Dyslexia and Reading Problems

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Purpose of this paper

The purpose of this paper is to provide an overview of the recent literature regarding dyslexia and its relationship to reading and comprehension, working memory and other facets of executive function. Recent evidence exists indicating that cognitive training enhances executive function, working memory, and reading and comprehension and that sustained, reproducible physical changes in brain activity and structure may underlie these improvements. This review of dyslexia, reading, and the brain regions affected may help guide physicians, educators and other professionals in making recommendations to individuals with dyslexia and their parents who are interested in brain-based strategies to improve reading abilities.

Dyslexia and Reading Problems

Dyslexia is a brain-based type of learning disability affecting 5 to 17 percent of U.S. children that specifically impairs a person's ability to read (Shaywitz, 1998). In order to read, a child must be able to separate spoken words into smaller elements of speech (phonemes) and recognize that the letters in written words represent these sounds. This ability is largely missing in dyslexic children and can affect the development of reading comprehension skills as well as overall academic achievement. While there is variability in the manifestation of dyslexia, most people exhibit difficulty with phonological processing (the manipulation of sounds), spelling, rapid visual-verbal responding, and reduced vocabulary and strategies needed for reading comprehension (for reviews, see Gabrieli, 2009; Melby-Lervag, 2012).

Previously, criteria for identifying dyslexia focused on children with normal or above-average intelligence that struggled with reading and demonstrated a clear mismatch between their general cognitive abilities and their reading scores. Recent brain imaging studies suggest that this criteria is too restrictive and that children with lower IQ scores may also experience specific deficits associated with dyslexia that are not simply a byproduct of lower cognitive abilities (Tanaka, 2011). This study used functional MRI (fMRI) to measure brain activity by detecting associated changes in blood flow related to energy use by brain cells. They found that children who are poor readers have the same brain difficulty for the phonological processing of printed words regardless of IQ score. Poor readers uniformly demonstrated reduced brain activity in six regions compared to average readers, indicating that a common neural mechanism underlies dyslexia and reading difficulties independent of cognitive ability.

The independence of IQ is further supported by studies showing that children with higher and lower IQ scores can benefit from reading interventions (Stuebing, 2002; Vellutino, 2006). Based on this information, the percentage of dyslexic children may actually be higher than the frequently quoted 5 to 17 percent. Thus, a greater number of children have the potential to benefit from reading interventions, which offers hope to more families, but potentially taxes an already over-burdened educational system. Independent reading and cognitive intervention programs that focus on strengthening weak skills are one resource for families struggling with dyslexia and whose needs may exceed what is realistically available in the everyday classroom setting.

Brain Basis for Dyslexia

While the causes for dyslexia remain an area of intense investigation and some controversy, there is a growing body of evidence indicating differences in specific brain regions and cortical connections in children struggling with dyslexia (Gabrieli, 2009; Heim, 2010; Blau, 2010; Kovelman, 2011; Vandermosten, 2012) and reading comprehension (Friederici, 2011). Auditory processing, visual processing, and working memory are cognitive functions that can be localized to specific brain regions implicated in dyslexia. Additionally, several genes have been implicated in reading ability and brain activation in language-related regions (Darki, 2012).

This focus on brain areas involved in dyslexia has been driven, in part, by the knowledge that neuronal connections are not static, but capable of changing throughout the life span (for review, see Rabipour and Raz, 2012). Changes in cerebral blood flow, neuronal activity, and myelination have been documented using high resolution imaging processes, including fMRI, diffusion tensor imaging (DTI), which allows visualization of brain white matter architecture in response to a broad range of stimulation, and electroencephalography (EEG). Indeed, research focused on brain plasticity and its implications for the improvement of dyslexia and reading comprehension has exploded in recent years in the fields of neuroscience, cognitive psychology, and education with mounting evidence that exercises designed to strengthen reading deficits correlate with physical changes in the brain. These studies may help identify dyslexic children before they are even capable of reading (Raschle, 2012; Franceschini, 2012) and may also predict which children have the highest potential to benefit from reading programs (Hoeft, 2011; McNorgan, 2011). Because reading is such a critical skill that must be acquired early in the education process, early interventions designed to remediate these known deficits based on physiological and biological data have the potential to be the most successful.

