (see Figure 6.3). Specifically, children with higher phonological awareness—as measured by standardized measures—show greater differentiation among these three consonants (Hornickel et al., 2009).

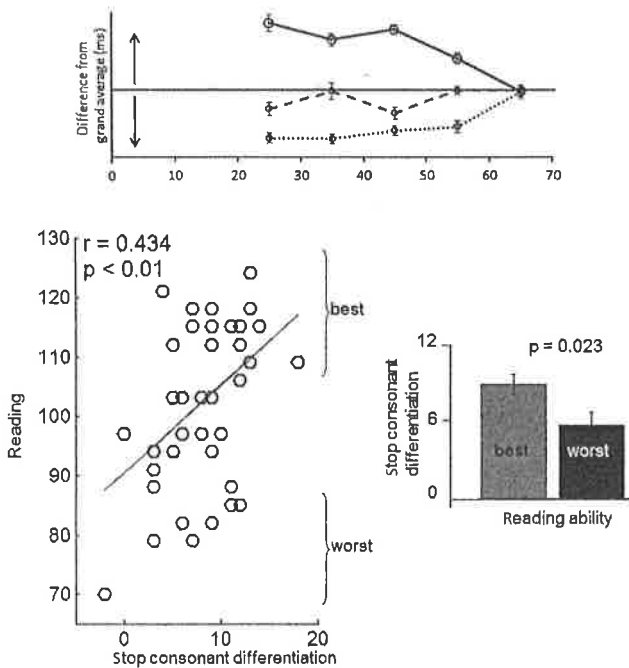


Figure 6.3. Top: Normalized response timings (x-axis represents time in milliseconds) to /ba/ (solid line), /da/ (dashed line), and /ga/ (dotted line). Timing differences persist only for the duration of the formant transition. Bottom: The subcortical differentiation score, a composite rendering of direction and extent of timing differences among responses to the three syllables, with higher scores signifying better neural differentiation, is significantly correlated with phonological awareness, and is significantly different between the top and bottom performers (inset). (Source: Hornickel, Skoe, Nicol, Zecker, & Kraus, 2009.)

EFFECT OF BACKGROUND NOISE ON BRAINSTEM REPRESENTATION OF SPEECH FEATURES IN GOOD AND POOR READERS

The noise exclusion hypothesis argues that background noise is particularly debilitating for poor readers, and this may represent a core impairment in some affected individuals. In an examination of the effect of background noise on the brainstem representation of speech, brainstem responses were recorded to the speech syllable /da/ in quiet and in background noise from a group of school-age children (Anderson, Skoe, Chandrasekaran, Zecker, & Kraus, 2010). The children were grouped into top and bottom readers based on standardized reading scores. Consistent with previous results (Cunningham, Nicol, Zecker, Bradlow, & Kraus, 2001), it was determined that background noise delayed the timing of the brainstem response to speech syllables in these individuals. However, children with poor reading scores showed a greater quiet-to-noise timing shift relative to good readers, suggesting that poor readers are more vulnerable to the deleterious effects of noise (see Figure 6.4).

EFFECT OF CONTEXT (STATISTICAL LEARNING) ON BRAINSTEM RESPONSES IN GOOD AND POOR READERS

The ability to tune into regularities in the auditory environment is fundamental to processing behaviorally relevant auditory signals (Suga, 2008). There is considerable evidence that even human infants are adept at extracting regularities, suggesting that the brain is exquisitely tuned to statistical properties in the auditory environment even during infancy (Saffran, Aslin, & Newport, 1996; Saffran, Johnson, Aslin, & Newport, 1999). A number of behavioral studies have shown that children with developmental dyslexia

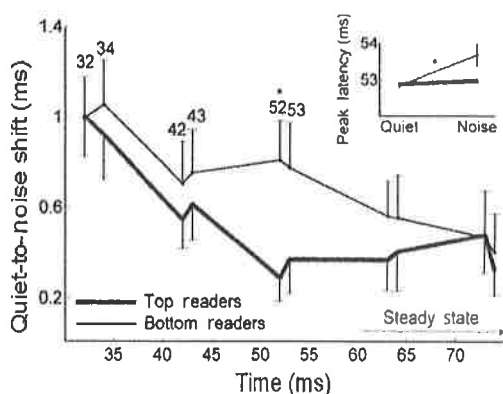


Figure 6.4. Latency (timing) shifts from quiet-to-noise for good reading (thick black line) and poor reading (thin grey line) groups. Inset shows differences between the two groups in noise for one of the peaks. The two groups did not differ in the quiet listening condition. (Used with permission of the Society for Neuroscience, from Neural timing is linked to speech perception in noise, Anderson, S., Skoe, E., Chandrasekaran, B., & Kraus, N., *The journal of neuroscience: The official journal of the Society for Neuroscience*, 30[14], 2010; permission conveyed through Copyright Clearance Center, Inc.)

