American Psychologist

Training the Brain: Practical Applications of Neural Plasticity From the Intersection of Cognitive Neuroscience, Developmental Psychology, and Prevention Science

Richard L. Bryck and Philip A. Fisher

Online First Publication, July 25, 2011. doi: 10.1037/a0024657

Training the Brain

Practical Applications of Neural Plasticity From the Intersection of Cognitive Neuroscience, Developmental Psychology, and Prevention Science

Richard L. Bryck and Philip A. Fisher
University of Oregon and Oregon Social Learning Center

Prior researchers have shown that the brain has a remarkable ability for adapting to environmental changes. The positive effects of such neural plasticity include enhanced functioning in specific cognitive domains and shifts in cortical representation following naturally occurring cases of sensory deprivation; however, maladaptive changes in brain function and development owing to early developmental adversity and stress have also been well documented. Researchers examining enriched rearing environments in animals have revealed the potential for inducing positive brain plasticity effects and have helped to popularize methods for training the brain to reverse early brain deficits or to boost normal cognitive functioning. In this article, two classes of empirically based methods of brain training in children are reviewed and critiqued: laboratory-based, mental process training paradigms and ecological interventions based upon neurocognitive conceptual models. Given the susceptibility of executive function disruption, special attention is paid to training programs that emphasize executive function enhancement. In addition, a third approach to brain training, aimed at tapping into compensatory processes, is postulated. Study results showing the effectiveness of this strategy in the field of neurorehabilitation and in terms of naturally occurring compensatory processing in human aging lend credence to the potential of this approach.

Keywords: plasticity, training, intervention, developmental cognitive neuroscience

Supplemental materials: http://dx.doi.org/10.1037/a0024657.supp

To what extent are children's brains pliable and trainable? Moreover, what are the most effective techniques for training and shaping the brains of children to achieve positive and prevent negative outcomes? What are the advantages and disadvantages of laboratory-based versus ecologically grounded, family- and community-based approaches? Should we think of these approaches as alternatives to traditional psychotherapeutic techniques or as complementary approaches? At what developmental points are such programs most beneficially employed, and is there a point past which such programs are not likely to be effective? Are all brain systems equally pliable? If not, which show the greatest degree of plasticity in response to intervention? Last, are there circumstances under which we should be concerned about potential iatrogenic effects of intervention or training programs?

Although the answers to these questions are complex and, in many cases, unresolved, interest in children's brain plasticity and interventions that promote plasticity appears to be widespread and rapidly growing. Such interest exists among neuroscientists focused on understanding the basic science of brain development, developmental psychologists focused on the emergence of key competencies necessary for healthy adjustment over time, child psychologists and other clinicians focused on understanding and treating psychological disorders, prevention scientists and educators focused on designing effective programs for reducing risks and promoting resiliency in high-risk populations, and policymakers focused on allocating funding and resources for such programs. In addition, the media and general public appear to be intrigued by this subject, as indicated by the frequency with which the results of neuroscientific investigations of plasticity published in professional journals are being covered in the popular press. Furthermore, the burgeoning array of commercial products aimed at "brain fitness"—from online tutorials to computer software packages to object-based games—now available to the general public marks an important penetration of brain science into

Richard L. Bryck and Philip A. Fisher, Department of Psychology, University of Oregon, and Oregon Social Learning Center, Eugene, Oregon.

This research was supported by the following grants: MH059780 and MH078105 (National Institute of Mental Health, U.S. Public Health Service); HD045894 (Eunice Kennedy Shriver National Institute of Child Health and Human Development, U.S. Public Health Service); DA021424 and DA029320 (National Institute on Drug Abuse, U.S. Public Health Service); and R324A080026 (Institute of Education Science, U.S. Department of Education). We thank Matthew Rabel for manuscript editing.

Correspondence concerning this article should be addressed to Philip A. Fisher, Oregon Social Learning Center, 10 Shelton McMurphey Boulevard, Eugene, OR 97401. E-mail: philf@oslc.org

 0003-066X/11/$12.00
DOI: 10.1037/a0024657

Richard L. Bryck

the consumer marketplace.[1] Put simply, this is an important and much-debated topic.

In this article, we explore the state of the science in this area, with the goal of stimulating dialogue on the topic of training the brain in children, paying particular attention to how research in this area can inform current policy and shape prevention and intervention programs for high-risk children and their families. We focus on efforts to train cognitive control (commonly referred to as executive functioning [EF]), reviewing evidence from the two approaches employed in this area among children with attention-deficit/hyperactivity disorder (ADHD) and children who manifest neurodevelopmental difficulties as a result of exposure to early stressful environments: (a) laboratory-based studies that directly train specific neurocognitive processes and (b) ecologically based interventions informed from a neurobiological perspective. We concentrate on studies that provide instructional training rather than rote, unguided learning via repetition only. We then speculate on a possible third route to brain training in children that is grounded in neurorehabilitation and adult aging research: utilization of compensatory neural processes. Finally, we consider the future directions for this work.

