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1 Mapping the Word Reading Circuitry in Skilled and Disabled Readers[1]

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Research on the neurocognitive foundations of reading in typically and atypically developing readers has benefited in recent years from advances in several neuroimaging technologies (see Papanicolaou, Pugh, Simos, & Mencl, 2004, for a review). In this chapter we describe recent studies from our lab, and from others, that were designed to generate data, not only on localization of reading-related brain activation, but also to examine patterns of interactions and trade-offs among these distributed reading-related systems. Acquiring data of this sort is necessary, in our view, if we are to begin to construct neurobiological models of word identification that can speak to the complexities and dynamics of reading performance. Indeed, computational models of reading stand or fall, not by their capacity to account for simple group differences on behavioral measures of reading performance or main effects of isolated variables, but rather by whether they can account for complex interactions among them (Harm & Seidenberg, 1999). Ultimately, the same criteria must be applied to neurobiologically grounded models as well. Thus, it is critical that we begin to look beyond simply more fine-tuned localization and consider also a systems-level approach. Research on systems appears to be a realistic possibility at this stage in the development of these new technologies, given the evidence that extant neurophysiologic measures are amenable to sophisticated psycholinguistic designs (Dehaene et al., 2004; Frost et al., 2005; Sandak, Mencl, Frost, Mason, Rueckl, et al., 2004). When we add to all this the clinically oriented goal of better understanding what differences in activation patterns between skilled and struggling readers imply about core deficits and optimal remediation, it becomes all the more pressing to develop a more comprehensive neurobiological account of how component processes interact and change with learning and development (Pugh et al., 2006). We focus here primarily on studies of phonological processing in reading, given that this stage is typically the most sensitive in discriminating nonimpaired (NI) from reading disabled (RD) cohorts (Pugh, Mencl, Shaywitz, et al., 2000).

We begin with a short review of relevant behavioral studies of component processing in fluent word identification, focusing on the role of sublexical phonology, which studies have shown to be compromised in RD cohorts. We then discuss the current literature on the neurobiology of skilled and disabled reading, along with consideration of a series of recent studies from our lab that aim to capture brain correlates of component processes, again with an emphasis on how the findings help to better understand the cooperative–competitive dynamics of the neurocircuitry supporting word identification. Finally, we take stock of what we consider to be crucial next steps (both technical and theoretical) in the emerging cognitive neuroscience of reading and its disorders.

BEHAVIORAL STUDIES OF SKILLED READING

A central issue in studies of skilled readers concerns the question of whether phonological information mediates access to the mental lexicon visual word identification. As indicated earlier, given that measures of the ability to map from spelling to pronunciation are typically the most sensitive in discriminating nonimpaired from RD cohorts (Pugh, Mencl, Jenner, et al., 2000), acquiring behavioral data on this question is crucial if we are to correctly interpret reader group differences in patterns of activation across the reading circuitry. Many studies have now demonstrated that phonological access in visual word recognition is early and automatic for skilled readers (see R. Frost, 1998, for review). For example, Van Orden and his colleagues showed that participants in a semantic categorization task produced more false-positive responses to words that are homophones or pseudohomophones of category exemplars than for spelling foils (e.g., categorizing ROWS/ROZE as a flower more often than the control foil ROBS/REEZ; Van Orden, 1987; Van Orden et al., 1988). Moreover, this effect persisted, even at brief exposure durations, indicating that phonological recoding occurred early in processing and, because pseudohomophones are not represented lexically, Van Orden et al. (1988) concluded that the effect must occur before lexical access.

Findings from studies using brief exposure paradigms, such as backward masking and priming, also point to an early and robust influence of phonology on lexical access (Lesch & Pollatsek, 1993; Lukatela, Frost, & Turvey, 1999; Lukatela & Turvey, 1994a, 1994b; Perfetti & Bell, 1991; Perfetti, Bell, & Delaney, 1988). For example, Perfetti and colleagues (1988) found significantly better identification rates when briefly presented target words were followed by pseudoword masks that were phonemically similar than when they were graphemically similar, suggesting that phonological information was automatically extracted from the pseudoword mask and contributed to the identification of the target (Perfetti & Bell, 1991; Perfetti et al., 1988). Lukatela and Turvey (1994a; see also Lesch & Pollatsek, 1993) observed priming of a target word (e.g., FROG) at a short prime-target interval for a semantic associate (TOAD), a homophone of the associate

(TOWED), and a pseudohomophone of the associate (TODE) relative to matched controls. At a long interval, both TOAD and TODE effects were observed, but TOWED effects were eliminated. The authors concluded that the initial access code must be phonological in nature, with orthographic constraints coming into play relatively late.

