

## Basic Science Advances

# Reading Development and Impairment: Behavioral, Social, and Neurobiological Factors

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**ABSTRACT.** What are the cognitive and neurobiological building blocks necessary for children to acquire literacy, a skill that is crucial for academic and life achievement? In this review we discuss the behavioral and neurobiological evidence concerning the bases of reading development and impairment. The means by which reading achievement may be influenced by the background and experiences that a child brings to the classroom are discussed. Finally, we review a series of experimental studies that have examined the cognitive and neurobiological response prior to and following reading intervention in struggling readers. The importance of appropriate control groups is stressed, as well as the ultimate goal of designing reading interventions that target individual needs. *J Dev Behav Pediatr* 26:370–378, 2005. Index terms: *reading, neurobiological basis of reading, reading intervention.*

As literate adults, we process written words automatically and nearly instantaneously, in hundreds of milliseconds.<sup>1</sup> In fact, skilled adult readers cannot stop themselves from involuntarily reading words presented to them, even when instructed to focus on other aspects of the stimulus, such as the color of the ink in which it is written.<sup>2</sup> Further, this rapid, automatic process occurs even when the reader is not consciously aware of seeing a written word.<sup>3</sup> However, such skilled expertise requires years of specialized training and practice. What are the building blocks necessary for children to acquire this skill that is so crucial for academic and life achievement? In this review, we discuss the fundamental cognitive precursors of reading acquisition. We review the evidence from behavioral studies of reading development, and present evidence suggesting that two main brain regions support the neurobiological basis of reading. As reading skill is not acquired in a vacuum, the background and experiences that a child brings to the classroom are intimately involved in shaping reading development. The degree to which socioeconomic background can influence other factors involved in reading acquisition is discussed. Finally, we report on several efforts to design intervention strategies that monitor neural development in concert with reading skill.

### BEHAVIORAL EVIDENCE: PHONOLOGICAL AWARENESS

The task required of the developing reader is complex. How does a child come to rapidly and automatically

recognize that a certain set of letters in a particular order represents a specific sound and meaning – a culturally invented ability that has only been present for an evolutionarily insignificant five millennia?<sup>4</sup> A large body of literature has shown that *phonological awareness*, or an understanding of the sound structure of language, is fundamentally necessary for the successful acquisition of reading skill.<sup>5–11</sup> That is, the ability to analyze, synthesize and manipulate the sounds of a language must be mastered in order for a child to adequately learn precisely how these sounds correspond to the arbitrarily defined shapes known as letters.

Phonological awareness is measured by standardized tasks that assess a child's ability to manipulate the sounds of language using units smaller than words, such as syllables or *phonemes*, the smallest unit of sounds in speech. In one such task, an experimenter might ask a child to say the word *bat*, and then to say the word again without saying the /b/ sound (such that the correct answer is *at*). To successfully perform such a task, the child must be able to identify and manipulate the distinct sounds in the word *bat*. Such assessments increase in difficulty and complexity, thereby fully characterizing a child's ability to manipulate phonemes in many positions of a word. Given that reading requires the ability to map between the distinct sounds in words and distinct letter combinations, it follows that individual children's differences in phonological skill are tightly related to their variable progress in learning to read. This association has been demonstrated empirically, as preliterate children who have better phonological awareness skills are in turn quicker to learn to read,<sup>7</sup> and

