uals with different levels of cognitive-affective integration respond to a variety of emotion-activating events, both in the laboratory and in real life? Do those levels help explain why some individuals are able to grow from difficult experience, whereas others break or close down? Looking beyond behavioral data, what are the exact ways in which cognition and representation work to alter the dynamics of emotional activation? New neurobiological studies are beginning to show that this regulative function involves setting of new higher-order circuits in the brain (see Metcalfe & Mischel, 1999) that in turn are related to reduced levels of activation, as originally suggested by Freud, Luria, and Piaget. Such research brings the exciting promise of bridging the mental operations that characterize complex affects and the biological processes by which they become embodied in the brain.

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## Note

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# Language Learning Disabilities: Integrating Research Approaches

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*Abstract*

Developmental language learning impairments affect 10 to 20% of children and increase their risk of later literacy problems (dyslexia) and psychiatric disorders. Both oral- and written-language impairments have been linked to slow neural processing, which is hypothesized to interfere with the perception of speech sounds that are characterized by rapid acoustic changes. Research into the etiology of language learning impairments not only has led to improved diagnostic and intervention strategies, but also has raised fundamental questions about the neurobiological basis of speech, language, and reading, as well as hemispheric lateralization.

*Keywords*

speech; language; reading; dyslexia; hemispheric lateralization; temporal processing

Although some aspects of language may be innate, it is clear that people must learn from experience which speech sounds (phonemes) will form the building blocks of their native language (Jusczyk, 2002; Kuhl, 2000). Historically, few techniques have been available to study the neurobiological basis of language learning. However, one approach that has proven remarkably informative has been to study individuals with impairments in learning oral or written language. Whether language learning impairments (LLI) derive from speech-specific deficits or from more basic processing deficits on which language learning depends has been the focus of considerable research and theoretical debate.

Developmental language impairments affect 10 to 20% of children and increase their risk of literacy problems (dyslexia) and psychiatric disorders. More than three decades of research have shown that many individuals with LLI not only have linguistic deficits, but also are characterized by deficits in their ability to process brief, rapidly successive stimuli that are input to the sensory, perceptual, and motor systems (Tallal & Benasich, 2002; Tallal, Merzenich, Miller, & Jenkins, 1998). Furthermore, the rate of processing of brief, rapidly successive nonlinguistic acoustic stimuli in infancy has been shown to be the single best predictor of subsequent language development. Those infants who respond correctly to rapidly presented stimuli develop language best, whereas those who can respond correctly only to more slowly presented stimuli are most at risk for LLI (Benasich & Tallal, 2002).

Why should the rate of auditory processing play such a critical role in normal as well as aberrant language development? One answer comes from an analysis of the acoustic properties of speech, which shows that the ability to track brief, rapidly successive frequency changes within the acoustic waveform of speech (known as formant transitions) is crucial for language development. For example, Figure 1 shows spectrograms (plots of acoustic frequency changes across time) that result from the production of two speech syllables, /ba/ and /da/. The consonants differentiating these syllables must be processed within the brief (40-ms) initial acoustic changes (formant transition), which are followed rapidly by the longer, louder, steady-state vowel. This example is representative of many acoustic transitions that characterize speech sounds.

The link between language learning and the ability to process rapid frequency changes can be understood better by considering how phonemes are initially represented in the brain. Each language has its own set of phonemes that must be learned from experience and represented as distinct neural firing patterns in the brain areas responsible for auditory processing (Recanzone, Schreiner, & Merzenich, 1993). Hebb (1949) proposed that when neurons are excited nearly simultaneously, that pattern is remembered as a unit and such units guide perception of the environment and consequently behavior. Repeated exposure to consistent sensory inputs, such as speech, will enhance the likelihood that a particular neural firing pattern will come to be distinctly represented. This type of statistical learning is referred to as Hebbian learning or neuroplasticity.