BEHAVIORAL STUDIES OF READING DISABILITY

Significant progress has been made in understanding the cognitive and linguistic skills that must be in place to ensure adequate reading development in children (Bruck, 1992; Liberman, Shankweiler, Fischer, & Carter, 1974; Shankweiler et al., 1995; Stanovich & Siegel, 1994). With regard to reading disability, deficits in behavioral performance are most evident at the level of single word and pseudoword reading; RD individuals are both slow and inaccurate relative to NI readers. A number of explanations have been proposed to account for these reading difficulties, including processing speed deficits (Wolf & Bowers, 1999), rapid auditory processing (Tallal, 1980), general language deficits (Scarborough & Dobrich, 1990), or visual deficits (Cornelissen & Hansen, 1998). However, there is growing consensus that for the majority of struggling readers, a core difficulty in reading manifests itself as a specific deficiency within the language system at the level of phonological representation and processing (Ziegler & Goswami, 2005; Liberman, 1992).

Many lines of evidence converge on the conclusion that the word and pseudoword reading difficulties in RD individuals are, to a large extent, manifestations of more basic deficits at the level of assembling the phonological code represented by a given letter string (Bradley & Bryant, 1983). The failure to develop efficient (both accurate and rapid) phonological assembly skill in word and pseudoword reading, in turn, appears to stem from difficulties—at the earliest stages of literacy training—in the development of phonological awareness. Phonological awareness, in general, is defined as the metalinguistic understanding of the segmental nature of speech; that spoken words are composed of segments including the smallest of these segments, phonemes, which in turn can be represented by alphabetic characters (Bruck, 1992; Liberman et al., 1974; Shankweiler et al., 1995; Stanovich & Siegel, 1994).

As for why RD readers should have exceptional difficulty developing phonological awareness, the etiological underpinnings of this difficulty are still actively being investigated and the question of whether such language-level challenges might, in some children at least, be linked to more basic deficits in one or more of the above-mentioned domains is much debated. Nonetheless, a large body of evidence directly relates deficits in phonological awareness, and fine-grained phonemic awareness in particular, to difficulties in learning to read: phonological awareness measures predict later reading achievement (Bradley & Bryant, 1983; Stanovich et al., 1984; Torgesen et al., 1994); deficits in phonological awareness consistently separate RD and nonimpaired children (Fletcher et al., 1994; Stanovich & Siegel, 1994); phonological deficits persist into adulthood (Bruck, 1992; Shaywitz et al., 1998); and instruction in phonological awareness promotes the acquisition of reading skills (Ball & Blachman, 1991; Foorman, Francis, Fletcher, Schatschneider, & Mehta, 1998; Torgesen, Morgan, & Davis, 1992). For children with adequate phonological skills, the process of phonological assembly in word and pseudoword reading becomes highly automated, efficient, and, as the evidence here suggests, continues to serve as an important component in rapid word identification even for mature skilled readers (R. Frost, 1998).

FUNCTIONAL IMAGING STUDIES OF SKILLED READING AND READING DEVELOPMENT

Given the importance of phonological information evidenced from behavioral studies of skilled and impaired reading, identifying the neuroanatomical correlates of phonology and their interactions with regions that support orthographic, morphological, and lexico-semantic component processes represents an important step toward understanding the functional architecture of reading and reading failure. Evidence from functional imaging studies indicates that skilled word recognition involves a left hemisphere (LH) cortical reading circuit with ventral, dorsal, and anterior components (see Pugh, Mencl, Jenner, et al., 2000; Sarkari et al., 2002, for reviews). This circuit broadly includes an anterior subsystem and two posterior subsystems: a ventral (occipitotemporal) and a dorsal (temporoparietal) system.