show an impaired ability to improve sensory processing with repetition. In tasks with a large number of trials, good readers improve performance over time, but poor readers do not improve over time (Ahissar et al., 2006). This suggests that children with dyslexia are unable to use prior experience (context) to improve ongoing perception. Consistent with this proposal, it was determined that stimulus context influences encoding in the auditory brainstem (Chandrasekaran et al., 2009; Strait, Hornickel, & Kraus, 2011). Specifically, typically developing children showed enhanced spectral representation at the level of the auditory brainstem when the syllable was presented in a repetitive context, relative to when it was presented in a variable context (see Figure 6.5). In contrast, children with reading disorders showed an impairment in repetition-induced spectral fine-tuning at the level of the brainstem. Such context-dependent effects can be explained within the framework of our cognitive-to-sensory (corticofugal) theoretical model. Surprisingly, in children with dyslexia, there is enhanced spectral representation in the variable condition (relative to the repetitive context). These results are consistent with the view that in dyslexics, sensory representation may not be modulated by prior experience—a fact that may contribute to a more “creative” sensory representation. Further studies are required to disentangle the biological underpinnings of this interesting finding.

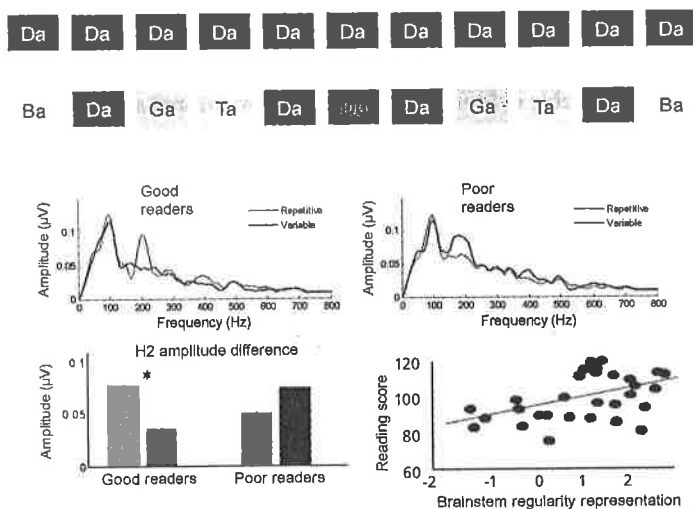


Figure 6.5. Context effects are seen for good readers but not for poor readers. The speech sound /da/ was presented in predictive (top row) and variable (second row) contexts. Grand-average spectra over the formant transition period for the good (left) and poor (right) readers show enhanced harmonic encoding in the repetitive condition in the good readers and in the variable condition in the poor readers. Bar plots of H2 amplitude support the response spectra, with greater H2 amplitude in good (left) than poor (right) readers in the repetitive condition and the opposite effect in the variable condition. The normalized difference in H2 magnitude between the two conditions reflecting brainstem regularity representation) is related to standardized scores of reading ability. Poor readers show inferior regularity enhancement in the brainstem relative to good readers. (From Chandrasekaran, B., Hornickel, J., Skoe, E., Nicol, T., & Kraus, N., [2009]. Context-dependent encoding in the human auditory brainstem relates to hearing speech in noise: Implications for developmental dyslexia. *Neuron*, 64[3], pp. 311–319. Copyright 2009 Elsevier. Reprinted by permission from Elsevier.)

BRAINSTEM-CORTICAL RELATIONSHIP IN CHILDREN WITH A WIDE RANGE OF READING ABILITY

It is well established that the left auditory cortex is specialized for processing rapid acoustic signals, and therefore crucial for speech perception (Belin et al., 1998; Niogi & McCandliss, 2006; Schwartz & Tallal, 1980; Gaab, Gabrieli, Deutsch, Tallal, & Temple, 2007). Less established is the role of the auditory brainstem in cerebral lateralization, as well as how brainstem-cortical relationships underlie speech perception ability. Auditory brainstem timing significantly predicts cerebral lateralization as measured by cortical event-related potentials (Abrams et al., 2006). Children who had atypical brainstem timing showed less cortical asymmetry, which was also associated with poor reading skills. This convergent data suggests that processing in the brainstem and the cortex are strongly linked and that subtle impairment at the level of the brainstem can dramatically alter cortical processing of speech sounds.