It would be easy to understand how phonemes come to be neurally represented if they occurred in isolation, in invariant acoustic patterns, and with distinct boundaries separating them within words. However, phonemes occur within an ongoing acoustic stream and differ acoustically within different contexts. Because there are no clear boundaries between phonemes within syllables or words, in learning to represent the acoustic waveform of speech the brain must segment the acoustic stream into chunks of time and then form neural representations based on the consistency and frequency of occurrence (i.e., the statistical probability) of neural firing patterns. Consistencies within the speech waveform occur in chunks of various durations. Short-duration chunking (tens of milliseconds)

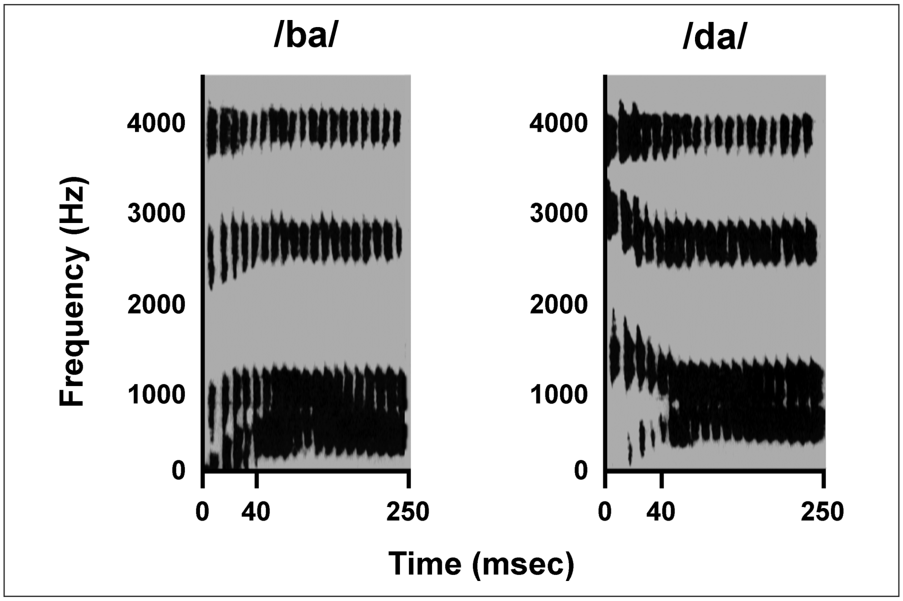

**Fig. 1.** Spectrograms (frequency-by-time displays) of the acoustic content of two speech syllables consisting of a consonant followed by a vowel, /ba/ and /da/.

will allow for the fine-grained analysis that represents phonemes. Chunking over longer periods (hundreds of milliseconds) will result in firing patterns consistent with syllable- or word-level representations.

Benasich and I (Benasich & Tallal, 2002) have hypothesized that individual differences in rapid-auditory-processing thresholds, which can be observed in infancy, affect what each brain binds together as nearly simultaneous, and this significantly affects the grain of analysis that will be represented for speech. Substantial behavioral and physiological evidence shows that many individuals with early oral-language impairments are impaired in processing brief, rapidly successive acoustic cues within the tens of milliseconds needed for optimal phoneme representation. Similarly, many people with reading impairments (dyslexia) are characterized by deficits that reflect a difficulty segmenting words into sharply represented, discrete phonemes. This skill is critical for learning letter-sound associations. It has been hypothesized that the high incidence of co-occurrence of developmental oral- and written-language impairments is the result of common phonological deficits (for a review, see Habib, 2000).

## NEUROPLASTICITY AND REMEDIATION STUDIES

Traditionally, researchers thought that Hebbian learning operated primarily during critical periods of early development, when sensory neural maps were established for a lifetime. However, more recent research has challenged that perspective. Physiological studies have demonstrated that sensory neural maps can be significantly altered at the cellular level by intensive behavioral training, even in adult animals. Of particular relevance to LLI are animal studies demonstrating that the capacity to segment rapidly successive auditory events can be sharpened by behavioral training based on Hebbian learning principles (Recanzone et al., 1993).