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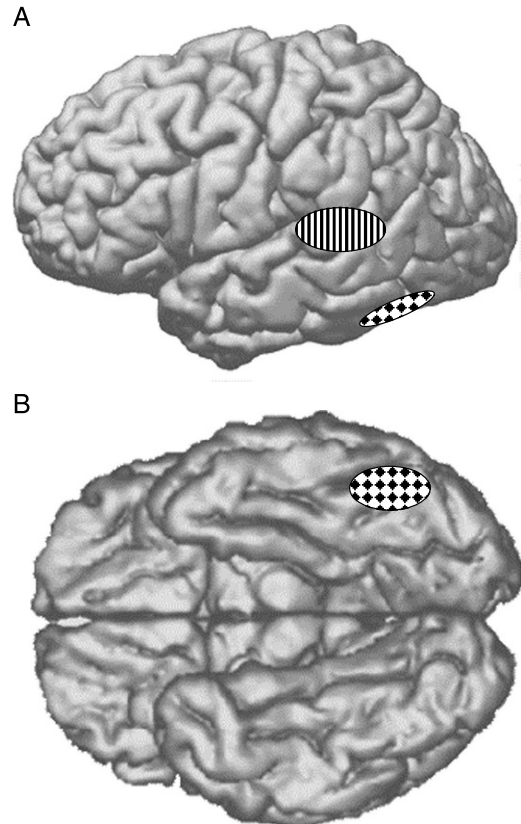
both the absolute level<sup>12</sup> and rate of acquisition<sup>13</sup> of early phonological awareness are excellent predictors of elementary reading skills. In fact, kindergarten phonological awareness is a better predictor of teenage reading ability than is kindergarten reading skill.<sup>14</sup> Furthermore, differences in children's phonological awareness levels continue to accurately predict differences in their reading abilities through the late elementary years, whereas other cognitive indices such as vocabulary level become less predictive of reading skill as children get older.<sup>15</sup> Studies of twins have suggested that phonological skills have a genetically heritable component,<sup>16,17</sup> and a deficit in phonological processing is now believed to be the primary core deficit in developmental dyslexia, a reading disability in which children exhibit a difficulty in accurately or fluently reading at age-appropriate levels.<sup>18</sup> Importantly, experimental manipulations in which reading-disabled children were exposed to both phonological skill training and explicit instruction in letter-sound correspondence rules have resulted in improved reading ability, relative to various reading-disabled control groups,<sup>7,19–22</sup> suggesting that phonological skill is not merely associated with reading, but actually plays a causal role in its development. This well established link between phonological awareness and reading acquisition has greatly influenced our understanding of both mainstream and remedial education practices, and has had a large impact on education policy.<sup>18</sup>

### NEUROBIOLOGICAL BASIS OF READING

Cognitive neuroscience has greatly expanded our understanding of the neural bases of reading development and impairment. A large and distributed network of cortical regions is implicated in reading skill. However, two brain regions have consistently been shown to both support the normal development of reading and exhibit dysfunction in cases of reading impairment: the left perisylvian region, and the left temporo-occipital region (See Figure 1).<sup>23</sup> As reviewed in this section, non-impaired readers tend to show increased activity in these regions during tasks that involve reading, relative to control tasks. In contrast, impaired readers tend not to show a modulation of activity in these regions as a function of reading. In some cases, it has also been observed that individuals with reading difficulties show increased recruitment of other regions, as discussed below.

#### Left Perisylvian Region

In non-impaired adult readers, the left perisylvian cortex, including the superior temporal gyrus (STG) and middle temporal gyrus (MTG), shows increased activity during tasks involving the phonological processing skills described above.<sup>24–26</sup> For instance, one investigation showed that areas of the left perisylvian region are more active during a task in which subjects decide whether two words rhyme – thus requiring subjects to focus on the sounds of language – relative to a control task in which subjects simply decide whether the letters in the two words are the same case.<sup>26</sup> Conversely, numerous studies employing a range of paradigms have also shown that there is a re-



**FIGURE 1.** (A) Lateral cortical surface of the left cerebral hemisphere. The left perisylvian region (highlighted with stripes) has been associated with phonological processes, and is implicated in reading impairment. (B) Ventral surface of the cerebral hemispheres. The left fusiform region (highlighted with diamonds) has been associated with visual word form processing, and has also been implicated in reading impairment. (Reprinted with Permission<sup>23</sup>)

duced tendency of reading-impaired individuals to recruit left perisylvian regions when faced with a phonologically challenging task, whether the task explicitly involves reading<sup>25–27</sup> or does not.<sup>28</sup> This common finding has been proposed as a neurophysiological hallmark of reading impairment.<sup>26</sup>