The Learning Model and Reading Improvement

Reading, perhaps more than any other academic challenge, depends on strong cognitive skills for consistent success. Among these critical skills are attention, working memory, auditory processing, and visual processing. These and other intellectual functions are collectively referred to as executive functions and can be clustered into several different measurable domains based on the Cattell-Horn-Carroll (CHC) theory of intelligence, the most researched and widely accepted theory of the composition of intellectual abilities (Cattell, 1941; Horn, 1965; Carroll,1993).

The Gibson Test of Cognitive Skills is a comprehensive assessment of these cognitive abilities. The test measures strengths of key cognitive skills and help identify areas of weakness that might benefit from cognitive training and improve reading ability:

- *Attention (three types):* Sustained attention is the ability to stay on task; selective attention is the ability not to be distracted; divided attention is the ability to handle more than one task at a time.
- *Short-Term (Working) Memory*: The ability to apprehend and hold information in immediate awareness while simultaneously performing a mental operation.
- *Processing Speed*: The ability to perform automatic cognitive tasks, particularly when measured under pressure to maintain focused attention.

- *Logic & Reasoning*: The ability to reason, form concepts, and solve problems using unfamiliar information or novel procedures.
- *Visual Processing*: The ability to perceive, analyze, and think in visual images.
- *Auditory Processing (Phonemic Awareness):* The ability to analyze, blend, and segment sounds.
- *Long-Term Memory*: The ability to recall information that was stored in the past.

A goal of cognitive training programs for dyslexic individuals is to enhance weak cognitive abilities that will ultimately result in sustained reading improvements. Studies demonstrating effects of cognitive training often focus on a small subset of cognitive domains and significant effects have been demonstrated in one or more areas, including working memory, auditory and visual processing and/or word attack skills. Two recent studies clearly demonstrate that intensive cognitive training can improve phonological decoding (Keller, 2009) and reading comprehension abilities (Meyler, 2008), which are especially important as reading for meaning is the purpose for learning to read and the basis for general knowledge acquisition.

Executive function is based primarily in the prefrontal regions of the frontal lobe, although visual and auditory processing tasks also invoke activity in the occipital and auditory lobes, respectively (Alvarez, 2006). Neuroimaging research indicates that tasks specific to reading engage a left-hemispheric network of frontal, temporoparietal and occipito-temporal cortical regions that may underlie the ability to link the visual perception of letters and words onto auditory and conceptual representations (see Vandermosten, 2012 and references therein). Imaging and electrophysiological studies indicate brain activity and connectivity differences between dyslexic and non-dyslexic children. Intensive cognitive training can enhance the activity in brain areas associated with weak reading skills and these biological changes are measurable up to a year following intervention. Changes in the gray matter volume have also been documented in dyslexic children following reading interventions. Details on specific cognitive skills, interventions and the involvement of brain areas in dyslexia are summarized in the following sections.

Reading and Auditory Processing

Auditory processing is the ability to analyze, synthesize, and discriminate auditory stimuli, including the ability to process and discriminate speech sounds that may be presented under distorted conditions. It is a complex ability that includes phonemic awareness, discrimination between tones, and tracking auditory temporal events. Central Auditory Processing Disorder (CAPD) is an umbrella term referring to a group of disorders linked to disruptions in the ways that the brain processes auditory information (Miller, 2011). These disorders are associated with deficits in listening, selective attention, auditory memory and sound-blending skills.

There is evidence of the coexistence of CAPD and dyslexia (King, 2003; Sharma, 2009), and auditory processing deficits are linked with phonological coding and phonemic awareness (Veuillet, 2007). Electrophysiological data also indicate differences in auditory processing in dyslexic individuals. Event-related potentials (ERPs) can be measured noninvasively using scalp electrodes to examine localized changes in brain activity. In individuals with dyslexia, the amplitude of the ERP is diminished compared to normal individuals in response to fluctuations in sound intensity, speech sound features, and sound frequency, which are all indicative of auditory processing problems (for reviews, see Schulte-Körne, 2012; Hämäläinen, 2012). Recent evidence further suggests that this weakness in language learning extends to the recognition of human voices (Perrachione, 2011).