The anterior system, centered in and near Broca's area in the inferior frontal gyrus (IFG), is associated with phonological coding during reading, among other functions (e.g., phonological memory, syntactic processing); 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 are more strongly engaged by low-frequency words (particularly, words with irregular/inconsistent spelling-to-sound mappings) and pseudowords than by high-frequency words (Fiebach, Friederici, Mueller, & von Cramon, 2002; Fiez & Peterson, 1998). The temporoparietal system, which includes the angular gyrus (AG) and supramarginal gyrus (SMG) in the inferior parietal lobule, and the posterior aspect of the superior temporal gyrus (Wernicke's area), seems to be involved in mapping visual percepts of print onto the phonological and semantic structures of language (Black & Behrmann, 1994; Price, Winterburn, Giraud, Moore, & Noppeney, 2003). Similar to the IFG, regions within the LH temporoparietal system (particularly the SMG) respond with greater activity to pseudowords than to familiar words, and to print more than pictures (Price, Wise, & Frackowiak, 1996; Sandak, Mencl, Frost, Mason, Rueckl, et al., 2004; Simos, Breier, et al., 2002). We have speculated that this temporoparietal system operates in close conjunction with the anterior system to decode new words during normal reading development (Pugh, Mencl et al., 2000).

The ventral system includes extrastriate areas, a left inferior occipitotemporal/fusiform gyrus, and appears to extend anteriorly into the middle and inferior temporal gyri (MTG, ITG). Whereas the more anterior foci within the ventral system extending into the MTG to ITG appear to be semantically tuned (Fiebach et al., 2002; Simos, Breier, et al., 2002a), it has been suggested by some researchers that the occipitotemporal (OT) region functions as a presemantic visual word form area (VWFA; c.f. Cohen et al., 2002, but see Price et al., 2003 for an alternative conceptualization). Importantly, the functional specificity of sites along the ventral pathway for reading appears to be late developing and critically related to the acquisition of reading skill (Booth et al., 2001; see Shaywitz et al., 2002, discussed later), leading us to refer to this region more neutrally as the ventral "skill zone." The ventral system, particularly the posterior aspects thought to be prelexical and presemantic, is also fast acting in response to print stimuli in skilled readers but not in RD individuals (Salmelin et al., 1996). Although there is disagreement in the literature about the precise taxonomy of critical subregions comprising the ventral system (Dehaene et al., 2004; Price et al., 2003), recent studies examining both timing and stimulus-type effects suggest that subregions respond to word and word-like stimuli in a progressively abstracted and linguistic manner as one moves anteriorly along the ventral pathways (Dehaene et al., 2004; Tagamets, Novick, Chalmers, & Friedman, 2000; Tarkiainen, Cornelissen, & Salmelin, 2003).

Of these three systems, the dorsal and anterior systems appear to dominate during initial reading acquisition in normally developing beginning readers with an increased ventral response to print stimuli as proficiency in word recognition increases. Shaywitz et al. (1998) observed that in normally developing children younger than 10.5 years of age, activation during pseudoword and real-word reading tasks is largely limited to the temporoparietal and anterior systems; in contrast, children older than 10.5 years of age showed increased engagement of the ventral system, which in turn was positively correlated with reading skill. Indeed, when multiple regression analyses examined both age and reading skill (measured by performance on standard reading tests) the critical predictor was reading skill level: the higher the reading skill, the stronger the response in the LH ventral cortex (with several other areas including right hemisphere [RH] and frontal lobe sites showing age- and skill-related reductions). RD readers, by contrast, showed age-related increases in a widely distributed set of regions across both the LH and RH. Based on these cross-sectional developmental findings, we suggest that a beginning reader on a successful trajectory employs a widely distributed cortical system for print processing including temporoparietal, frontal, and RH posterior areas. As reading skill increases, LH ventral sites become more active, and presumably more central to the rapid recognition of printed (word) stimuli (see Turkeltaub, Gareau, Flowers, Zeffiro, & Eden, 2003, for similar arguments).

REFINING OUR ACCOUNT OF NEUROBIOLOGY OF SKILLED WORD RECOGNITION

As outlined earlier, we have speculated that the temporoparietal and anterior systems are critical in learning to integrate orthographic, phonological, and semantic features of words, whereas the ventral system develops, as a consequence of adequate learning during reading acquisition, to support fluent word identification in normally developing, but not reading disabled, individuals. This general taxonomy, however, is both coarse grained and underspecified. To explore functional subspecialization further we have recently conducted a series of experiments with skilled readers (Frost et al., 2005; Katz et al., 2005; Sandak, Mencl, Frost, Mason, & Rueckl, et al., 2004; summarized in depth by Sandak, Mencl, Frost, Mason, & Pugh, 2004). We examined phonological/semantic trade-offs (Frost et al., 2005) and critical factors associated with repetition effects (Katz et al., 2005) and adaptive learning (Sandak, Mencl, Frost, Mason, & Rueckl, et al., 2004). This line of research is aimed at providing more information on both subspecialization with the major LH regions and how different component systems modulate processing in relation to one another in response to varied stimuli and at different stages during learning. Given the importance of the ventral pathway in the development of fluent reading, we are particularly interested in assessing the tuning characteristics of the skilled-correlated OT region (along with remote areas most closely linked to processing within this ventral area).

