

## Examining Reading Development and Reading Disability in English Language Learners: Potential Contributions from Functional Neuroimaging

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Neuroimaging studies have suggested that across different written languages, skilled reading behavior is supported by similar, largely left hemisphere (LH), networks. In addition, recent studies of reading disability (RD) in monolingual readers, conducted in several languages, suggest a common neurobiological signature for this syndrome (disruption of LH posterior regions that support fluent reading). Thus, at the neurobiological level of analysis, reading and its disorders appear to be more similar than dissimilar across languages. In this article, we consider the neurobiology of reading development and RD in English language learners (ELL). There is some evidence suggesting that fluent bilingual readers tend to engage primarily overlapping circuits for both L1 and L2. There is, however, a paucity of neurobiological research on both reading development and RD in this population. Using the existing research on RD as a starting point, we consider in this article how developmental neuroimaging techniques might be applied to (1) help identify RD readers in the ELL populations, and (2) provide neurobiological outcome measures to help evaluate the efficacy of different approaches to the teaching of reading in English.

The acquisition of literacy skill is a major cognitive challenge for any child, and in any population significant numbers of children will fail to obtain age-appropriate reading levels (Adams, 1990). For English language learners (ELL), especially those children with limited English proficiency (LEP), the challenge can be all the more acute, and the incidence of reading difficulties in this population is alarmingly high. The National Assessment of Educational Progress (NAEP, 2000) reports that LEP students, especially Hispanic students, lag far behind their White and Asian peers in reading performance. While socioeconomic factors clearly contribute to this reading crisis, the linguistic and cognitive challenges associated with learning to read in a nonprimary language are likely to be contributing factors as well (August & Hakuta, 1998; Snow, Burns, & Griffin, 1998).

Using standard diagnostic criteria, we would certainly classify many of these children as reading disabled (RD). Although RD, as a gene-linked syndrome, likely occurs with similar frequency in all populations and across all written languages (Grigorenko et al., 1997), because of the struggles inherent in learning to read in a second language, the tendency for misdiagnosis in ELL children looms. In this article, we are charged with addressing two questions. First, can neuroimaging techniques be used to help identify reading problems that are of a congenital origin? This kind of information, if obtainable, could be useful in helping us to distinguish true RD from the reading problems associated with the

myriad of environmental and linguistic factors that challenge many ELL children. Second, how might these techniques be employed in assessing the efficacy of different approaches to the teaching of reading in ELL children? Recent neuroimaging studies of English monolinguals have begun to reveal the neurobiological signatures of successful training and remediation programs (Shaywitz et al., 2004; Simos, Breier et al., 2002; Temple et al., 2003); it would be desirable, we think, to make similar use of neuroimaging in evaluating effects of contrasting approaches to reading instruction for ELL children.

While a good deal of neuroimaging research has been conducted on reading development, reading disability, and effects of intensive intervention, many of these studies have examined only monolingual speakers of English (for a review, see Pugh, Mencl, Jenner et al., 2000; Sandak, Mencl, Frost, & Pugh, 2004). Good progress has been made though, both in mapping out neurobiological trajectories (i.e., the development of a left hemisphere [LH] circuitry for fluent reading) in typically developing children (Shaywitz et al., 2002; Turkeltaub, Gareau, Flowers, Zeffiro, & Eden, 2003), and in isolating the neurobiological markers of RD (cf. Brunswick, McCrory, Price, Frith, & Frith, 1999; Pugh, Mencl, Shaywitz et al., 2000; Rumsey et al., 1997; Shaywitz et al., 1998, 2002). If this body of evidence is going to provide a reasonable framework from which to begin to explore RD in ELL populations we must address the following question: Can we expect the cognitive and neurobiological characteristics of reading acquisition (and RD) in ELL children to be similar or dissimilar to monolingual English-speaking children studied to date?

In this article, we examine several domains of research that may be relevant to this question. We broadly consider the evidence from studies of monolingual readers in different languages (and different writing systems) for language-invariant or language-specific circuits, along with the current evidence for language-invariant neurobiological signatures of RD. In addition, we consider the existing evidence for overlapping or distinct spoken language and written language systems for L1 and L2 fluent bilinguals. This research can help to frame our expectations and hypotheses as we further explore reading acquisition (at both the behavioral and neurobiological levels-of-analysis) in ELL children.

### **SPOKEN AND WRITTEN LANGUAGE CIRCUITS IN DIFFERENT LANGUAGES**

Both historically and ontologically, spoken language capacity develops prior to the derived abilities of reading and writing. While brain organization for spoken language perception and production is, to a large degree at least, a biological specialization, reading by contrast is almost certainly not (Lieberman, 1992). Indeed, reading skill, unlike speech communication skills, must be explicitly taught, and failure is more likely in the print modality than in the spoken modality. Given the biological constraints on spoken language development (and processing), it would seem likely that, despite differences in morphological and syntactic principles, different languages would tend to have similar neurobiological foundations. Data from both lesion studies, and functional neuroimaging studies of speech perception and production in multiple languages (cf. Indefrey & Levelt, 2004) are broadly consistent with this expectation. LH temporal and frontal (perisylvian) language zones are uniformly activated for tasks tapping spoken language processes in both alphabetic and nonalphabetic languages (Indefrey & Levelt, 2004).