Functional neuroimaging studies of phonological awareness using purely auditory tasks in the absence of visually presented materials show brain activation in the left dorsolateral prefrontal cortex (DLPFC) in normal readers, a region important for spoken language (Kovelman, 2011). The tasks included a rhyme task that required participants to listen to a pair of words and decide if the endings were identical or not and a match task that asked whether two words were identical or not. Activation was also observed in the bilateral superior temporal gyri, left insular, right insular cortex/frontal gyrus, medial frontal, and bilateral occipital/cuneus regions, other regions involved in phonological awareness. In contrast, children with dyslexia showed markedly reduced activation in the left DLPFC, but greater activation in a right temporoparietal region than normal readers. This area is thought to be critical in sensory-motor integration of speech and may represent a neural compensatory mechanism caused by the greater processing and attention demand in children with dyslexia.

Other fMRI studies support the involvement of the superior temporal gyrus and left posterior temporal and parietal regions with different reading and speech tasks, indicating that a common network underlies the development of phonemic awareness and phonological skills that is disrupted in individuals with dyslexia (Blau, 2010, Gabrieli, 2009). Diffusion tensor imaging studies that measure differences in white matter tracts and neural connectivity also demonstrate lower activity in these temporoparietal regions in dyslexic individuals (Vandermosten, 2012).

There is a vast literature focused on management and possible remediation of auditory processing because of the profound effects that disorders of this system have on daily functioning and academic achievement (for reviews, see Musiek, 1995; Chermak 1992; Dawes, 2009; Fey, 2011). It has been suggested that management of auditory processing disorders should be comprehensive, integrating specific skills development and general problem solving strategies (Chermak, 1992; Chermak, 2002). Specific techniques, such as auditory memory enhancement, that integrate motor and spatial processes and use more working memory skills, have been shown to be effective in helping formulation and recall of important concepts (Musiek,1999).

Audiovisual training in reading-impaired children using a computer game consisting of abstract, nonverbal tasks that require audiovisual tracking resulted in measurable changes in reading skill tests as well as in electrophysiological measures in the region of the frontal lobe (Kujala, 2001). This training was associated with immediate brain changes and enhanced reading skill and speed, but no changes in performance IQ and no data supporting lasting changes over time. In another type of auditory training task involving frequency discrimination, improvements were demonstrated within 5 training sessions (over one week) with neuroimaging data identifying regions of the auditory cortex altered following the training (Jancke, 2001).

More recent work indicates that intensive phonologically based reading instruction increases both reading ability and activation in the left parietotemporal cortex as might be predicted based on the reported brain activity deficits in poor readers (Shaywitz, *et al*., 2004; Temple, 2003). Extended remedial instruction for 100 hours improved sentence comprehension and increased cortical activation in dyslexic children to near normal levels (Meyler, 2008). These striking changes persisted up to one year following training, suggesting that reading programs targeting the skills associated with these weak areas of activation may have profound and lasting effects. Another neuroimaging study using diffusion tensor imaging, a measure sensitive to axonal density, size, myelination, and structural integrity of white matter, indicates increases in white matter density following intensive remedial instruction of poor readers (Keller, 2009). Their results noted an increase in the myelination in a frontal lobe region that differed between good and poor readers prior to the intensive reading intervention. This neural pathway may mediate the enhanced brain activation in cortical regions involved in auditory processing and reading ability.

Reading and Working Memory

Working memory is the capacity to maintain and manipulate information in the presence of distraction and is directly related to the ability to hold attention. It is a system to actively hold information when needed for verbal and nonverbal tasks, such as reasoning and reading comprehension, and to make them available for further processing. Neuroimaging studies have identified prefrontal regions of the frontal lobe and superior parietal regions with working memory (Wager, 2003). Atypical activations in dyslexia are found in these brain regions associated with verbal working memory, and working memory deficits have been associated with language impairment (Montgomery, 2003; Montgomery, 2010). When performing a working memory n-back task, dyslexics had poorer performance related to controls. Corresponding fMRI data from this study indicate reduced activation in prefrontal and parietal cortices, further supporting a role for working memory deficits in dyslexia (Beneventi, 2010).

Although the direct connection between reading and working memory is not fully understood, it is thought that working memory deficits could make phonological decoding and reading comprehension much slower and more difficult since there is a reduced ability to store and manipulate information quickly (Montgomery, 2003). Strong correlations between working memory and phonological awareness suggest that working memory is a critical component of reading ability (Rohl and Pratt, 1995). Following eight-week training focused on mental imagery, articulation, and tracing of letters, groups of letters, and words, dyslexic children exhibited improvements in reading skills and increases in gray matter volume in regions associated with memory, including the left anterior fusiform gyrus/hippocampus and right hippocampus (Krafnick, 2011).