Training Modulates Auditory Brainstem Responses to Speech

It is well established from animal models that processing in the auditory brainstem is experience dependent and plays a crucial role in auditory learning (Bajo, Nodal, Moore, & King, 2010; Luo, Wang, Kashani, & Yan, 2008; Suga, 2008; Suga & Ma, 2003). It is important to note that brainstem encoding of speech can be ameliorated with software-based auditory training, suggesting that auditory processing in the brainstem is malleable to experience, and not hard wired (Carcagno & Plack, 2011; Russo, Hornickel, Nicol, Zecker, & Kraus, 2010; Song, Skoe, Banai, & Kraus, 2011; Song, Skoe, Wong, & Kraus, 2008). However, training does not change all aspects of the brainstem response. Rather, the plasticity is specific. For example, children with learning impairments show superior quiet-to-noise correlations after auditory training, suggesting improved fidelity of neural representation as a result of this training (Russo, Nicol, Zecker, Hayes, & Kraus, 2005).

Music as a Viable Training Approach

Music training is known to induce neuroplastic changes throughout the nervous system (Habib & Besson, 2009; Münte, Altenmüller, & Jäncke, 2002). Music training induces plastic changes that benefit music processing but also can improve processing in other domains including language and reading as well (reviewed in Kraus & Chandrasekaran, 2010). Based on this evidence, a number of researchers have argued for the viability of music as an indirect training approach in children with developmental dyslexia (Anvari, Trainor, Woodside, & Levy, 2002; Chandrasekaran & Kraus, 2010a; Overy, 2003; Strait & Kraus, in press; Tallal & Gaab, 2006). One line of research has been to evaluate the role of musical training in shaping the auditory brainstem response to musical and speech stimuli. It has been demonstrated that musical experience enhances the brainstem representation of native

and nonnative speech sounds (Musacchia, Sams, Skoe, & Kraus, 2007; Wong, Skoe, Russo, Dees, & Kraus, 2007). Musical training also improves the representation of speech in noisy backgrounds (Parbery-Clark, Skoe, & Kraus, 2009). Musicians show superior stimulus-to-response correlations in noise, suggesting better fidelity of responses in challenging backgrounds. From a cognitive perspective, musicians show enhancement of a number of skills including working memory and auditory stream segregation—skills known to be deficient in children with dyslexia (Chandrasekaran & Kraus, 2010a; Parbery-Clark et al., 2009; Parbery-Clark, Strait, Anderson, Hittner, & Kraus, 2011). Taken together, these studies provide evidence for the possible utility of musical training as a potential remediation approach (Habib & Besson, 2009; Tallal & Gaab, 2006).

Theoretical Model: A Dynamic, Reciprocally Interactive, Positive-Feedback Process Between Cortex and Brainstem

Massive efferent projections from the cortex to subcortical regions form the structural basis for cognitive-to-sensory fine-tuning (Luo et al., 2008; Suga, 2008; Suga, Gao, Zhang, Ma, & Olsen, 2000; Suga & Ma, 2003; Suga, Xiao, Ma, & Ji, 2002; Winer, 2006). Efferent connections provide excitatory and inhibitory control over the brainstem nuclei. Thus, repeated stimulation by behaviorally relevant stimuli, electrical stimulation of forebrain structures, and auditory training have all been shown to induce plastic changes in the neuronal response properties in the auditory brainstem in animal models (Bajo et al., 2010; Luo et al., 2008; Suga, 2008; Suga et al., 2002). These animal studies support the view that corticofugal modulation can change processing in the subcortical structures in a behaviorally relevant manner. This forms the basis for a theoretical model that argues for a bidirectional processing scheme in the auditory system, in which sensory and cognitive factors interact to determine the end realization of a stimulus.