However, this general pattern of overlapping circuits across various spoken languages does not imply the absence of any language-specific variation at all. For instance, Valaki et al. (2004), using magneto-encephalography (MEG), compared Spanish, English, and Mandarin speakers performing a spoken word (memory) processing task. While all three groups showed largely overlapping LH activation patterns, relative to the first two cohorts, Chinese speakers showed reliably greater contributions from the right hemisphere (RH) during performance of this task. The authors speculate that increased demands on prosodic coding in tonal languages such as Chinese, may promote a heightened RH involvement. Thus, while the general claim that speech perception and production in different languages has a largely uniform neurobiological organization seems to have been clearly established at this point, we should remain cognizant of potential differences. It is conceivable that the process of building the neural circuitry for spoken and then written English might subtly differ in ELL children with Chinese, as opposed to Spanish, as the native language.

We need to remember that the ELL child, especially one with LEP, is not merely coping with the challenges of learning to read English, but also is still at a fairly early stage in developing a bilingual brain circuitry for spoken language. The

neurobiological mechanisms associated with becoming bilingual are actively being investigated in many domains, and many populations at present (e.g., Dehaene et al., 1997; Kim, Relkin, Lee, & Hirsch, 1997; Perani et al., 1998). Some general findings have emerged (see Abutalebi, Cappa, & Perani, 2001, for a discussion) that might help provide some context for our work with ELL children. Whereas most studies have reported largely overlapping systems for the spoken forms of L1 and L2 in fluent bilinguals, the degree of overlap appears to depend heavily upon factors such as age of acquisition, and perhaps most importantly, degree of proficiency in L2 (see Abutalebi et al., 2001, for a discussion). Highly proficient speakers of L2 show greater integration of L1 and L2 in the brain than less proficient speakers (Kim et al., 1997; Klein, Milner, Zatorre, Meyer, & Evans, 1995; Perani et al., 1998). Thus, spoken language proficiency in L2, by virtue of its effects on brain organization for speech, might impact the ways in which reading circuits develop as literacy skills are taught. This may be an important individual difference dimension to keep in mind as we begin to map out neurobiological trajectories for reading and RD in ELL children. Additionally, as noted above, differences in hemispheric distributions of activation have been reported for Chinese (Valaki et al., 2004), and the unique demands of being bilingual are associated with the need to develop brain mechanisms to cope with the demands of language switching and suppression (Price, Green, & von Studnitz, 1999). All these types of variables will need to be examined as we begin to chart the neurobiological changes as ELL children learn to master both speech and reading in L2.

We now turn to the issue of reading in different languages. All orthographies code the phonology of the spoken language, but the manner in which this is represented varies across written languages. For example, in alphabetic orthographies graphemes code-specific consonants and vowels, whereas in syllabaries (such as compose part of the Japanese and Korean writing systems) each grapheme represents a complete syllable. In contrast, Chinese characters provide limited information about the phonological forms of the words they represent, though some information relevant to phonological form is contained in the phonetic component of compound characters (DeFrancis, 1989; Hung & Tzeng, 1981; Perfetti, 1985). Moreover, even within alphabetic orthographies there are differences in the consistency with which individual letters correspond to particular phonemes. Finnish, for example, is considered to be a “transparent” orthography because it displays a consistent mapping between letter and sound, with each letter mapping onto one and only one consonant or vowel and vice versa. English, by contrast, is an “opaque” orthography; the mapping in English is considerably less consistent (Frost, Katz, & Bentin, 1987).

Our read of cross-language studies of word recognition in skilled adult readers suggests to us that lexical access does not differ in any fundamental manner in transparent versus opaque orthographies (Frost, 1998; Lukatela & Turvey, 1994; Perfetti, 1985). For instance, Lukatela and Turvey (1994) and Lukatela, Savic, Urosevic, and Turvey (1997) used a variety of priming tasks and observed similar and robust effects of sublexical phonological processes on word identification

latencies for both English and Serbo-Croatian (Serbo-Croatian employs a very transparent orthographic system relative to English). Language differences have been reported relative to types (or grain size) of the phonological units relevant to lexical access (e.g., see the German/English comparison study of Ziegler, Perry, Jacobs, & Braun, 2001), but, in general, sublexical phonological influences appear to be strongly influencing word perception across languages. Indeed, there is even some accumulating evidence that readers of Chinese are sensitive to sublexical phonological information contained in the phonetic components of compound words (Liu, Chen, & Sue, 2003; Perfetti, Zhang, & Berent, 1992), suggesting certain parallels with lexical access mechanisms identified in alphabetic writing systems. To summarize, while reading will not be entirely uniform in all of aspects across different orthographies, and this is an active research domain with many outstanding disagreements and debates (see Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Harm & Seidenberg, 2004), we would argue, along with Perfetti (1985) and Frost (1998), that word recognition in reading develops on very similar cognitive principles in very different orthographies. In our view, this is so because of the universal requirement to develop fast and efficient access to already well-learned phonological forms, this requirement pressures the reader to be maximally sensitive to sublexical phonological variables in order to facilitate this process (Frost, 1998; Van Orden, Pennington, & Stone, 1990). Accordingly, we would predict that the brain circuit that develops to support reading behavior is necessarily quite similar across languages.