Working memory is a basic cognitive skill that is critical, not only for reading comprehension, but for a broad range of cognitive abilities. Numerous studies target working memory for cognitive training to enhance overall academic performance (for review, see Rabipour, 2012). For individuals with dyslexia, intervention strategies that target weak cognitive abilities and enhance working memory along with specific word decoding skills may be more effective than interventions focused exclusively on phonemic awareness.

Reading and Visual Processing

Visual processing is the ability to perceive, analyze, and think in visual images. Visual attention is the process by which the brain filters salient visual information from distracting information to further analyze. In addition to auditory processing deficits, considerable evidence supports the involvement of visual processing and attention deficits in dyslexia (for reviews, see Wright, 2009; Schulte-Korne, 2010). For example, the "magnocellular hypothesis" of dyslexia posits that a deficit in the visual magnocellular pathway relaying information from the retina to the visual cortex to the posterior parietal cortex is characteristic of dyslexia. This pathway may contribute to the rapid integration of visual information while reading.

It is clear that there is heterogeneity of symptoms in dyslexic individuals and visual processing deficits may be involved in certain subgroups of dyslexic populations (Wandell, 2012). fMRI studies demonstrate that deficits resulting from visual attention and phonological processing can be dissociated into distinct changes in parietal lobe activity (Bosse, 2007; Peyrin, 2012). The visual deficits may contribute to dyslexia through a pathway that is independent of the phonological and auditory processing pathways. There is evidence suggesting that not only is visual attention crucial for reading abilities, but parietal visual attention functioning may actually be predictive of future reading difficulties (Franceschini, 2012).

Neurophysiological studies using ERP recordings as well as fMRI studies also support the importance of visual processing in dyslexia. ERP recordings near the occipitotemporal cortex reveal a slower processing rate in dyslexics, suggesting a weakness in the brain's visual processing systems (Schulte-Korne, 2010). fMRI studies targeting this same region of the ventral occipitotemporal (VOT) cortex show responses to single-word identification are smaller in poor readers compared to good readers. The Visual Word Form Area (VWFA) is a well-defined brain region in this VOT cortical area that is selective for the processing of visual words (Szwed, 2011). This region is thought to be important in the creation of a "visual dictionary" that allows for instant word recognition once a word has been learned (Glezer, 2009). The VOT and VWFA cortical regions may mediate the slower visual word processing observed in dyslexics and also the integration of the visual and phonological information essential to link word sounds to word images (Blau, 2010; Wandell, 2012).

Critical components of Effective Interventions for Dyslexia

Early theories regarding the cause of dyslexia centered on phonological awareness and decoding skills related to deficits in auditory processing. Behavioral and biological research strongly supports a role for auditory processing in dyslexia, and interventions focused exclusively on improving phonemic awareness can improve reading fluency and enhance brain activity. Shaywitz (2004) used an intensive phonologically-based individual tutoring program for 8 months and demonstrated increases in left occipitotemporal activity that was sustained for a year after the intervention. As noted earlier, intensive interventions by Meyler (2008) and Keller (2009) produced lasting behavioral and neurological improvements, demonstrating that prolonged and intense stimulation of neural pathways strengthen connections mediating aspects of reading. A number of other intervention programs also focus on phonological awareness and improvement of auditory processing, but the problem of dyslexia remains, suggesting that this strategy is effective in some cases, but overall is not sufficient.

Intervention strategies employing visual and audiovisual tasks have also had limited success in improving function in dyslexic children. In one study, dyslexics were trained on a computerized game that used abstract, nonverbal tools and required 'audiovisual mapping' (Kujala, 2001). The participants were tested on their ability to match a sound sequence to a visual pattern. After 7 weeks and 14 training sessions, the reading skill and speed was improved and corresponding brain activity changes were recorded by ERP. While these studies lacked longitudinal data, they do provide support for an intervention model that engages multiple processes, not exclusively phonological skills.