On the basis of these studies, my colleagues and I (Merzenich et al., 1996; Tallal et al., 1996) hypothesized that it may be possible to improve the capacity of children with LLI to process the rapidly successive acoustic changes within ongoing speech. With the aid of computer technology, we developed a novel training approach (Fast ForWord®)[2] disguised as a series of computer games. In a series of experiments, we studied the effectiveness of these games in improving the linguistic abilities of children with LLI. In one game, subjects indicate the temporal order of tones that are either rising or falling in pitch. The tones are designed to cover the range of frequencies and speeds that typify the acoustic frequency changes that occur in formant transitions in consonants. The computer program adaptively changes (increases or decreases) the duration of each tone and the rate at which one tone follows another based on each subject's trial-by-trial performance, with the goal of increasing the ability to process more rapidly changing acoustic stimuli. In another approach, we use a computer algorithm to acoustically modify (amplify and temporally extend) the rapidly successive acoustic changes that occur within ongoing speech. This acoustically modified speech signal is used in a series of games to train language comprehension at all levels, from the phoneme to the whole sentence. As linguistic performance improves, the amount of acoustic modification adaptively decreases so that the stimuli become increasingly more like the stimuli that occur in normal speech. The goal is to improve all aspect of language comprehension.

In our initial studies, two matched groups of children with LLI participated in daily training for 4 weeks. The experimental group was trained with the two approaches I have just described. The treatment control group received the same language comprehension training, but with speech that was not modified, and instead of the auditory tone-sequencing game, the control group played non-temporally adaptive visual computer games. After training, the experimental group showed significantly greater improvements than the control group on both rate of acoustic processing and performance on standardized language tests. The language gains made by the experimental group were dramatic, bringing the children into the normal range (Merzenich et al., 1996; Tallal et al., 1996). These results support the hypothesis that basic acoustic frequency and temporal (spectrotemporal) processing constraints play a significant role in LLI. Furthermore, they demonstrate that training using acoustically modified speech can ameliorate these processing constraints, as well as the effect they have on speech and language processing. Habib et al. (2002) obtained similar results in an independent study with French children with dyslexia.

## HEMISPHERIC SPECIALIZATION—INTEGRATING BEHAVIORAL AND NEUROIMAGING RESEARCH

One of the most well-established findings about the neural basis of language is that speech is preferentially processed in the left hemisphere. This finding derives primarily from observing the effects of brain lesions in adults on language functions and from experiments using procedures such as dichotic listening, which involves presenting different speech sounds to the two ears simultaneously. Studies have shown that when the right and left ears receive different speech input nearly simultaneously, the speech sounds presented to the right ear (which are processed by the left hemisphere) dominate. This so-called right-ear advantage (REA) was presumed to be speech specific because nonlinguistic acoustic stimuli initially used as control stimuli failed to show an REA. However, subsequent studies have found that altering the rate of frequency change within both speech and nonspeech stimuli has a significant effect on the pattern of hemispheric response, and that it is possible to demonstrate an REA for both speech and nonspeech stimuli that incorporate comparable rates of acoustic change.

Schwartz and I (Schwartz & Tallal, 1980) were the first to show that the REA for speech is significantly reduced when the duration of the formant transitions within speech syllables is extended in time. Subsequently, it was shown that an REA was obtained when subjects indicated the sequence of nonspeech tone pairs, but only at rapid presentation rates. A similar result was found for nonspeech stimuli designed specifically to mimic the rapid formant transitions that characterize consonant-vowel syllables. More recently, brain-imaging studies have shown that activation is significantly greater in the left hemisphere than in the right hemisphere not only during processing of speech that incorporates rapidly changing acoustic cues, but also during processing of nonspeech tone sequences incorporating acoustic changes comparable to those within speech. However, speech stimuli (such as steady-state vowels) that do not incorporate rapid acoustic changes fail to activate the left hemisphere (for a review, see Tallal et al., 1998).

Researchers also have used structural magnetic resonance imaging (MRI) to address issues pertaining to hemispheric specialization. In a recent study with adults with normal language ability, researchers investigated the relationship between brain anatomy and the ability to learn novel nonnative speech sounds, as well as either rapidly changing or steady-state nonlinguistic sounds (Golestani, Paus, & Zatorre, 2002). Results showed that those individuals who learned the novel speech sounds most quickly had more white matter in the parietal lobe of their brain (the area above and behind the ear), especially in their left hemisphere. The difference in brain anatomy between fast and slow phonetic learners was similar to the difference between fast and slow learners of the nonlinguistic stimuli that incorporated rapid acoustic changes, but not fast and slow learners of the steady-state nonlinguistic stimuli. The authors hypothesized that the greater asymmetry in the amount of white matter in faster phonetic learners may relate to greater myelination. As myelin in the brain acts like insulation on a wire, greater myelination allows more efficient neural processing of rapid temporal variation.