Trade-Offs Between Phonology and Semantics

RD readers have acute problems in mapping from orthography to phonology and appear to rely on semantic information to supplement deficient decoding skills (Plaut & Booth, 2000; Strain & Herdman, 1999). NI readers too appear to show a trade-off between these component processes. Strain, Patterson, and Seidenberg (1995) provided behavioral confirmation of this, demonstrating that the standard consistency effect on low-frequency words (longer naming latencies for words with inconsistent spelling-to-sound mappings such as PINT relative to words with consistent mappings such as MILL) is attenuated for words that are highly imageable. Importantly, this interaction reveals that semantics can attenuate the difficulties associated with reading words that have inconsistent orthographic-to-phonological mappings.

Using functional magnetic resonance imaging (fMRI), we sought to identify the neurobiological correlates of this trade-off between semantics and phonology (Frost et al., 2005). A go/no-go naming paradigm was employed in an event-related fMRI protocol with word stimuli representing the crossing of frequency, imageability, and spelling-to-sound consistency. High-imageable words reduced consistency-related activation in the IFG, SMG, and OT, but increased posterior parietal (AG) and middle temporal activation. This appears to be the principal neural signature of the behavioral trade-off between semantics and phonology revealed by Strain and colleagues (1995). These findings provide evidence that skilled performance results from cooperative–competitive processing involving different components of the reading circuitry.

Adaptive Learning

Increased familiarity with specific words and increased reading skill are associated with a shift in the relative activation of the cortical systems involved in reading, from predominantly dorsal to predominantly ventral (Turkeltaub et al., 2003). We are carrying out functional neuroimaging experiments to provide a more precise characterization of the means by which practice with unfamiliar words results in this shift and to gain insights into how these systems learn to read new words. In one study from our group (Katz et al., 2005) we examined repetition effects (comparing activation for thrice repeated words relative to unrepeated words) in both lexical decision and overt naming. Across tasks, repetition was associated with facilitated processing as measured by reduced response latencies and errors. Many sites, including the IFG, SMG, supplementary motor area, and cerebellum, showed reduced activation for highly practiced tokens. Critically, we observed a dissociation within the ventral system: the OT skill zone showed repetition-related reduction (like the SMG and IFG sites), whereas more anterior ventral sites, particularly the MTG, were stable or even showed increased activation with repetition. Thus, we concluded that a neural signature of increased efficiency in word recognition has more efficient processing in dorsal, anterior, and posterior ventral sites, with stable or increased engagement of more anterior middle and inferior temporal sites.

In another study from our group, Sandak, Mencl, Frost, Mason, Rueckl, et al. (2004) examined whether the type of processing engaged in during learning would modulate the repetition-related patterns of activation observed by Katz et al. (2005). That is, we hypothesized that repetition alone is not sufficient to optimize learning; rather, we predicted that the type of processing engaged in during learning would affect the quality of the lexical representations established when new words are learned and the cortical regions engaged when that word is subsequently read. To address this question, participants completed a behavioral session prior to MRI scanning, acquiring familiarity for three sets of pronounceable pseudowords while making orthographic (consonant–vowel pattern), phonological (rhyme), or semantic (category) judgments. (Note that in the semantic condition, participants learned a novel semantic association for each pseudoword.) Following training, participants completed an event-related fMRI session in which they overtly named the trained pseudowords, untrained pseudowords, and real words.

Behaviorally, phonological and semantic training resulted in faster naming times relative to orthographic training. Of the three training conditions, we found that only phonological training was associated with both facilitated naming and the pattern of cortical activations previously implicated as characteristic of increased efficiency for word recognition (Katz et al., 2005). We suggest that for phonologically trained items, engaging in phonological processing during training facilitated learning, which, in turn, resulted in efficient phonological processing (instantiated cortically as relatively reduced activation in IFG and SMG) and efficient retrieval of presemantic lexical representations during subsequent naming (instantiated cortically as relatively reduced activation in the OT skill zone). Emphasizing semantic processing during training also facilitated learning but was associated with increased activation in areas previously implicated in semantic processing, suggesting that the establishment and retrieval of semantic representations compensated for less efficient phonological processing for these items.