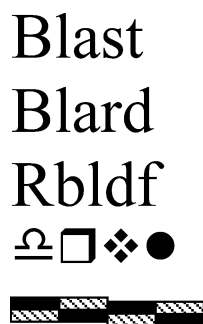
Only recently has functional neuroimaging begun to be used with younger populations, permitting the investigation of these phenomena in children. Studies of developing populations have generally found results consistent with the adult literature, in that better phonological skills are associated with increased recruitment of the left perisylvian region during reading-related tasks. In one study of typically developing readers, phonological skill was found to correlate with activity in the left perisylvian region in pediatric subjects ranging in age from six to 18 years.<sup>29</sup> Further, reading-disabled children are less likely than typically developing readers to show an increase in activity in this region in response to a phonologically demanding reading task.<sup>30–32</sup>

Populations with reading difficulties have sometimes been found to exhibit anomalous anatomy of left perisylvian structures, in addition to atypical function. Diffusion Tensor Imaging (DTI), a technique which measures

the organization of white matter tracts, has been used to show that microstructural anomalies of perisylvian white matter are associated with impaired reading in both adults and children.<sup>33,34</sup> Other studies have investigated gross anatomical structural differences in brain morphology as a function of reading ability,<sup>35,36</sup> though this has been somewhat more controversial, in that patterns of results have not always been replicated across studies.<sup>37</sup> Nonetheless, studies that quantify phonological abilities on a continuum rather than by focusing on categorical distinctions between dyslexics and non-impaired readers have typically demonstrated robust correlations between measures of phonological skill and macrostructural asymmetries in perisylvian brain regions.<sup>38,39</sup>

### Left Temporo-Occipital Region

The left temporo-occipital region, including the fusiform gyrus, has also been implicated in the neural basis of reading development. This region is active during the automatic perception and processing of visually presented words in skilled adult readers. The visual perception of words reliably activates the left fusiform gyrus to a greater degree than other stimuli that control for visual stimulation.<sup>40–48</sup> For instance, this region shows a greater response when subjects are presented with words than with other stimuli such as checkerboards,<sup>49</sup> auditory words,<sup>50</sup> or even unfamiliar characters that control for letter-like qualities<sup>40,51,52</sup> (See Figure 2). Activity in this area is also sensitive to the organization of letters within a word form. Both familiar words and novel letter strings that follow the



**FIGURE 2.** Top to bottom: word, pronounceable letter string, randomly ordered consonant string, false font, checkerboard. To isolate a particular cognitive process, neuroimaging studies include an experimental condition and a control condition. In the literate, English-speaking adult, the left fusiform gyrus shows increased activation to stimuli that follow the regular spelling rules of English (or the subject's native language), relative to other stimuli. That is, activation is seen both for words and for pronounceable letter strings, relative to consonant strings, unfamiliar characters or checkerboards. Some control conditions provide more information than others, however. For instance, in contrasting pronounceable letter strings to checkerboards, differences in activation could reflect differences in orthographic processing, but could also reflect differences in other perceptual aspects of these types of stimuli. In contrast, both pronounceable letter strings and randomly ordered consonant strings consist of letters with similar visual properties, but only pronounceable letter strings contain orthographic information. A direct comparison of these two types of stimuli is thus more precise.

patterns of the writing system (i.e. *blard*) typically produce greater responses than randomly ordered letter strings, or strings of consonants,<sup>4</sup> although such findings do not establish that this region is specialized for word reading to the exclusion of any other function.<sup>53</sup> Responsiveness of this region to written words gradually develops over the course of learning to read, and is associated with the gains in expertise of the typically developing reader.<sup>54–57</sup>