Other studies have revisited an older technique of Rapid Automatized Naming (RAN) as a simple task that invokes multiple components of reading and the underlying brain circuits (Norton, 2012). This review incorporates a broader view of the processes needed for effective reading interventions to include phonological interventions, processing speed tasks, and comprehension drills. While accentuating the importance of strengthening these weak cognitive skills, the article does not offer clear, practical approaches to remediation.

Recommendations for reading interventions for dyslexia and other reading problems have emerged based on a convergence of evidence from these and other studies. A common factor underlying the more successful interventions is an approach that is systematic, intensive, and sustained (Lyon, 2004). This makes behavioral and biological sense as any skill that is repeated is likely to improve over time and is mediated by the strengthening of neural pathways that are subject to this repeated stimulation. Successful reading is the result of the interaction between multiple brain regions through distributed neural networks. Based on mounting neuroscientific evidence, reading strategies should engage auditory and visual systems, working memory, comprehension skills, and executive functioning (Willis, 2009). As indicated above, most reading interventions are limited in their focus to a subset of these weak cognitive skills essential for reading success.

How BrainRx Programs Are Different from Other Interventions

The focus of BrainRx cognitive training programs, including the ReadRx program, is to strengthen underlying brain skills that are essential for reading and for learning, in general. The BrainRx system trains the student to develop the appropriate strategy to complete a given task through the structured experience provided by the training procedures (see www.BrainRx.com for more information). A synergistic “drill for skill” and metacognitive approach to developing cognitive skills provide the framework for a successful system achieving sustained results. This system employs all of the reading intervention recommendations noted above with a brain-based approach to reading.

Unlike other intervention programs, the BrainRx program doesn't make assumptions about the root cause of the reading difficulty. Instead, the program begins with the comprehensive Gibson Test of Cognitive Skills. Using the test results, weak areas are identified and targeted with intensive training programs. The BrainRx reading program includes the BrainRx cognitive training consisting of 24 procedures with over 500 levels available based on individual ability, with tasks becoming more difficult as training progresses. All cognitive skills are addressed, but the program can be tailored to meet individual needs and strengthen deficient areas.

Among the available intervention programs that seek to strengthen essential reading skills, the BrainRx program is unique in its demonstrated success at strengthening auditory processing, visual processing, and working memory skills as well as other executive functions. The reading program also incorporates ReadRx which focuses on auditory processing, basic and complex coding skills, fluency, comprehension, spelling, and writing. It is a comprehensive and intensive program that is continually being informed by the latest neurobiological and cognitive science research. It is not constrained by bias toward a phonological awareness or visually-focused approach, but recognizes the interconnectivity and interdependence of these neurobiological systems in the development of reading and comprehension skills.

The value of BrainRx intervention is that it invokes several cognitive domains and is supported by multiple studies utilizing this cognitive training methodology (BrainRx, 2017; Carpenter, 2009; Luckey, 2007; Marachi, 2006). Data collected from more than 2,000 children indicate that tasks emphasizing auditory or visual processing and requiring attention and reasoning throughout training have profound effects on cognitive abilities (Luckey, 2007). During 2009, 1,343 students in the ReadRx training program for less than six months gained between 2.5 and 3.2 years in age-equivalent reading skills. Percentile gains were measured in all cognitive areas associated with reading ability, including auditory processing, visual processing, processing speed, working memory, and general intellectual ability (BrainRx, 2017).

Another recent study utilizing cognitive training supports the importance of strengthening specific cognitive skills with evidence of excellent gains in post-training central auditory testing in children with CAPD (Jedlicka, 2008). Similar gains were reported in adults with Auditory Processing Disorders who also underwent the cognitive training tasks with improvements in filtered words, competing words and competing sentences.

Clearly, the BrainRx cognitive training program is highly effective in remediating deficits associated with dyslexia and reading problems through the use of intensive, repetitive models of training. As would be expected from using a prolonged intense approach, these changes in reading and cognitive abilities are sustained over time. Although the studies have not yet been completed, these changes are likely mediated through strengthened neural projections between regions in occipitotemporal and parietal cortices, as suggested by recent literature.

As parents, educators, and other professionals look for effective interventions for dyslexia and reading problems, it is essential to critically evaluate the programs and their basis in scientific knowledge. The BrainRx system provides an excellent resource as a uniquely multidimensional, multisensory program grounded in the most recent neuroscience research, regularly informed by an independent scientific advisory board, and supported by data from thousands of students who have benefited from the programs.

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