Our recent experiments examining phonological–semantic trade-offs and critical factors associated with adaptive learning in reading have yielded findings that allow for the development of a more fine-grained picture of the functional neuroanatomy and subspecializations within these systems, and begin to provide information on learning-related modulation and trade-offs among component regions. Across these studies, identical sites in the SMG (within the temporoparietal system), IFG (within the anterior system), and the OT skill zone (within the ventral system) showed increased activation for spelling-to-sound-inconsistent relative to consistent words, and repetition-related reductions that were most salient in the phonologically analytic training condition. This pattern with regard to phonological variables suggests a phonological "tuning" in these subregions. (It is particularly noteworthy that the developmentally critical OT skill zone—the putative VWFA—appears to be phonologically tuned. It makes good sense that this region should be so structured given the failure to develop this system in reading disability when phonological deficits are one of the core features of this population.) By contrast, the angular gyrus (within the temporoparietal system) and the middle/inferior temporal gyri (within the ventral system) appear to have more abstract lexico-semantic functions across our studies (see Price, Moore, Humphreys, & Wise, 1997, for similar claims).

From these findings, we speculate that subregions within the SMG and IFG operate in a yoked fashion to bind orthographic and phonological features of words during learning; these systems also operate in conjunction with the AG where these features are further yoked to semantic knowledge systems distributed across several cortical regions. Adequate binding, specifically adequate orthographic/phonological integration, enables the development of the presemantic OT skill zone into a functional pattern identification system. As words become better learned, this area becomes capable of efficiently activating lexico-semantic subsystems in the MTG/ITG, further enabling the development of a rapid ventral word identification system.

FUNCTIONAL IMAGING STUDIES OF READING DISABILITY

Evidence for Altered Circuits in Reading Disability

There are clear functional differences between NI and RD readers with regard to activation patterns in dorsal, ventral, and anterior sites during reading tasks. In disabled readers, a number of functional imaging studies have observed LH posterior functional disruption, at both dorsal and ventral sites during phonological processing tasks (Brunswick, McCrory, Price, Frith, & Frith, 1999; Paulesu et al., 2001; Pugh, Mencl, Shaywitz, et al., 2000; Salmelin et al., 1996; Shaywitz et al., 1998, 2002; Temple et al., 2001). This disruption is instantiated as a relative underengagement of these regions specifically when processing linguistic stimuli (words and pseudowords), particularly during tasks that require decoding. This functional anomaly in posterior LH regions has been observed consistently in children (Shaywitz et al., 2002) and adults (Salmelin et al., 1996; Shaywitz et al., 1998) and is evident in measures of activation and in analysis of functional connectivity (Horwitz et al., 1998; Pugh, Mencl, Shaywitz, et al., 2000). Moreover, hypoactivation in three key dorsal and ventral sites—the cortex within the temporoparietal region, the angular gyrus, and the ventral OT skill zone—is detectable as early as the end of kindergarten in children who have not reached important milestones in learning to read (Simos, Fletcher, et al., 2002).

Potentially Compensatory Processing in Reading Disability

A number of studies have shown that on tasks that make explicit demands on phonological processing (pseudoword- and word-reading tasks), RD readers show a disproportionately greater engagement of IFG and prefrontal dorsolateral sites than NI readers (Shaywitz et al., 1998, 2002; see also Brunswick et al., 1999; Salmelin et al., 1996, for similar findings). In addition, several studies provide evidence of increased activity in posterior RH regions. Using MEG, Sarkari et al. (2002) found an increase in the engagement of the RH temporoparietal region in RD children. More detailed examination of this trend, using hemodynamic measures, indicates that hemispheric asymmetries in activity in posterior temporal and temporoparietal regions (MTG and AG) vary significantly among reading groups (Shaywitz et al., 1998): There was greater RH than LH activation in RD readers but greater LH than RH activation in NI readers. Rumsey et al. (1999) examined the relationship between RH activation and reading performance in their adult RD and NI participants and found that RH temporoparietal activation was correlated with standard measures of reading performance only for RD readers (see also Shaywitz et al., 2002).