In contrast, a lack of word-specific responsiveness of this region is consistently demonstrated in reading-impaired individuals. Various neuroimaging studies have shown that while skilled readers show increased activity in the left fusiform region in response to word-reading tasks, dyslexic adults are less likely to upregulate activity in this region in response to written words.<sup>31,44,58–61</sup> Reading-related activity in this area has been directly related to reading skill in children as well. One study showed that, across 144 dyslexic and non-impaired children aged 7–18, standardized reading scores were significantly and positively correlated with the degree of activation in this region during a reading task.<sup>31</sup> This brain-behavior relationship was present across the full range of scores including both dyslexic and non-impaired children, and remained significant even when the effects of age were covaried. These results suggest a significant relationship between the degree to which a child reads successfully and the degree to which his or her left fusiform gyrus is responsive during reading tasks.

Anatomical lesion analyses have established that the left temporo-occipital region is not merely associated with the rapid perception of word forms, but is actually necessary for such perception. Binder and Mohr<sup>62</sup> demonstrated that across a number of studies, damage restricted to this area leads to pure alexia, a syndrome of functional loss that drastically impairs the ability to perceive the letters of a word in an integrated fashion, resulting in laborious attempts at reading, with reaction time proportional to the number of letters in the word being read.<sup>63</sup> In most cases, individuals with this syndrome exhibit damage to this region or to fibers providing input to this region.<sup>64,85</sup>

Thus, reading impairment is associated with the atypical development of a network of left perisylvian and left temporo-occipital regions. It is likely that the development of these two regions is related. One potential developmental mechanism under investigation incorporates a hypothesis that atypical phonological processing leads to inefficient mappings between sounds and letters during the early years of learning.<sup>65</sup> In the preliterate child, perisylvian regions associated with phonological processing may impact the process of functional specialization of the left fusiform region during the first several years of reading exposure. In this way, phonological processing deficits may disrupt the typical development of rapid and automatic word recognition ability.<sup>4,23</sup>

### Regions of Relative Overactivation Among Reading-Impaired Individuals

Finally, although the largest body of evidence has supported the idea that reading difficulties are characterized by a relative underactivation of left perisylvian and left

temporo-occipital regions in response to reading tasks, it should be noted that certain investigations have reported regional patterns of atypical *overactivation* in response to reading, as well. For instance, it has been reported that dyslexic adults show greater reading-related activity in the left inferior frontal gyrus than do non-impaired adult readers.<sup>26</sup> Although the opposite pattern has been shown in studies contrasting dyslexic and non-impaired children,<sup>31,66</sup> it has also been reported that reading-related activity in the left inferior frontal region is significantly correlated with age among children with dyslexia, whereas this is not the case for non-impaired children,<sup>31</sup> suggesting that increased activation in this region might occur following the atypical development of the classical reading-related regions. Other studies have observed that children who are poorer readers tend to show greater reading-related activity in right perisylvian regions, whereas this activation decreases as readers gain expertise.<sup>29,30</sup> Finally, it has been reported that individuals who were formerly reading-impaired as children but who ultimately demonstrated improved reading accuracy as adults show increased reading-related activity in both right perisylvian and frontal regions, relative to individuals who consistently demonstrated reading difficulties both as children and in adulthood.<sup>67</sup> It is tempting to conclude that reading-impaired individuals may recruit these regions as a form of compensatory activity, and that increased activation here reflects an alternative processing strategy. It should be noted, however, that other possibilities, such as a dysregulation of typical inhibition or lateralization could lead to a similar result. Thus, establishing that an atypical overactivation is functioning as a compensatory mechanism requires establishing a direct relationship with a function.