The functional neuroanatomy of word recognition (and sentence processing) in reading has been investigated in a variety of languages (which employ both alphabetic and non-alphabetic writing systems) in recent years (e.g., Chee, Tan, & Thiel, 1999; Fiebach, Friederici, Mueller, & von Cramon, 2002; Kuo et al., 2003; Paulesu et al., 2000; Salmelin, Service, Kiesila, Uutela, & Salonen, 1996). Neuroimaging studies of alphabetic languages implicate a set of LH cortical regions including occipitotemporal, temporoparietal, and inferior frontal networks; these networks are almost always engaged in reading irrespective of the specific language and/or writing system under investigation. Language-specific differences appear to be most a matter of degree, not of kind. That is, in one language, a given neural network might be more or less activated than in another language, but the general circuit appears similar in its taxonomic organization (Paulesu et al., 2000). It has been suggested that these relative differences in the "weighting" of one or another network within the broad reading circuit might be associated with variation in processing demands associated with factors such as the orthographic depth of the writing system (Paulesu et al., 2000). This overlap is perhaps not surprising given the evidence for similar demands on subword processing. Even in languages with orthographies as distinct as Chinese broadly similar activation has been reported at occipitotemporal, temporoparietal, and inferior frontal sites (Kuo et al., 2003). Some differences have been reported for Chinese reading at both superior parietal (Kuo et al., 2003), and left middle frontal regions (Tan et al., 2001), but overall the reading networks are largely sim-

ilar to those observed for alphabetic writing systems (Kuo et al., 2003).

These similarities across languages, at both the behavioral and brain levels-of-analysis, would lead us to anticipate a highly integrated reading circuitry for L1 and L2 in fluent bilingual readers; though a good deal of pressure on the brain for both integration and for maintaining distinctions would follow from this common neural system (Price et al., 1999). Bilingual reading studies appear to reinforce this expectation, at least for readers proficient in L1 and L2 (e.g., Chee et al., 1999; Illes et al., 1999; Price et al., 1999).

What type of guidance can the research reviewed here provide as we begin to investigate reading development and RD in ELL readers? In the most general sense, the broad principles of brain organization for speech and reading appear to be largely uniform across languages. This implies, we think, that there are pervasive, perhaps universal, biological (and cognitive) constraints on how and where in the brain the reading circuit will be developed. For this reason, and especially given the existing evidence on the reading circuitry in skilled bilingual readers for L1 and L2, we suspect that the development of a reading circuitry in children will follow similar broad principles in any population of readers whether bilingual or monolingual. Differences between ELL and monolingual children learning to read English are likely to manifest in variables such as rate of acquisition; fundamental differences in functional brain organization are not anticipated. We now turn for guidance to the extant developmental neuroimaging literature on reading development, RD, and remediation in non-ELL populations.

### **NEUROBIOLOGICAL STUDIES IN ENGLISH: THE POSTERIOR AND ANTERIOR READING CIRCUITRY IN TYPICAL DEVELOPMENT AND RD**

Substantial converging evidence suggests that visual word identification involves a LH posterior cortical reading system with ventral, dorsal, and anterior components (Pugh, Mencl, Jenner et al., 2000). The dorsal system includes the angular gyrus and supramarginal gyrus in the inferior parietal lobule, and the posterior aspect of the superior temporal gyrus (Wernicke's area). This region seems to be involved in mapping visual percepts of print onto the phonological and semantic structures of language (Black & Behrmann, 1994; Geschwind, 1965; Price, 2000). In skilled readers, temporoparietal aspects of the dorsal system (particularly the supramarginal gyrus) respond with greater activity to pseudowords and low-frequency words than to familiar words (Simos, Fletcher et al., 2002; Xu et al., 2001). Indeed, in beginning readers who will eventually become skilled readers, our studies suggest that the dorsal system predominates as it first learns to decode print; in RD readers this system is disrupted (Pugh, Mencl, Shaywitz et al., 2000; Shaywitz et al., 1998, 2002). This is consistent with behavioral studies that implicate skill in the phonological analysis of speech (measured by phonological awareness tasks and pseudoword reading) as critical predictors of success in early reading

acquisition (Bradley & Bryant, 1985; Wagner & Torgesen, 1987). Together, these findings suggest that the dorsal system is associated with decoding and is critical for extracting and learning the relationships between the orthography and its phonological forms (O → P), and connecting these to morphological and semantic information (Price, 2000).