In summary, adult and cross-sectional developmental studies have identified reading group differences in both functional neuroanatomical and behavioral trajectories. NI children develop a left hemisphere posterior (ventral) reading system capable of supporting fluent word identification, whereas RD readers, with demonstrable anomalies in temporoparietal and frontal activation (and associated difficulties with phonologically analytic processing on behavioral tests), fail to adequately "train" the ventral subsystem. We hypothesize that RD readers tend to strongly engage inferior frontal sites due to increased reliance on covert pronunciation (articulatory recoding) in an attempt to cope with their inefficient phonological analysis of the printed word. In addition, heightened activation of the posterior RH regions with reduced LH posterior activation may reflect the fact that, behaviorally, poor readers compensate for their inadequate phonological awareness and knowledge of letter–sound correspondences by overrelying on contextual cues to read individual words; their word reading errors tend to be visual or semantic rather than phonetic (see Perfetti, 1985, for review). That is, the heightened posterior RH activation suggests a process of word recognition that relies on letter-by-letter processing in accessing RH localized visuo-semantic representations rather than relying on phonologically structured word-recognition strategies.

Neurobiological Effects of Reading Remediation With Children

Converging evidence from other studies supports the notion that gains in reading skill resulting from reading intervention are associated with a more "normalized" localization of reading processes in the brain. In a recent MEG study, eight young children with severe reading difficulties underwent a brief but intensive phonics-based remediation program (Simos, Fletcher, et al., 2002). After intervention, the most salient change observed on a case-by-case basis was an increase in the engagement of the LH temporoparietal region, accompanied by a moderate reduction in the activation of the RH temporoparietal areas. Similarly, Temple et al. (2003) used fMRI to examine the effects of an intervention (FastForword) on the pattern of reading-related activation of a group of 8- to 12-year-old children with reading difficulties. After intervention, increased LH temporoparietal and inferior frontal activation were observed. Moreover, the LH increases correlated significantly with increased reading scores. In a study by Blachman, Tangel, Ball, Black, and McGraw (1999) a treatment RD group of young children received 9 months of an intensive phonologically analytic intervention. The treatment group was matched with two control groups: a typically developing and an untreated RD group (average age was 6.5 years at Time 1 for all groups). Relative to RD controls, RD treatment participants showed reliable gains on reading measures (particularly on fluency-related measures). In addition to behavioral indices, children received a pre- and posttreatment fMRI employing a simple cross modal (auditory/visual) forced-choice letter-match task (Shaywitz et al., 2004). When RD groups were compared at posttreatment (Time 2), reliably greater activation increases in LH reading-related sites were seen in the treatment group. When Time 2 and Time 1 activation profiles were directly contrasted for each group, both RD treatment and typically developing, but not RD controls, showed reliable increases in LH reading-related sites. Prominent differences were seen in the LH IFG and, importantly, in the LH ventral skill zone. These changes were quite similar to those found in the NI controls as they also learned to read. Importantly, a follow-up fMRI scan for the treatment group revealed progressive LH ventral increases along with decreasing RH activation patterns even 1 year after treatment was concluded. These initial neuroimaging treatment studies suggest that a critical neurobiological signature of successful intervention, at least in younger children, appears to be increased engagement of major LH reading-related circuits and reduced compensatory reliance on RH homologues.

Neurobiological Evidence for Plasticity in Adolescent Readers

Although the evidence from intervention studies suggests that compromised LH systems in young RD populations are responsive to intensive training (Simos, Fletcher, et al., 2002; Shaywitz et al., 2004; Temple et al., 2003), it is not clear whether the same holds true for older children with persistent reading difficulties (Pugh, Mencl, Shaywitz, et al., 2000). We decided to explore the degree of plasticity in the cortical circuitry for reading of adolescent RD readers, focused on whether factors that alleviate processing demands on the neurocircuitry for reading might reveal latent functionality in LH systems and potentially reduce RH compensatory activation (Pugh et al., 2008). Experiment 1 examined phonological–semantic trade-offs in printed word naming as described earlier (Frost et al., 2005). Given behavioral findings indicating heightened top-down facilitative effects in RD readers (Plaut & Booth, 2000; Strain & Herdman, 1999), we compared the reader groups on difficult-to-decode (inconsistent) words that differ with regard to top-down support from frequency and imageability. Behaviorally, both groups were faster and more accurate for high-frequency, high-imageable, inconsistent words relative to low-frequency, low-imageable, inconsistent words with a larger effect on accuracy for RD readers. Neurobiologically, a dissociation was observed such that inconsistent words with top-down support produced decreases in activation levels across the major LH reading areas for NI readers; however, RD readers showed the opposite pattern—increases in activation levels in LH reading areas, particularly SMG and STG. We interpret these finding to indicate that the reading subsystems in adolescent RD readers are weak but not fundamentally disrupted.