### SOCIAL FACTORS

Extensive work has shown that phonological awareness is causally related to reading ability. More recent investigations have begun to reveal the neurobiological bases of reading development, suggesting that phonological processing supported by the left perisylvian region is critical for the acquisition of visual expertise in recognizing words, supported by the left temporo-occipital region. To fully understand the neural bases of reading, however, it is imperative that developmental researchers, clinicians, and educators understand how a cognitive factor such as phonological awareness interacts with the background and experiences that a child brings to the classroom.

Socioeconomic status (SES), most commonly indexed by a combination of education, occupation, and income,<sup>68</sup> is a strong predictor of reading ability.<sup>69–72</sup> It is often suggested that a major determinant of the relationship between SES and reading ability is the SES gradient in reading-related experiences, such as the home literacy environment, degree of early print exposure, and quality of early schooling.<sup>71</sup> That is, SES is highly predictive of both the quantity and quality of children's early reading-related experiences,<sup>69,73,74</sup> and these reading-related experiences are in turn predictive of reading skill.<sup>73,75</sup> Although abundant independent work has established clear evidence that

reading ability is highly associated with socioeconomic background on one hand, and with phonological awareness on the other, surprisingly few studies have examined how SES relates to phonological awareness in predicting individual differences in reading ability.

Recent work conducted in our laboratory has suggested that not only is reading ability affected by both phonological awareness and SES, but that these two factors actually work together to influence reading achievement, supporting a "multiplicative risk factors" hypothesis.<sup>76,77</sup> Specifically, at higher phonological awareness levels, children were generally found to decode novel words very well irrespective of socioeconomic background, such that SES differences were not associated with differences in reading outcome. At lower phonological awareness levels, however, SES differences were influential, such that most children from higher socioeconomic backgrounds were still reading relatively well, whereas many children from lower socioeconomic backgrounds were struggling. One possible interpretation of these data is that the greater access to resources associated with growing up in a higher SES environment can actually serve to buffer reading skills among children with lower phonological skill. These data further suggested that the mechanisms underlying poor reading in the context of a lower SES environment may be quite different from the mechanisms underlying reading difficulties that occur *despite* a higher SES environment. Unfortunately, although socioeconomic factors have been repeatedly associated with reading achievement, little investigation concerning the relationships between SES and the neurobiological systems that support reading has been reported.

In one study of a group of subjects who demonstrated a range of reading-related skills, clear associations were seen between reading skills and SES, as well as between reading skills and a measure of perisylvian neuroanatomy.<sup>38</sup> This suggested that both neural and social factors contribute to reading achievement. This study may be limited in providing insights about how neural and social factors work together in contributing to reading achievement, however. Given the well established association between reading achievement and SES, studies that are not specifically designed to represent a broad range of SES at each reading level typically confound the two factors, such that individuals with lower socioeconomic backgrounds are overrepresented within the lower reading levels, and individuals with higher socioeconomic backgrounds are overrepresented within the higher reading levels. Thus, in this study, the effect of SES was somewhat difficult to interpret. Interestingly, however, in the few cases in which children from different socioeconomic backgrounds demonstrated similar reading-related cognitive skills, a trend was present such that, within a given low reading level, lower SES children tended to show a typical neuroanatomical profile in the left perisylvian region, whereas higher SES children tended to exhibit an atypical profile. Again, this suggests that the mechanisms underlying poor reading might vary depending on the socioeconomic context. However, explicitly testing this possibility requires the recruitment of a socioeconomically diverse population with similar cognitive abilities.

Another study used functional magnetic resonance imaging (fMRI) to contrast the patterns of brain activity during reading-related tasks for two groups of adult readers who had tested in the reading-impaired range as children, and a third group of adults without any history of reading difficulty.<sup>67</sup> Of the adults with childhood reading disability, one group had subsequently demonstrated improved reading accuracy as adults (“Accuracy Improved Readers”), whereas the other group showed persistently poor reading skills (“Persistently Poor Readers”). When the three groups of adults were studied using functional neuroimaging, typically developing readers replicated the general pattern of activity reviewed above: reading-related tasks resulted in increased recruitment of the left perisylvian and left temporo-occipital regions. Somewhat paradoxically, the Persistently Poor Readers activated a pattern of brain regions very similar to that seen in the typically reading adults. In contrast, the Accuracy Improved Readers demonstrated results that are most typically reported for dyslexic adults: underactivation of left perisylvian regions relative to typical adult readers. This group of readers also demonstrated other regions of atypical overactivation compared to typical readers, including right perisylvian and superior frontal cortices, potentially reflecting compensatory neural systems that supported their improved accuracy in reading tasks.