An anterior system centered in posterior aspects of the inferior frontal gyrus (IFG) appears to be associated with phonological recoding during reading, among other functions (e.g., phonological memory, syntactic processing); the more anterior aspects of IFG seem to play a role in semantic retrieval (Poldrack et al., 1999). The phonologically relevant components of this multifunctional system have been found to function in silent reading and in naming (see Fiez & Peterson, 1998 for review) and, like the temporoparietal system, are more strongly engaged by low-frequency words and pseudowords than by high-frequency words (Fiebach et al., 2002; Fiez & Peterson, 1998), and by low-frequency words with inconsistent orthographic-to-phonological mappings (e.g., “pint”) relative to consistent words (“mill”). We have speculated that this anterior system operates in close conjunction with the temporoparietal system to decode new words during normal reading development (Pugh, Mencl, Jenner et al., 2000).

The ventral system appears to be late developing and appears to support fluent reading performance subsequent to initial instruction (Booth et al., 2001; Shaywitz et al., 2002). It includes a LH inferior occipitotemporal/fusiform area and extends anteriorly into the middle and inferior temporal gyri. It has been suggested that occipitotemporal components of this ventral system function as a presemantic visual word form area by some researchers (cf. Cohen et al., 2002, but see Price, Winterburn, Giraud, Moore, & Noppeney, 2003 for an alternative account). More anterior foci within the ventral system extending into the middle to inferior temporal gyri appear to be semantically tuned (Fiebach et al., 2002; Simos, Breier et al., 2002; Tagamets, Novick, Chalmers, & Friedman, 2000). The ventral system, particularly the more occipitotemporal aspect, is also fast acting in response to linguistic stimuli in skilled readers, but not in RD individuals (Salmelin et al., 1996; Tarkiainen, Cornelissen, & Salmelin, 2003). Indeed, recent studies examining both timing and stimulus-type effects suggest that moving anteriorly through this system, subregions respond to word and word-like stimuli in a progressively abstracted and linguistic manner (Tarkiainen et al., 2003).

For both children and adults with reading disabilities, there are marked functional differences with regard to activity generated in the dorsal, ventral, and anterior systems during reading (Brunswick et al., 1999; Paulesu et al., 2001; Pugh, Mencl, Shaywitz et al., 2000; Rumsey et al., 1997; Salmelin et al., 1996; Shaywitz et al., 1998, 2002). Specifically, RD readers tend to underengage the LH posterior dorsal and ventral systems used by nonimpaired readers in word and pseudoword reading; this disruption is also evident as reduced functional connectivity among these regions during reading (Horwitz, Rumsey, & Donohue, 1998; Pugh, Mencl, Shaywitz et al., 2000). Instead, they tend to show evidence of two, apparently compensatory, responses to their LH posterior dysfunction: an increased functional role for RH posterior sites (Sarkari et al., 2002; Pugh, Mencl, Shaywitz et al., 2000;

Shaywitz et al., 1998, 2002) and increased bihemispheric IFG activation (Brunswick et al., 1999; Shaywitz et al., 1998, 2002).

In our cross-sectional developmental study, we examined changes in the LH circuitry in nonimpaired and RD cohorts ranging in age from 7 through 17 (Shaywitz et al., 2002). Multiple regression analyses were employed to examine correlations between activation at different brain regions and reading skill (measured by performance on standard reading tests). The critical finding for typically developing children was that the higher the reading skill, the stronger the response in the LH ventral cortex (with several RH regions showing age- and skill-related reductions). Thus, we argued that a beginning reader on a successful trajectory employs a widely distributed cortical system including RH temporoparietal and frontal regions. As reading skill increases, these regions still play some role, but importantly, the LH ventral system appears to become the critical support for fluent recognition of printed (word) stimuli (see Booth et al., 2001; Turkeltaub et al., 2003 for similar findings). In contrast, for children who are RD, this pattern of ventral development is disrupted. This disruption is characterized neurobiologically by (1) poorly developed LH dorsal and ventral function, (2) increased reliance with age on the anterior system, and (3) an increased tendency with age to engage RH homologues to the dysfunctional LH posterior circuits (Sarkari et al., 2002; Shaywitz et al., 2002).

A body of evidence is accumulating suggesting that there are many commonalities in the ways in which reading disability manifests across languages (e.g., early problems in metalinguistic processing and phonological decoding; Wimmer, 1993; Ziegler, Perry, Ma-Wyatt, Ladner, & Schulte-Korne, 2003). Given this behavioral evidence, and given the evidence for common circuits in different written languages, we might expect language-invariant neurobiological signatures to be associated with reading disability as well. The evidence to date from alphabetic languages is supportive of this expectation (Paulesu et al., 2001; Salmelin et al., 1996; Shaywitz et al., 2002). Functional disruptions in LH posterior cortex (particularly the occipitotemporal region) in RD individuals performing reading tasks during neuroimaging have been found in several languages varying in orthographic depth (English, Finnish, German, French, Italian). This common neurobiological signature, within a largely language-invariant circuitry for reading in the LH, reinforces the need to understand reading development and reading remediation from a cross-linguistic perspective. A recent study of Chinese RD readers (Siok, Perfetti, Jin, & Tan, 2004) reported a language-specific difference in the RD signature (specifically diminished activation of middle frontal regions for RD readers relative to controls). This finding has not been reported in alphabetic languages. However, these authors also found diminished activation in RD readers at the same LH occipitotemporal region previously reported by Paulesu and others in RD within alphabetic languages (Brunswick et al., 1999; Paulesu et al., 2001; Salmelin et al., 1996; Shaywitz et al., 2002). More studies need to be done in nonalphabetic writing systems to examine the implications of both the similarities and the differences with respect to RD; such studies will be critical in establishing the generality neurobiological profiles of RD.

