Brain Plasticity and Cognition: A Review of the Literature

Submitted by: Lori Bryan, PhD

Purpose of this paper

The purpose of this paper is to provide an overview of the recent literature regarding brain plasticity and its relationship to executive function, learning and cognition. Substantial evidence exists that cognitive training approaches to enhance executive function, cognition, learning, and memory can induce sustained, reproducible physical changes in brain activity and structure. This review of cognitive training and the brain regions affected may help guide physicians and other practitioners in making recommendations to their patients with executive function and other cognitive concerns or who are interested in the potential for enhancing existing functioning.

Background

In less than 20 years, an underlying tenet in neuroscience that the brain does not change beyond early childhood has undergone a radical shift. It has been demonstrated that not only can the brain change, but it is capable of doing so 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 functional MRI (fMRI), which measures changes in local blood flow, diffusion tensor imaging (DTI), which allows visualization of brain white matter architecture, in response to a broad range of stimulation, and electroencephalography (EEG). Significant changes in gray matter density have also been reported following practice of specific tasks, such as intensive, prolonged studying or playing the violin or piano. Indeed, research focused on brain plasticity and its implications for executive function and cognition has exploded in recent years in the fields of neuroscience, cognitive psychology and education, with mounting evidence that exercises designed to strengthen cognition correlate with physical changes in the brain. More recent studies hint that tasks that engage multiple aspects of cognition may engage common neural networks to induce “transferable” brain changes that are not limited to a single specific task (Jaeggi, 2011). This has tremendous implications for early child development, children and young adults with learning difficulties, adults seeking to enhance their cognitive skills to gain an ‘edge’ in the workplace, and even older adults concerned with memory changes and eventual loss of executive functions.

The Learning Model and Cognitive Training

Executive function is an overarching term that is inclusive of cognitive abilities such as attention, working memory, problem solving, logic & reasoning, inhibitory control, and multi-tasking. These and other intellectual functions can be clustered in several different measurable domains based on the Cattell-Horn-Carroll (CHC) theory of intelligence, the most researched and widely accepted of theory of the composition of intellectual abilities (Cattell, 1941; Horn, 1965; Carroll,1993). The concept of fluid intelligence (Gf), or fluid reasoning, comes from the CHC theory and is defined as the ability to reason abstractly and solve novel problems. A goal of cognitive training programs is to enhance weak cognitive abilities that will ultimately result in a more generalized change in fluid intelligence as Gf is highly predictive of educational and professional success (Rohde, 2007).

The Woodcock-Johnson Tests of Cognitive Abilities, Third Edition and the Woodcock-Johnson Tests of Achievement are the gold standards for comprehensive assessment of these cognitive abilities. These tests measure strengths of key cognitive skills and help identify areas of weakness that might benefit from cognitive training:

- *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.

This testing also generates a General Intellectual Ability (GIA) score, also referred to as general intelligence or IQ (Woodcock, 2001).

Studies demonstrating effects of cognitive training often focus on a small subset of these cognitive domains and significant effects have been demonstrated in one or more areas, including working memory, attention, processing and logic & reasoning. 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). Imaging and electrophysiological studies following cognitive training indicate that physical changes in the brain are associated with increases in these cognitive abilities and are detailed below.

Attention and Working Memory

Attention is broadly defined as the process of selectively concentrating on one aspect of the environment while ignoring surrounding, potentially distracting stimuli. 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. Neuroimaging studies have identified prefrontal regions of the frontal lobe and parietal regions with these functions (for reviews, see Fan, 2005; Raz, 2004; Raz and Buhle, 2006). Specifically, the dorsolateral prefrontal cortex, the anterior cingulate cortex, and the orbitofrontal cortex appear to comprise part of a neural circuit coordinating attention and information processing. Genomic mapping and cortical dopamine receptor binding data support a role for dopamine in this system (Fossella, 2002; McNab, 2009). Deficits in attention and working memory may involve weaker connections in these regions, thereby affecting academic performance and the ability to maintain focused behavior (for review see Rabipour and Raz, 2012). Consequently, attention and working memory have been targets for cognitive interventions and neuroimaging studies that demonstrate brain changes related to cognitive improvements.