On the surface, these results may appear paradoxical. After all, why should those with persistent symptoms of reading impairment fail to show the typical neural pattern of dyslexia, and conversely, why should those with somewhat remediated symptoms of reading impairment continue to show the typical neural pattern of dyslexia? Considering the socioeconomic context in which these two groups of reading-impaired individuals were identified provides additional insights into differences in the brain activity patterns between the Accuracy Improved and Persistently Poor Readers. A key socioeconomic difference was present between the two groups of adults identified with childhood reading disability: compared to never-impaired adults, the Persistently Poor Readers were significantly more likely to come from a disadvantaged school, whereas the Accuracy Improved Readers were not. These findings thus suggest the possibility that an individual who is reading in the impaired range in the context of a more disadvantaged environment may demonstrate a typical pattern of functional activation when engaged in very elementary reading tasks. In contrast, an individual who demonstrates childhood reading impairment despite increased access to educational resources is more likely to demonstrate an atypical pattern of functional activation, even if compensatory strategies ultimately enable the individual to overcome difficulties in reading accuracy.

Although the results from these two studies were suggestive of the ways in which sociological and neurobiological factors may work together in influencing reading development, additional research is required to answer more specific questions about how such factors contribute to reading achievement and our basic understanding of the development of brain mechanisms that support the cognitive functions of reading. Recent work in our laboratory examined the degree to which the reading-related neural

activity seen in children exhibiting lower phonological awareness skills differed as a function of SES.<sup>78,79</sup> Children from the lower end of the SES continuum with lower phonological awareness skills were found to be more likely to exhibit typically reported brain-behavior relationships, such that during a simple word reading task, increased phonological skill was associated with increased activity in the left fusiform region, and with a trend toward increased activity in the left perisylvian region. In contrast, higher SES children with similar low phonological skill tended to demonstrate atypical brain-behavior relationships, including a reduced association between phonological awareness and activity in these regions, as well as increased associations between phonological awareness and activity in atypical (right perisylvian and superior frontal) regions. This suggested that socioeconomic background can modulate the relationship between phonological awareness and the neural response to reading in developing readers, rendering any study that examines the neural basis of reading development without accounting for SES somewhat limited in its interpretability. One possibility is that socioeconomic differences in literacy exposure and experiences could result in differences in familiarity with words or strategies used in decoding. These differences could in turn result in different brain-behavior relationships. Such hypotheses could be tested using a longitudinal interventional approach.

### A NEUROBIOLOGICAL APPROACH TO READING INTERVENTION

As stated earlier, many studies have provided behavioral evidence that interventions providing training in phonological awareness coupled with alphabetic decoding skills can benefit children with reading difficulties. Recent examinations of the neural effects of such behavioral studies provide a better understanding of how such programs improve skills. Several investigators have used neuroimaging techniques to follow brain changes in children over the course of an intervention.<sup>23,80</sup> As described below, the absence of appropriate control groups frequently limits interpretation of the specific cause of observed changes. However, these studies clearly demonstrate the plausibility of using brain imaging in children to quantify changes in processing that occur over several weeks to months of intervention, and suggest that patterns of brain activity associated with reading skills may prove to be quite malleable to directed interventional techniques.