## IDENTIFYING RD IN ELL POPULATIONS

To the question of how neuroimaging might help to identify markers of RD within ELL populations we begin by considering the language-invariant disruption of LH ventral cortex reported thus far (e.g., Paulesu et al., 2001; Rumsey et al., 1997; Salmelin et al., 1996; Shaywitz et al., 1998, 2002). However, because this ventral system, critical in fluent reading skills, appears to be relatively late-emerging for typically developing readers (Shaywitz et al., 2002), for beginning ELL readers (or any population of reading novices) patterns of activation in this region might not be terribly diagnostic of RD at the onset of literacy instruction. But, by measuring success or failure in training-up this system (over time) and determining how this varies with type of reading instruction focus on the ventral system might provide a means of better understanding individual differences in developmental trajectories within ELL cohorts.

The apparent disruption of LH temporoparietal regions with the corresponding RH shift during language tasks (Sarkari et al., 2002; Shaywitz et al., 2002; Simos et al., 2000) might be more diagnostic of RD, even in beginning ELL readers, and this should be investigated carefully. The disruption of those LH temporoparietal regions critical for learning to integrate orthography, phonology, and semantics, has been observed even in beginning readers (Simos, Fletcher et al., 2002) and is evident even during performance of spoken language tasks (Rumsey et al., 1992; Temple et al., 2003). Thus, a RH shift within the temporoparietal system for L1 and/or L2 might be diagnostic of RD in ELL children even during the earliest stages of reading instruction (Simos et al., 2002). Indeed, the degree to which adequate integration and distinctiveness is developed for the spoken forms of L1 and L2, likely depends on intact temporoparietal function from the outset; therefore, we hypothesize that anomalies in activation patterns in this system might be the key neurobiological variable predicting success or failure in developing an optimized LH reading circuitry over time in these children. Longitudinal studies will be crucial in testing this hypothesis.

With a goal of identifying latent RD in ELL children diagnostic markers for RD outside of the language domain should be examined as well. For example, several studies have observed anomalous responses to simple visual motion detection in MT/V5 for RD readers (Demb, Boynton, & Heeger, 1998; Eden et al., 1996). This type of nonlanguage neurobiological marker might help to identify at risk children early on, even for populations where matching on language experience is not possible. In addition, many technologies are available to examine structural and neurochemical factors in RD, and many intriguing findings and some RD markers have been reported at these levels of analysis (Klingberg et al., 2000; Habib, 2000). These sorts of neurophysiological indices might be extremely helpful in identifying latent RD in struggling populations of ELL children, where functional imaging is complicated by performance variation.

We might also begin to search for potential anomalies in the neurobiological circuits supporting more complex cognitive operations such as attentional control, response inhibition, and verbal working memory; these domains are likely

critical to success both in language switching and language integration in ELL readers. There is little guidance from the existing studies thus far on how these variables might relate to latent RD, but given the unique demands that bilingualism places on brain systems, research of this sort has real potential to broaden our understanding of ELL development in general.

Finally, beyond the question of identifying RD within ELL populations, functional neuroimaging can be particularly helpful in assessing the efficacy of different approaches to the teaching of reading in ELL (Simos, Breier et al., 2002). As seen in recent remediation studies in monolinguals (Simos, Fletcher et al., 2002; Shaywitz et al., 2004; Temple et al., 2003), successful training approaches have profound effects of normalizing LH trajectories in struggling readers. Reduced RH reliance and increased LH activation following training has been seen in all of these remediation studies (each compared pre- and post-intervention activation profiles). These studies converge to indicate that development of the LH posterior reading system constitutes an important neurobiological outcome variable associated with successful instruction and remediation. Thus, functional neuroimaging might be used in this manner to help in evaluating the sorts of reading instruction that work best for ELL children whether at risk for RD or not. Finding a neurobiological signature of successful intervention/instruction (e.g., LH posterior increases) can help to discriminate between “better or worse” approaches that might all produce some transient gains in reading performance.

In conclusion, the extant cross-language research on the brain organization for speech and reading in monolingual and bilingual populations suggests that, while the rate of acquisition may differ between these populations, the development of an optimal reading circuitry in ELL children should follow a similar trajectory and a predictable course with respect to localization. Moreover, several potential neurobiological markers for RD have been identified (both language and nonlanguage based) which we believe will be helpful in distinguishing latent RD from environmental factors in ELL children.