For example, children with working memory deficits who engaged in a variety of working memory tasks in a computerized game environment daily in school for five to seven weeks demonstrated improvements that were sustained as long as six months following training on tasks targeted to working memory (Holmes, 2009). Similarly, another study using a computerized cognitive training protocol showed improvements in trained tasks of working memory and reasoning, but not to the unpracticed skill (Nutley, 2011). Another study combining fMRI with a face/scene working memory task identified enhancements in dorsolateral prefrontal cortex and parahippocampal place area activity that was correlated with increases in selection attention and working and long-term memory (Wendelken, 2011). Electrophysiological data also support brain changes associated with cognitive training. Event-related potentials (ERPs) can be measured noninvasively using scalp electrodes to examine localized changes in brain activity. In a study examining the effects of training on attention, changes in ERPs were documented following five days of training on 9 to 10 exercises (Rueda, 2005).

While most studies indicated show only “training to task”, rather than generalizable improvements in cognitive function, the changes in brain activity measured with several independent techniques indicate that brain plasticity underlies these changes. For individuals struggling with weak or declining cognitive abilities, there is neurobiological data to support cognitive training to improve aspects of brain function. As indicated in sections below, the cognitive training strategies used make a tremendous difference in how long changes are sustained and whether training for specific cognitive skills results in more globalized enhancements in intelligence and academic performance.

Processing Speed, Visual Processing and Logic & Reasoning

Processing speed, visual processing and logic & reasoning encompass cognitive skills that share the underlying neural circuitry of the prefrontal and parietal brain regions involved in attention and working memory. In addition, fMRI data supports the involvement of the lateral fronopolar cortex, the inferior parietal sulcus area, ventral and premotor cortex in cognitive tasks that involve decision making under pressure and distraction (Bunge and Wendelken, 2009). Visual processing is frequently involved as distinctions must be made between stimuli and visualization and imagery are part of many reasoning tasks and involves activation of occipital cortex (Haxby, 1991; Malach, 1995).

A recent study examining the effects of reasoning and processing speed training in children found that training specifically for each of these abilities led to significant improvements in those domains, but also small improvements in working memory and significant gains in fluid intelligence (Mackey, 2011). These results support the activation of a common neural network of executive function that is malleable with cognitive training. Importantly, the students were tested using standardized assessments to which they were not exposed during the cognitive training, suggesting that the cognitive training skills improved broader cognitive functioning. More intensive cognitive training approaches that engage working memory, processing speed, and logic & reasoning abilities suggest that some paradigms may generalize beyond task-specific skills and improve fluid intelligence (Jaeggi 2008; Jaeggi, 2011), a goal of most cognitive training programs. The cognitive training employed by Jaeggi, *et.al*. is limited in both its reproducibility and the long-term sustainability of the general intelligence improvements. However, these studies support the notion that interventions involving multiple cognitive domains may have greater potential for lasting, meaningful changes in fluid intelligence and overall academic functioning.

The value of interventions invoking several cognitive domains is further supported by multiple studies utilizing the LearningRx cognitive training system (Marachi, 2006; Carpenter, 2009; Luckey, 2009; LearningRx, 2011, Jedlicka 2012). Data collected from more than 2,000 children indicates that these tasks emphasizing auditory or visual processing and requiring attention and reasoning throughout training have profound effects on cognitive abilities (Luckey, 2009). The LearningRx system trains the subject to develop the appropriate strategy to complete a given task through the structured experience provided by the training procedures (see www.learningrx.com for more information). A synergistic “drill for skill” and meta-cognitive approach to developing cognitive skills provide the framework for a successful system achieving sustained results. The Woodcock-Johnson Tests of Cognitive Abilities, Third Edition, and the

Woodcock-Johnson Tests of Achievement, were used as standardized, norm-referenced tests that were independent of the training received by the students. Visual processing, long-term & working memory, and logic & reasoning are all enhanced with this training. Among the largest gains noted with this cognitive training system were evident in the tests related to auditory processing. Perhaps most striking, however, are the data that demonstrate significant gains in general intellectual ability (fluid intelligence) percentiles that are sustained one year following cognitive training (LearningRx, 2011).