MODEL PREDICTIONS

In predictable contexts, the cortex is able to detect statistical regularities and modulate processing at the level of the brainstem via the selective extracting of relevant regularities, thereby improving cortical signal quality (Figure 6.6). Specifically, the feedback from the cortex fine tunes the encoding of the acoustic elements of speech at the brainstem, such that relevant aspects of the signal are enhanced and irrelevant details are suppressed, leading to an overall sharpening. This model is consistent with a proposal developed to explain cross-domain plasticity induced by musical training. This proposal suggests that subcortical plasticity may be a result of several factors, involving cortex and limbic systems (Patel, 2011). Effective efferent feedback is established in the system in predictable contexts; such plasticity occurs rapidly, persists over time, and functions to

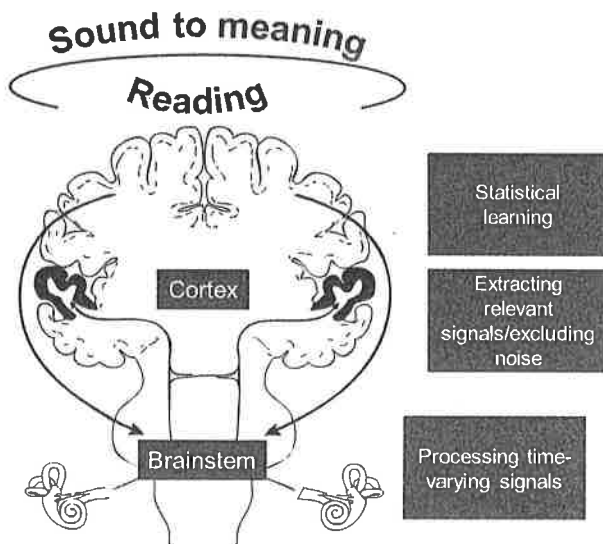


Figure 6.6. Theoretical model: The auditory system is composed of the auditory cortex and several brainstem nuclei that are connected bidirectionally (feedforward as well as feedback connections). Such interconnectivity allows for information transfer from the brainstem to the cortex, as well as feedback regulation (cortical influences on the brainstem). The cerebral cortex is adept at detecting and extracting statistical regularities in the auditory environment. Feedback from the cortex can selectively enhance relevant aspects of signal as well as suppress irrelevant signals (noise) at the auditory brainstem. Data reviewed in the main text argue for a relationship between brainstem encoding of speech and reading ability. Such a relationship reflects the cognitive-sensory nature of reading (dys)function, the biological basis for which may be the corticofugal (feedback) loops connecting the cortex and the brainstem.

improve overall signal quality in challenging backgrounds. In impaired systems (i.e., children with developmental dyslexia), our model predicts an impairment in the rapid and automatic extraction and storage of relevant auditory information (pattern detection impairment) at the level of the auditory cortex that permeates to lower-level encoding impairments via reduced feedback from the corticofugal network. Thus, in this model, both sensory and cognitive factors can contribute to ultimate reading (dys)function, mediated by an auditory system that has both feedforward as well as feedback loops. Specific contributions of various sensory and cognitive factors can explain variability in reading skills by using structural-equation modeling, a multivariate analyses technique (Hornickel et al., 2011; Strait, Hornickel, & Kraus, 2011.) The results demonstrate that specific brainstem signatures (reviewed above) contribute significantly toward explaining a high proportion of reading variance, providing a biological basis for establishing objective markers of reading ability.

CONCLUSION

Reading relies on a complex and multifaceted combination of processes that have proven difficult to disentangle. Children with reading difficulties show a broad range of impairments in cognitive and sensory processing.

The studies reviewed in this chapter show that children with reading difficulties exhibit impairments in subcortical processing of sound, as well as reduced cortical asymmetry. Finally, reading ability correlates significantly with a number of brainstem measures, including neural timing, representation of higher harmonics, resistance to background noise, and the ability to use prior experience (i.e., profit from stimulus repetition) to improve spectral representation. These factors, when incorporated in a structural-equation model, significantly predict variability in reading ability (Hornickel et al., 2011). On the basis of the studies reviewed here, we argue that the auditory brainstem response to speech serves as a significant and accessible factor underlying reading ability and impairment.

FUTURE DIRECTIONS

Future directions to further the understanding of the biological basis of reading and its application to education and clinical management include: 1) refining the subcortical neural signature for reading ability and its developmental trajectory, 2) using brainstem activity as an early neurobiological marker of reading ability, 3) integrating subcortical-neural signatures with animal physiology and genetic models, and 4) integrating information obtained through cutting-edge emerging technologies that are meaningful in individuals (i.e., subcortical physiology with structural measures, e.g., diffusion tensor imaging).

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