## REFERENCES

- Abutalebi, J., Cappa, S. F., & Perani, D. (2001). The bilingual brain as revealed by functional neuroimaging. *Bilingualism: Language and Cognition*, 4, 179–190.
- Adams, M. J. (1990). *Beginning to read: Thinking and learning about print*. Cambridge, MA: MIT Press.
- August, D., & Hakuta, K. (Eds.). (1998). *Educating language-minority children*. Committee on Developing a Research Agenda on the Education of Limited-English-Proficient and Bilingual Students, National Research Council and Institute of Medicine.
- Black, S. E., & Behrmann, M. (1994). Localization in alexia. In A. Kertesz (Ed.), *Localization and neuroimaging in neuropsychology* (pp. 331–376). New York: Academic Press.
- Booth, J. R., Burman, D., Van Santen, F., Harasaki, Y., Gitelman, D., Parrish, T., et al. (2001). The development of specialized brain systems in reading and oral-language. *Child Neuropsychology*, 7, 119–141.
- Bradley, L., & Bryant, P. (1985). *Rhyme and reason in reading and spelling*. Ann Arbor, MI: University of Michigan Press.
- Brunswick, N., McCrory, E., Price, C., Frith, C. D., & Frith, U. (1999). Explicit and implicit processing of words and pseudowords by adult