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 also evidence that some forms of dyslexia may result from weaknesses in auditory processing, affecting their phonemic awareness (Veuillet, 2007).

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). A recent study utilizing the LearningRx cognitive training program 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 LearningRx cognitive training tasks with improvements in filtered words, competing words and competing sentences.

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 auditory training task involving frequency discrimination, improvements were demonstrated within five training sessions (over one week) with neuroimaging data identifying regions of the auditory cortex altered following the training (Jancke, 2001). Another neuroimaging study using diffusion tensor imaging, a measure sensitive to axonal density, size, myelination, and structural integrity of white matter, indicate increases in white matter density following intensive remedial instruction of poor readers (Keller, 2009). The pattern of their results suggests increased myelination in a region of the frontal lobes that differed between good and poor readers prior to the intensive reading intervention.

While this study is limited in its focus on word-decoding remediation, the finding that connections between brain regions can be influenced by cognitive training suggests that broader interventions may be effective in strengthening the neural circuits underpinning executive function and produce more substantial changes in overall functioning. The LearningRx cognitive training programs are highly effective in remediating deficits associated with auditory processing with intensive, repetitive models of training and sustained results that may be mediated through these strengthened neural projections between regions in the frontal lobes. Future studies that include neuroimaging data with cognitive training enhancements would help confirm this as the potential mechanism underlying the improvements.

Critical components of Effective Cognitive Training

Although substantial evidence supports the effects of cognitive training on brain plasticity, the concept of cognitive training remains controversial. This may be due, in part, to a lack of consistency between research studies and the cognitive training approaches used. For example, in the previous section, several studies demonstrating improvement and brain changes in auditory processing were mentioned, but there was not a common training program between the studies. Many cognitive training approaches demonstrate efficacy, but it is rarely transferable beyond the skill being trained. There is limited evidence that cognitive training programs result in changes in fluid intelligence, although some important exceptions were noted (Luckey, 2009; LearningRx, 2011; Jaeggi, 2011).

Two recent reviews summarize key components of effective cognitive training that can result in meaningful improvements in academic achievement and executive function (Green 2008; Diamond 2011). Specifically, learning paradigms where the learning is more generalizable are typically more complex involving attention, working memory, processing speed and decision making, and are not limited to one or two aspects of cognitive functioning. Frequently, existing cognitive training models and frameworks are limited to specific tasks and enhancements in the ability to perform these tasks.

Another key element to successful training seems to involve incremental increases in task difficulty to maintain interest and challenge the cognitive boundaries. Scaffolding techniques that provide additional practice and feedback enhance learning and transfer to novel situations (Ahissar and Hochstein, 2004). The LearningRx model is hierarchical and designed to target one or more specific cognitive skills with each task. The tasks repeatedly make demands on a person's processing abilities and progressively increase those demands. The repetition and increasing difficulty are based on the old neuroscience adage that "neurons that fire together, wire together", which is empirically supported by cognitive and neuroimaging studies, including those mentioned here that demonstrate changes in cognitive skills, brain activity and neuronal connectivity following intensive training.

Another potentially critical facet to a successful learning program involves feedback. Feedback to the learner may also influence how quickly tasks are mastered and cognitive skills are strengthened. An important component of the LearningRx training is the interactive nature of the sessions and feedback provided by the trainer to facilitate the learning of the student. The immediate reinforcement and feedback of both correct and incorrect responses is designed to enhance the student's learning and is also important for the sequential nature of the cognitive procedures. There is a wealth of information in the literature describing the brain systems underlying reward pathways and enhancement of dopaminergic activity. The precise relationships between these reward pathways, learning and plasticity have yet to be elucidated, but common neurotransmitter systems and brain regions are involved in these processes (Green, 2008) and may be part of the mechanism by which cognitive abilities are strengthened, reinforced, and sustained.