Another form of neuroimaging, called diffusion tensor imaging, allows the fine grain (microstructure) of white matter to be evaluated more thoroughly. In a study using diffusion tensor imaging, Klingberg et al. (2000) found that adults with dyslexia had bilateral microstructure abnormalities in the white matter tracts in the brain region between the temporal and parietal lobes known to be important for phonological processing. Furthermore, the degree of this abnormality in the left hemisphere correlated significantly with reading scores.

These two studies suggest that individual differences in the white matter in the left temporoparietal region are associated with efficiency of processing rapidly changing acoustic stimuli, phonetic learning, and reading.

## INTEGRATING BEHAVIORAL, REMEDIATION, AND NEUROIMAGING RESEARCH

Behavioral studies have shown a significant relationship between individual differences in spectrotemporal components of acoustic processing and various components of language learning, specifically phonological processing. Those individuals who are less able to process rapidly changing acoustic stimuli struggle throughout life with phonological aspects of oral and written language. My colleagues and I have demonstrated that remediation strategies that explicitly focus on spectrotemporal processing rate have a dramatic effect on phonological processing and language comprehension skills. We also have hypothesized that these strategies affect reading by strengthening and sharpening neural representations for distinct phonemes, thus improving the ability to segment words into the sounds that must be associated with letters, a skill critical for literacy.

Using functional magnetic resonance imaging (fMRI), researchers have demonstrated consistently that children and adults with LLI have aberrant metabolic activity during phonological processing tasks (see Fig. 2a) in language areas of the left hemisphere, specifically the temporoparietal region (for a review, see Temple et al., 2003). These data from functional neuroimaging studies are consistent with structural MRI data. Recently, Temple et al. (2003) integrated fMRI and remediation approaches to investigate whether the disruption in neural response to phonological demands observed in LLI can be ameliorated through behavioral training. Children with dyslexia and matched normal readers received two fMRI scans (approximately 8 weeks apart) while performing a letter rhyming task. Between scans, the dyslexic children completed Fast ForWord® training. After training, performance on both oral-language and reading tests significantly improved; training raised the dyslexic readers' scores into the normal range. As can be seen in Figure 2b, after training the dyslexic readers also showed increased metabolic activity during the letter rhyming task in multiple left- and right-hemisphere brain areas. Of specific note is the change in metabolic activity in left-hemisphere language regions, bringing brain activation in these regions closer to that seen in control children with normal reading skills. Furthermore, the magnitude of increased activation in the left temporoparietal cortex was significantly correlated with the magnitude of improvement in oral-language skills (Temple et al., 2003).