One investigation used magnetic source imaging<sup>a</sup> to compare eight children with reading difficulties to eight children without reading difficulties, and then scanned the

<sup>a</sup>Magnetic source imaging (MSI), involves using magnetoencephalography (MEG) to measure the magnetic fields associated with electrical activity induced from neuronal firing, and coregistering this information with high-resolution magnetic resonance imaging (MRI), providing excellent temporal and spatial resolution. In contrast, the more widely used technique of functional magnetic resonance imaging (fMRI) measures oxygenation changes in blood flow that arise from regional differences in neuronal activity, providing similar spatial resolution, but much less precise temporal resolution (on the order of seconds vs. milliseconds).

reading-impaired children again following an intensive reading intervention program.<sup>30</sup> The non-impaired readers showed an increased neural response in the left superior temporal gyrus region while performing a reading task, while, prior to intervention, the children with reading difficulties did not. Following a two-month intervention involving over 80 supervised hours of phonological training with one of two commercial packages, the reading-impaired children's scores improved dramatically, rising from the severely impaired range to the average range on some untimed tests of accuracy. Furthermore, after intervention, these children showed increases in left perisylvian activity and decreases in right-sided activity in response to a reading task, thus demonstrating a functional activation pattern similar to that seen in typically developing readers. The eight non-impaired children who did not participate in the intervention demonstrated stable brain responses over the same time span. Importantly, however, this study did not include a reading-impaired control group, making it impossible to tell whether changes were specific to the intervention or simply the result of generic tutoring or even schooling effects. Another interpretive difficulty lies in the fact that prior to intervention, the reading-impaired children showed very low accuracy in performing the task during the scan. The changes in brain activity following the intervention may therefore have been due not to a change in brain function *per se*, but rather to the children's new engagement in a task to which they had previously not attended.

Another study also measured changes in functional activity in a group of reading-impaired children. Again, pre-intervention fMRI conducted while children performed a reading task indicated reduced activity in reading-related regions relative to children in a control group.<sup>81</sup> After the children in the experimental group participated in a six-week, forty-five-hour intervention, including a commercial computer-training program and a special school curriculum for children with dyslexia, their reading improved significantly. However, changes in their post-intervention pattern of functional activity were widespread, extending to a number of brain regions. Some regions included those typically thought to be involved in reading; however, others were not, and some regions also showed changes in the non-impaired group. Again, this study is difficult to interpret because it lacked a reading-impaired control group randomized to a different intervention. To further complicate interpretation, a separate randomized controlled study of more than 200 children in an urban school district provided the same intervention, but children receiving the intervention showed no gains in reading compared with a control group of reading-impaired children who did not receive the program.<sup>82</sup> This finding not only underscores the need for a reading-impaired control group in imaging studies, but also suggests that the strict adherence to an intervention required in the laboratory setting may not always be realistic in the classroom.

A third intervention study showed some evidence of changes in neuroimaging profiles for reading-impaired children following an intervention as well.<sup>83</sup> This intervention involved 28 hours of training that included activities

stressing the phonological, linguistic and comprehension aspects of reading, and resulted in a behavioral improvement in certain reading skills. Prior to intervention, children with reading impairment showed less reading-related activity in a number of general brain regions relative to non-impaired children. This widespread activation involving multiple brain regions suggests that the functional activation task was not terribly specific to reading processes. Following intervention, the impaired group showed no significant change in the left perisylvian or left temporo-occipital regions typically associated with phonological processing and reading. Although some differences in post-intervention activity were reported between groups across a number of other cortical regions, it was unclear whether such changes reflected increased activity in the impaired group or decreases in activity in the non-impaired group. The non-specific nature of the pre-intervention activation patterns, and the ambiguities in the changes that occurred following intervention, underscore the importance of well-developed and validated tasks to characterize intervention-based changes in activity.<sup>80</sup>

Finally, a recent study followed a group of children who received an experimental intervention consisting of fifty minutes a day of individual tutoring focused on phonological awareness and the alphabetic principle, and contrasted them with a "community intervention" group who received normal school-based remedial reading instruction.<sup>84</sup> The children were tested before and after eight months of intervention and were also compared with a control group of non-impaired readers. Following the intervention, children in the experimental group made significantly greater gains in reading fluency than did the community intervention group. They also showed a greater change in reading-related activation in perisylvian and temporo-occipital regions relative to the community intervention group. In addition, the experimental intervention group continued to show increases in activation in these regions for at least a year after the end of the intervention, relative to their pre-intervention levels of activation.