Aging and Cognitive Training

The benefits of cognitive training programs are not limited to children and adolescents. Brain plasticity has been documented throughout the life span with behavioral and neuroimaging outcome data to support the efficacy of interventions in healthy adults and older adults (for reviews, see Lustig, 2009; May, 2011; Rabipour, 2012). In older adults, cognitive decline associated with normal aging limits functional capacity and independence. Consequently, efforts to slow or reverse this process through cognitive training techniques have been an area of intense research.

Numerous articles support the efficacy of cognitive training in older adults where strengthening cognitive skills results in immediate as well as sustained improvements in these skills. For example, older adults with some cognitive deterioration were tested in a memory training program consisting of 14 one-hour training sessions. Compared to a control group, the trained older adults showed significant improvements on a working memory test immediately after the training and in a nine month follow up study (Calero, 2007). Using a cognitive training approach focused on auditory processing, the IMPACT (Improvement in Memory with Plasticity-based Adaptive Cognitive Training) study demonstrated generalized improvements in memory and attention in older adults (Smith, 2009). This approach incorporated intensive practice, focus on speed and accuracy, and feedback in the training. The improvements were not limited to a specific, trained task, but the long-term effects have not yet been examined. Similarly, adult students ranging in age from 18 to 87 years old trained on the LearningRx cognitive programs showed generalized improvements in function as indicated by an average gain of 13 IQ points following evaluation with the Woodcock-Johnson Tests of Cognitive Abilities (LearningRx, 2011).

In 2002, the ACTIVE (Advanced Cognitive Training for Independent and Vital Elderly) trial was launched and is the largest multi-center, randomized longitudinal study to date designed to test the effectiveness and durability of cognitive interventions (Ball, 2002). The ACTIVE study consisted of ten 60-75 minute sessions over a five to six week period focused on memory training, reasoning training, or processing speed training and the task difficulty increased over time. Each training program produced an immediate effect on the corresponding cognitive ability and, most notably, these effects were sustained over a two-year period. The ACTIVE study also looked at measures of independent living to determine whether the specific interventions might improve performance on instrumental activities of daily living (IADLs). There were not improvements on more generalized tasks, but the rate of *decline* was significantly lower than expected for the age of the tested population. In a follow up study on the ACTIVE participants five years after the initial training, older adults continued to demonstrate improvements on cognitive skills compared to controls (Willis, 2006). Those trained on reasoning skills reported less functional decline in self-reported IADLs than the control group, further supporting that cognitive training may help delay declines in daily functioning.

Other studies indicate that for an aging population, processing speed training may be the most useful and potentially transferable mode of training to successfully reduce decline in functioning and quality of life. Rather than using a self-report measure of IADLs, Edwards, *et al*. (2005) utilized an independent measure, the Timed Instrumental Activities of Daily Living test, and showed that training to a speed task also improved scores on this test. They suggest that processing speed training more closely simulates cognitively demanding daily activities. In another two-year follow up study on the ACTIVE population, the processing speed training intervention successfully reduced decline in a self-reported measure of health related quality of life compared to the untrained control group (Wolinsky, 2006).

In a pilot study to examine the effects of cognitive interventions on brain plasticity, Carlson, *et al*. (2009) engaged participants in a community-based service program, Experience Corps. Through this program, older adults assist elementary school teachers with literacy and library functions and other activities to bolster memory and executive functions. Functional MRI data before and after the intervention indicated increases in activity in the left prefrontal cortex and the anterior cingulate cortex, regions associated with executive function. These anatomical data directly correlated with behavioral improvements in executive function. Other training-dependent brain changes have been extensively reviewed by May (2011) and reflect changes in the prefrontal and parietal corticies in adults.

Conclusions

The revelation that physical changes in the brain can and do occur across the lifespan provides a biological basis supporting the use of high quality, effective cognitive training programs. Weak cognitive skills can be strengthened and, with the appropriate training, general intellectual ability can also be measurably improved. While these approaches had been limited in the past to children, there is mounting evidence that anyone can benefit from cognitive training, including children, young adults, and healthy or declining older adults. Thus, it is critical that the professionals with whom these struggling adults and children consult have the most updated scientific information to guide their recommendations and connect them with available resources.

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