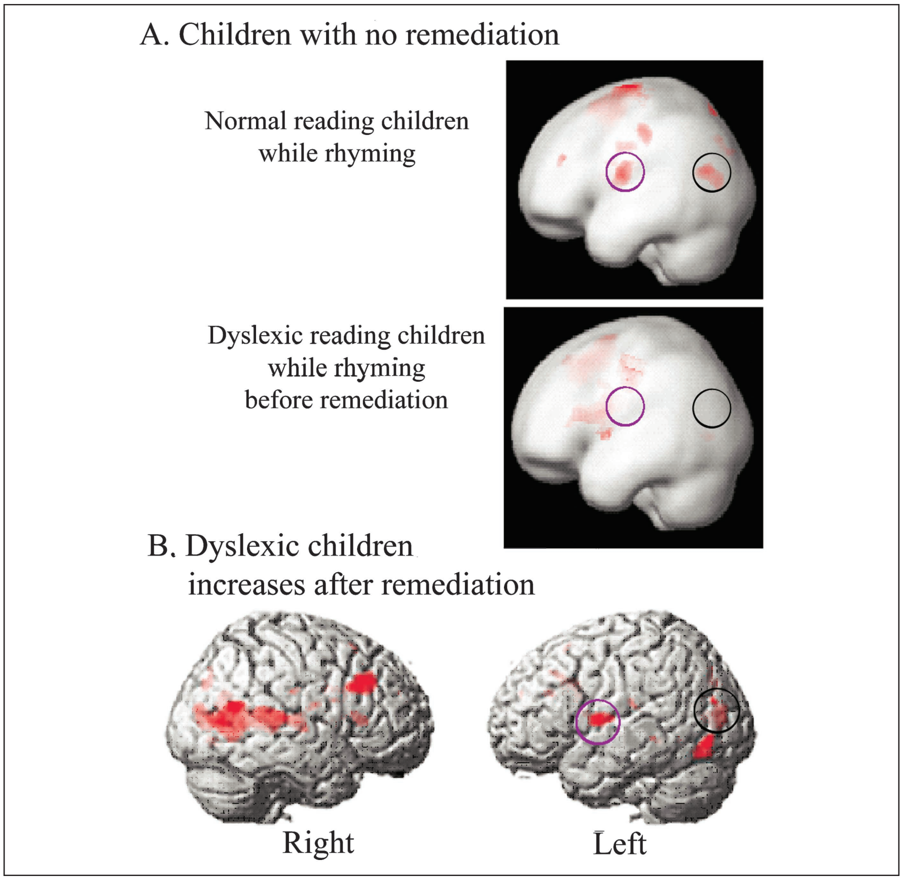

**Fig. 2.** Brain activation of normal and dyslexic readers before and after remediation. The top panel (a) shows statistically significant left-hemisphere metabolic activity (brightness of red indicates degree of activation) of control children and children with dyslexia while rhyming (as compared with matching) letters. The bottom panel (b) indicates both the right- and left-hemisphere brain areas that showed statistically significant increases in activity for rhyming (vs. matching) letters after (vs. before) remediation in children with dyslexia. Black circles highlight the left temporoparietal region, which is disrupted in children with dyslexia and affected by remediation. Purple circles highlight the left frontal region that is also affected by remediation in children with dyslexia. From "Neural Deficits in Children With Dyslexia Ameliorated by Behavioral Remediation: Evidence From Functional MRI," by E. Temple, G.K. Deutsch, R.A. Poldrack, S.L. Miller, P. Tallal, M.M. Merzenich, and J.D.E. Gabrieli, 2003, *Proceedings of the National Academy of Sciences, USA*, *100*, p. 2863. Copyright 2003 by the National Academy of Sciences. Reprinted with permission of the author.

## CONCLUSIONS AND FUTURE DIRECTIONS

One of the most fundamental assumptions about the human brain, derived primarily from studies with adults, is that language is an innately specified, specialized system that is encapsulated in a unique brain module lateralized in the left hemisphere. However, recent research that specifically integrates behavioral, physiological, and neuroimaging methodologies challenges some aspects of this basic theory. Although some aspects of language may be innately specified, it is increasingly clear that many components of language must be learned from environmental exposure. Furthermore, although many aspects of language clearly are lateralized in the left hemisphere, the basis of this lateralization may not be entirely linguistic specific. Prospective longitudinal studies, as well as cross-linguistic studies, suggest that the role of learning is far greater than previously expected for language development, and that nonlinguistic processes (such as rapid auditory processing) are involved in normal as well as aberrant language development, and also in hemispheric lateralization for speech (see Recommended Reading).

The study of children with developmental LLI, as well as of infants genetically at risk for such impairments, has challenged many of the basic assumptions pertaining to the neural basis of language. However, many important questions remain. For example, which components of language are innate and which require learning? What aspects of language are processed by mechanisms that are linguistic specific, and which derive from more domain-general sensory, motor, or cognitive processes? Which neural systems and circuits are involved in normal language development, and how do individual differences in the timing of maturation of these systems, as well as interaction between these systems, affect language development?

The advent of noninvasive genetic, physiological, and neuroimaging procedures provides new methodologies for addressing these questions from a developmental perspective. The optimal research approaches in the future will be those that track development prospectively and longitudinally and that integrate biological, behavioral, social, and demographic variables. Data derived from repeated assessments across periods of the most dynamic changes in development, as well as across multiple levels of analysis, have the potential to significantly advance understanding of normal language development and also to improve assessment and treatment for developmental LLI.

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## Notes

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2. For more information on the Fast ForWord® training programs, see www.scientificlearning.com. I am a cofounder and director of Scientific Learning Corporation, the company that developed these programs.

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