Together, these studies suggest that the brain regions typically involved in reading may prove to be quite malleable in reading-impaired individuals, in response to effective therapeutic interventions. Brain activation patterns in these regions can change dramatically over the course of relatively short-lived interventions. Through the rigorous use of control groups to examine both the behavioral efficacy and neural specificity of any intervention effects, as well as the use of validated tasks that are sensitive and specific to reading-related brain activity, we can successfully interpret the effectiveness of interventions. Ideally, improvements should be followed over time to verify that gains persist. Finally, interventions that succeed in the laboratory must be tested in real classroom environments before they can be widely implemented.

Importantly, the studies listed above all examined general changes across a group before and after intervention. However, it is not enough for an intervention to improve reading skills *on average*. Ideally, interventions should be tailored based on the needs of individual children. If, as we believe, similar low levels of reading performance may

result from different causes, then imaging the brain may help to tease such effects apart, extending our knowledge beyond the limits of behavioral data. We now have the ability to examine whether similar behavioral profiles associated with disparate risk factors might be rooted in different effects on brain development. In fact, it may be differences in brain development, rather than in behavioral performance, that ultimately predict an individual child's response to intervention. As reviewed above, preliminary evidence suggests that a child's socioeconomic background can fundamentally influence brain-behavior relationships.

This implies that reading achievement – and potentially response to intervention – is best predicted by combining information about social background and cognitive skill level. By taking this approach, we may one day be able to design interventions that meet an individual child's needs in ways that simple behavioral measures alone cannot.

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### *Literary Quotes*

#### **William Penn vs. William Penn**

*What happens to a son when his father, a major military figure, is absent during much of the boy's youth, is distant and unsupportive when at home, and at times is cruel. For example, when the son was expelled from Oxford for participating in unapproved religious gatherings there, he described “the bitter usage I underwent when I returned to my Father, whipping, beating, and turning out of Dores.” How favorable an outcome would we expect for this young man, William Penn (1644–1718), unless some ameliorating factors came into his life to counterbalance the effects of his father, Admiral Sir William Penn (1621–1670) and help him to redirect his considerable abilities?*

*Penn's biographer observes that the son as an adult had trouble relating to other adult males, and was not capable of maintaining continuous relationships, but he got along well with women, at least educated ones.*

*Nevertheless, we remember and revere him as the founder of the unique American colony of Pennsylvania, a refuge for Quakers and other seeking religious freedom, a truly remarkable achievement for 1682. “He conceived of and established a society without military defenses, with freedom of religion, with a criminal code humane beyond anything known to Englishmen with a written constitution containing guarantees of rights and checks on the power of the proprietor.” He deserves a more prominent place among our founding fathers like Jefferson and Franklin.*

*How was this outcome possible for a person with this background? Reports of the conditions of his complicated youth are sparse, but it is clear that he had several highly influential substitute role models of moral and purposeful behavior at college and later to replace his father, such as Dr. John Owen at Oxford and Thomas Loe in Ireland. Finally, just before he died, the senior Penn did communicate to the son that, although he could not approve of his Quakerism, he did respect his son's integrity and strength of character.*

*As citizens and pediatricians we occasionally observe examples of this good fortune of a nonfamily mentor helping a rebellious youth to refocus and redirect his or her life. Yet, we view many more situations into which we wish that such influences would enter but they do not.*

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*Submitted by William B. Carey, M.D.*