To further examine the limits on normalization of function, Experiment 2 measured behavioral and activation patterns NI and RD adolescents for high-frequency words presented six times over the course of each functional imaging run while performing a semantic categorization task (animacy judgment). Behaviorally, both groups showed reliable decreases in latency and increases in accuracy with repetition. Activation results were quite different. Consistent with our previous results with adults (Katz et al., 2005), we observed a reliable decrease in activation in adolescent NI readers as words were repeated in LH reading-related regions, including the OT, MTG, STG, SMG, and IFG; in contrast, RD readers (with low signal in LH regions on the first exposure) showed activation increases in these brain regions across repetitions. Moreover, activation differences between reader groups in several reading-related sites such as the STG and IFG were no longer apparent on late trials. We proposed that for NI readers, decreases in activation with word repetitions reflect increases in processing efficiency; for RD readers, increases in activation with repetitions ameliorate phonological processing difficulties such that RD readers begin to engage canonical LH reading-related regions that are not normally activated for this population. One important question that the data raise is why the initial activation response in the LH is so low given that RD readers have certainly seen the words used in this experiment hundreds of times. The most straightforward hypothesis, and one that would, coupled with clinical observations, point to a very specific learning problem in RD readers, is that these readers fail to consolidate the learning experience into longer term neural changes in processing and organization. Thus, the system might be available for processing but fails to demonstrate savings with longer term modulation of connections. We suggest that future studies will need to address this possibility by shifting from the more narrow focus on simple orthographic-to-phonological mapping deficits toward a broader, systematic investigation of the mechanisms of memory and learning.

FUTURE DIRECTIONS

Although functional imaging studies have established important signatures of reader group differences in developmental trajectories, they are nonetheless merely descriptive. That is, functional neuroimaging measures are not intrinsically explanatory; they describe brain organization at a given point in development. Links between multiple indices of reading (dis)ability, including genetic polymorphisms, brain structure and function, and cognitive deficits, promise to constitute the core scientific foundation for our understanding of neurodevelopmental disorders in the coming years, with the goal of progressing from descriptive neurobiological findings to potentially explanatory models. By establishing meaningful links between the behavioral–cognitive skills that must be in place to read and neuroanatomical, neurochemical, and genetic measures, we can begin to develop an explanatory account of neurocognitive divergences in typically developing and RD children (Grigorenko, 2001; Pugh, Mencl, Jenner, et al., 2000). That is, we believe that multilevel designs will allow specifications of the biological *pathways* predisposing for risk for the development of a reading disability and explorations of elements of these pathways that might be most suitable for pharmacological and behavioral intervention.

Finally, a large body of behavioral research supports the notion that word recognition engages common processes across languages and orthographies (despite some differences in behavioral manifestations of reading disability) that, we suggest, reflect the degree of transparency in the mapping between written and spoken forms. Functional neuroimaging studies have also provided support for a common neurobiological signature of skilled reading in which language-specific differences appear to be mainly a matter of degree, not of kind (Paulesu et al., 2001); however, some qualitative differences between alphabetic and nonalphabetic writing systems have been observed (Siok et al., 2004). Given the significant variability in orthographic form, orthographic-to-phonological mappings, methods of reading instruction, and manifestations of reading disability across languages and cultures, more work needs to be done in the area of cross-linguistic studies of reading, both in order to identify the neurobiological universals of reading and to understand how the functional organization of reading and reading development varies with language-specific features. For example, we might anticipate that the initial neurocircuitry for reading will be somewhat different across languages, reflecting the different challenges that writing systems place on orthography, phonology, morphology, visual memory, and the like. This would imply that whereas a common ventral reading specialization should eventually develop for each language, the computational organization of this common neural pathway will differ somewhat as a function of the language-specific challenges during early reading development. An adequate neurobiologically grounded reading theory must be able to account for both language variance (with respect to both properties of the spoken and written forms) and language invariance (with respect to common neural pathways) over the course of development. Cross-language studies, along with studies of interactions among component processing during adaptive learning, will continue to drive the conceptual and computational development of neurobiological theories in the next phase of our research.

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