- developmental dyslexics: A search for Wernicke's Wortschatz. *Brain*, 122, 1901–1917.
- Chee, M. W. L., Tan, E. W. L., & Thiel, T. (1999). Mandarin and English single word processing studied with functional magnetic resonance imaging. *The Journal of Neuroscience*, 19, 3050–3056.
- Cohen, L., Lehericy, S., Chochon, F., Lemer, C., Rivaud, S., & Dehaene, S. (2002). Language-specific tuning of visual cortex? Functional properties of the visual word form area. *Brain*, 125, 1054–1069.
- Coltheart, M., Rastle, K., Perry, C., Langdon, R., & Ziegler, J. (2001). DRC: A dual route cascaded model of visual word recognition and reading aloud. *Psychological Review*, 108, 204–256.
- DeFrancis, J. (1989). *Visible speech: The diverse oneness of writing systems*. Honolulu, HI: University of Hawaii Press.
- Dehaene, S., Dupoux, E., Mehler, J., Cohen, L., Paulesu, E., Perani, D., et al. (1997). Anatomical variability in the cortical representation of first and second language. *Neuroreport*, 8, 3809–3815.
- Demb, J. B., Boynton, G. M., & Heeger, D. J. (1998). Functional magnetic resonance imaging of early visual pathways in dyslexia. *Journal of Neuroscience*, 18, 6939–6951.
- Eden, G. F., VanMeter, J. W., Rumsey, J. M., Maisog, J. M., Woods, R. P., & Zeffiro, T. A. (1996). Abnormal processing of visual motion in dyslexia revealed by function brain imaging. *Nature*, 382, 66–69.
- Fiebach, C. J., Friederici, A. D., Mueller, K., & von Cramon, D. Y. (2002). fMRI evidence for dual routes to the mental lexicon in visual word recognition. *Journal of Cognitive Neuroscience*, 14, 11–23.
- Fiez, J. A., & Peterson, S. E. (1998). Neuroimaging studies of word reading. *Proceedings of the National Academy Sciences*, 95, 914–921.
- Frost, R. (1998). Toward a strong phonological theory of visual word recognition: True issues and false trails. *Psychological Bulletin*, 123, 71–99.
- Frost, R., Katz, L., & Bentin, S. (1987). Strategies for visual word recognition and orthographical depth: A multilingual comparison. *Journal of Experimental Psychology: Human Perception and Performance*, 13, 104–115.
- Geschwind, N. (1965). Disconnexion syndromes in animals and man: Part 1. *Brain*, 88, 237–294.
- Grigorenko, E. L., Wood, F. B., Meyer, M. S., Hart, L. A., Speed, W. C., Shuster, A., et al. (1997). Susceptibility loci for distinct components of developmental dyslexia on chromosomes 6 and 15. *American Journal of Human Genetics*, 60, 27–39.
- Habib, M. (2000). The neurological basis of developmental dyslexia: An overview and working hypothesis. *Brain*, 123, 2372–2399.
- Harm, M. W., & Seidenberg, M. S. (2004). Computing the meanings of words in reading: Cooperative division of labor between visual and phonological processes. *Psychological Review*, 111, 662–720.
- Horwitz, B., Rumsey, J. M., & Donohue, B. C. (1998). Functional connectivity of the angular gyrus in normal reading and dyslexia. *Proceedings of the National Academy Sciences*, 95, 8939–8944.
- Hung, D. L., & Tzeng, O. J. L. (1981). Orthographic variations in visual information processing. *Psychological Bulletin*, 90, 377–414.
- Illes, J., Francis, W. S., Desmond, J. E., Gabrieli, J. D. E., Glover, G. H., Poldrack, R., et al. (1999). Convergent cortical representation of semantic processing in bilinguals. *Brain and Language*, 70, 347–363.
- Indefrey, P., & Levelt, W. J. M. (2004). The spatial and temporal signatures of word production components. *Cognition*, 92, 101–144.
- Kim, H. S., Relkin, N. R., Lee, K. M., & Hirsch, J. (1997). Distinct cortical areas associated with native and second languages. *Nature*, 388, 171–174.
- Klein, D., Milner, B., Zatorre, R. J., Meyer, E., & Evans, A. C. (1995). The neural substrates underlying word generation: A bilingual functional-imaging study. *Proceedings of the National Academy of Science*, 92, 2899–2903.
- Klingberg, T., Hedehus, M., Temple, E., Salz, T., Gabrieli, J. D., Moseley, M. E., et al. (2000). Microstructure of temporo-parietal white matter as a basis for reading ability: Evidence from diffusion tensor magnetic resonance imaging. *Neuron*, 25, 493–500.
- Kuo, W. J., Yeh, T. C., Lee, C. Y., Wu, Y. T., Chou, C. C., Ho, L. T., et al. (2003). Frequency effects of Chinese character processing in the brain: An event-related fMRI study. *Neuroimage*, 18, 720–730.
- Liberman, A. M. (1992). The relation of speech to reading and writing. In R. Frost & L. Katz (Eds.), *Orthography, phonology, morphology, and meaning* (pp. 167–178). Amsterdam: Elsevier.
- Liu, In.-M., Chen, S.-C., & Sue, L.-R. (2003). Regularity and consistency effects in Chinese character naming. *Chinese Journal of Psychology*, 45, 29–46.
- Lukatela, G., & Turvey, M. T. (1994). Visual lexical access is initially phonological: 1. Evidence from associative priming by words, homophones, and pseudohomophones. *Journal of Experimental Psychology: General*, 123, 107–128.
- Lukatela, G., Savic, M., Urošević, Z., & Turvey, M. T. (1997). Phonological ambiguity impairs identity priming in naming and lexical decision. *Journal of Memory and Language*, 36, 360–381.
- National Assessment of Educational Progress. (2000). Available at <http://nces.ed.gov>.
- Paulesu, E., Demonet, J. F., Fazio, F., McCrory, E., Chanoine, V., Brunswick, N., et al. (2001). Dyslexia: Cultural diversity and biological unity. *Science*, 291, 2165–2167.
- Paulesu, E., McGrory, E., Fazio, F., Menoncello, L., Brunswick, N., Cappa, S. F., et al. (2000). A cultural effect on brain function. *Nature Neuroscience*, 3, 91–96.
- Perani, D., Paulesu, E., Galles, N. S., Dupoux, E., Dehaene, S., Bettinardi, V., et al. (1998). The bilingual brain: Proficiency and age of acquisition of the second language. *Brain*, 121, 19–32.
- Perfetti, C. A. (1985). *Reading ability*. New York: Oxford University Press.
- Perfetti, C. A., Zhang, S., & Berent, I. (1992). Reading in English and Chinese: Evidence for a “universal” phonological principle. In R. Frost & L. Katz (Eds.), *Orthography, phonology, morphology, and meaning* (pp. 227–248). Amsterdam: Elsevier.
- Poldrack, R. A., Wagner, A. D., Prull, M. W., Desmond, J. E., Glover, G. H., & Gabrieli, J. D. (1999). Functional specialization for semantic and phonological processing in the left inferior prefrontal cortex. *Neuroimage*, 10, 15–35.
- Price, C. J. (2000). The anatomy of language: contributions from functional neuroimaging. *Journal of Anatomy*, 3, 335–359.
- Price, C. J., Green, D. W., & von Studnitz, R. (1999). A functional imaging study of translation and language switching. *Brain*, 122, 2221–2235.
- Price, C. J., Winterburn, D., Giraud, A. L., Moore, C. J., & Noppeney, U. (2003). Cortical localization of the visual and auditory word form areas: A reconsideration of the evidence. *Brain and Language*, 86, 272–286.
- Pugh, K. R., Mencl, W. E., Jenner, A. R., Katz, L., Frost, S. J., Lee, J. R., et al. (2000). Functional neuroimaging studies of reading and reading disability (developmental dyslexia). *Mental Retardation & Developmental Disabilities Research Reviews*, 6, 207–213.
- Pugh, K., Mencl, W. E., Shaywitz, B. A., Shaywitz, S. E., Fulbright, R. K., Skudlarski, P., et al. (2000). The angular gyrus in developmental dyslexia: Task-specific differences in functional connectivity in posterior cortex. *Psychological Science*, 11, 51–59.
- Rumsey, J. M., Andreason, P. A., Zametkin, A. J., Aquino, T., King, A., Hamburger, S. D., et al. (1992). Failure to activate the left temporoparietal cortex in dyslexia: An oxygen 15 positron emission tomographic study. *Archives of Neurology*, 49, 527–534.
- Rumsey, J. M., Nace, K., Donohue, B., Wise, D., Maisog, J. M., & Andreason, P. (1997). A positron emission tomographic study of impaired word recognition and phonological processing in dyslexic men. *Archives of Neurology*, 54, 562–573.
- Salmelin, R., Service, E., Kiesila, P., Uutela, K., & Salonen, O. (1996). Impaired visual word processing in dyslexia revealed with magnetoencephalography. *Annals of Neurology*, 40, 157–162.
- Sandak, R., Mencl, W. E., Frost, S. J., & Pugh, K. R. (2004). The neurobiological basis of skilled and impaired reading: Recent findings and new directions. *Scientific Studies of Reading*, 8, 273–292.
- Sarkari, S., Simos, P. G., Fletcher, J. M., Castillo, E. M., Breier, J. I., & Papanicolaou, A. C. (2002). The emergence and treatment of developmental reading disability: Contributions of functional brain imaging. *Seminars in Pediatric Neurology*, 9, 227–236.
- Shaywitz, B., Shaywitz, S., Blachman, B., Pugh, K. R., Fulbright, R., Skudlarski, P., et al. (2004). Development of left occipitotemporal systems for skilled reading following a phonologically based intervention in children. *Biological Psychiatry*, 55, 926–933.
- Shaywitz, B. A., Shaywitz, S. E., Pugh, K., Mencl, W. E., Fulbright, R. K., Skudlarski, P., et al. (2002). Disruption of posterior brain systems for reading in children with developmental dyslexia. *Biological Psychiatry*, 52, 101–110.
- Shaywitz, S. E., Shaywitz, B. A., Pugh, K. R., Fulbright, R. K., Constable, R. T., Mencl, W. E., et al. (1998). Functional disruption in the organization

- of the brain for reading in dyslexia. *Proceedings of the National Academy of Sciences*, 95, 2636–2641.
- Simos, P. G., Breier, J. I., Fletcher, J. M., Foorman, B. R., Castillo, E. M., & Papanicolaou, A. C. (2002). Brain mechanisms for reading words and pseudowords: An integrated approach. *Cerebral Cortex*, 12, 297–305.
- Simos, P. G., Breier, J. I., Wheless, J. W., Maggio, W. W., Fletcher, J. M., Castillo, E., et al. (2000). Brain mechanisms for reading: The role of the superior temporal gyrus in word and pseudoword naming. *Neuroreport*, 11, 2443–2447.
- Simos, P. G., Fletcher, J. M., Bergman, E., Breier, J. I., Foorman, B. R., Castillo, E. M., et al. (2002). Dyslexia-specific brain activation profile becomes normal following successful remedial training. *Neurology*, 58, 1203–1213.
- Siok, W. T., Perfetti, C. A., Jin, Z., & Tan, L. H. (2004). Biological abnormality of impaired reading is constrained by culture. *Nature*, 431, 71–76.
- Snow, C. E., Burns, M. S., & Griffin, P. (Eds.). (1998). *Preventing reading difficulties in young children*. Committee on the Prevention of Reading Difficulties in Young Children, Commission on Behavioral and Social Sciences and Education, National Research Council.
- Tagamets, M. A., Novick, J. M., Chalmers, M. L., & Friedman, R. B. (2000). A parametric approach of orthographic processing in the brain: An fMRI study. *Journal of Cognitive Neuroscience*, 1, 281–297.
- Tan, L. H., Liu, H.-L., Perfetti, C. A., Spinks, J. A., Fox, P. T., & Gao, J.-H. (2001). The neural system underlying Chinese logograph reading. *NeuroImage*, 13, 836–846.
- Tarkiainen, A., Cornelissen, P. L., & Salmelin, R. (2003). Dynamics of visual feature analysis and object-level processing in face versus letter-string perception. *Brain*, 125, 1125–1136.
- Temple, E., Deutsch, G. K., Poldrack, R. A., Miller, S. L., Tallal, P., et al. (2003). Neural deficits in children with dyslexia ameliorated by behavioral remediation: Evidence from functional MRI. *Proceedings of the National Academy of Sciences*, 100, 2860–2865.
- Turkeltaub, P. E., Gareau, L., Flowers, D. L., Zeffiro, T. A., & Eden, G. F. (2003). Development of neural mechanisms for reading. *Nature Neuroscience*, 6, 767–773.
- Valaki, C. E., Maestu, F., Simos, P. G., Zhang, W., Fernandez, A., Amo, C. M., et al. (2004). Cortical organization for receptive language functions in Chinese, English, and Spanish: A cross-linguistic MEG study. *Neuropsychologia*, 42, 967–979.
- Van Orden, G. C., Pennington, B. F., & Stone, G. O. (1990). Word identification in reading and the promise of subsymbolic psycholinguistics. *Psychological Review*, 97, 488–522.
- Wagner, R. K., & Torgesen, J. K. (1987). The nature of phonological processing and its causal role in the acquisition of reading skills. *Psychological Bulletin*, 101, 192–212.
- Wimmer, H. (1993). Characteristics of developmental dyslexia in a regular writing system. *Applied Psycholinguistics*, 14, 1–33.
- Xu, B., Grafman, J., Gaillard, W. D., Ishii, K., Vega-Bermudez, F., Pietrini, P., et al. (2001). Conjoint and extended neural networks for the computation of speech codes: The neural basis of selective impairment in reading words and pseudowords. *Cerebral Cortex*, 11, 267–277.
- Ziegler, J. C., Perry, C., Jacobs, A. M., & Braun, M. (2001). Identical words are read differently in different languages. *Psychological Science*, 12, 379–384.
- Ziegler, J. C., Perry, C., Ma-Wyatt, A., Ladner, D., & Schulte-Korne, G. (2003). Developmental dyslexia in different languages: Language-specific or universal? *Journal of Experimental Child Psychology*, 86, 169–193.

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