Human Neural Development and Plasticity

Much of the current state of knowledge about neural plasticity in children is embedded in the science of brain development. Until the advent of modern neuroscience, conventional wisdom held that brain development was largely complete relatively early in life, perhaps owing to appreciable anatomy: The human brain has reached approximately 90% of its adult weight by early childhood and changes very little in size after age five (Durston et al., 2001; Reiss, Abrams, Singer, Ross, & Denckla, 1996). However, the results from histological postmortem studies on humans and nonhuman primates and from in vivo imaging studies have provided strong evidence that human brain development is far from complete by early childhood. In fact, dynamic and continuing changes in brain architecture occur throughout the course of development. For example, in humans, the ratio of gray matter (unmyelinated neurons) to white matter (myelinated neurons) changes dramatically from birth through adulthood, particularly in the cerebral cortex. Gray matter density follows a nonlinear trend of initial growth during early childhood, with a subsequent decrease in density during adolescence and young adulthood. Further, regional differences exist such that primary motor and sensory areas tend to mature the earliest in development, with higher level association and multimodal areas (e.g., the dorsolateral prefrontal cortex and the superior temporal gyrus) reaching adult levels the latest (Giedd, 2004; Gogtay et al., 2004; Reiss et al., 1996). White matter volume conversely follows a steady linear increase throughout childhood and up to adulthood (Giedd et al., 1999; Gogtay et al., 2004).

The inverse relationship seen between decreases in gray matter and increases in white matter has been postulated to reflect both synaptic pruning (loss of gray matter) and increased myelination (the formation of glial support cells); this pattern is thought to be due to a combination of loss in redundant or unused connections and the strengthening of relevant connections based on environmental input and experience (Huttenlocher, 1990). Functionally, these dynamic changes in brain architecture most likely reflect increased neural efficiency and faster network connections that parallel the behavioral changes observed during development.

As with physical development, brain development is genetically programmed. Although there are individual differences in the exact timing of this programming, there is a great degree of invariance in the sequence of maturation of particular brain regions for typically developing individuals. For example, auditory and visual regions mature early, language later, and higher order cognitive functions later still. However, the maturing brain is also strongly influenced by experience in the prenatal, childhood, and adolescent developmental periods; further, there is increasing evidence that brain development continues throughout adult life. This has led to the characterization of the extent to which the environment affects neural development in terms of the idea that experience shapes the architecture of the developing brain (National Scientific Council on the Developing Child, 2007). Indeed, it is within this experiential sculpting process that the plasticity of the developing brain might best be understood.

[1] It should be noted that many of these products are not based on a solid neuroscience framework; further, empirical evidence supporting the efficacy of some of these programs has recently been called into question (Owen et al., 2010).

Philip A. Fisher

Many of the early scientific demonstrations of neural plasticity highlighted the changes in the brain induced from deprivation of normal, experience-expectant stimulus input. For example, Wiesel and Hubel (1963) demonstrated the effect of profound sensory deprivation on the development of the visual cortex. In these experiments, kittens underwent monocular deprivation (i.e., one eye sewn shut) during a critical period of visual development. Normally, this interval (age four weeks to three months) corresponds to a period of preprogrammed ocular dominance column formation, in which alternating bands that are preferentially sensitive to input from either eye form in the primary visual cortex. In the case of monocular deprivation, however, profound visual impairment was seen after the deprived eye was reopened. However, these effects were not seen if the deprivation occurred later (i.e., age three–four months; Hubel & Wiesel, 1970). At the physiological level, the ocular dominance columns representing the deprived eye failed to develop and appeared to be replaced by the columns representing the nondeprived eye. This suggests that cortical areas are able to represent the winner of competitive interaction between environmental inputs received, at least during certain critical periods, rather than preprogrammed representation only (LeVay, Wiesel, & Hubel, 1980; Wiesel & Hubel, 1963). The results from these studies provided evidence of the profound ability of the brain to alter so-called hardwired connections as a result of subsequent environmental experiences, demonstrating for the first time the remarkable plasticity of the brain.

Much of the early evidence for neural plasticity came from sensory deprivation experiments using animal models, but parallel studies of plasticity in humans could not employ such methods for obvious reasons. Instead, scientists have relied on experiments of nature. An indication of the profound malleability of the human brain is given in the following examples. Neville and Lawson (1987) showed that, compared with individuals with normal hearing, individuals with congenital deafness exhibit an early attention effect when tracking motion presented in the peripheral visual field. Similarly, Bavelier et al. (2000) conducted a neuroimaging study that revealed greater activity in the motion-sensitive portion of visual cortex (the middle temporal cortex) among participants with congenital deafness than among participants with normal hearing when tracking motion. Similar results have been obtained with individuals with congenital blindness in response to auditory stimuli (Röder et al., 1999). Individuals who are deaf have also been shown to have tactile ability superior to that in nondeprived control samples; further, the primary visual cortex has been shown to be activated when participants who are blind perform tactile discrimination tasks, such as reading Braille (Levänen & Hamdorf, 2001). Thus, these results demonstrate cross-modal plasticity. That is, the blind or deaf participants showed enhanced use of brain regions typically associated with the deprived sense, suggesting that the cortical areas involved in a particular sensory modality, if unused, may be recruited by neighboring cortical areas (Pascual-Leone, Amedi, Fregni, & Merabet, 2005).

Negative Consequences of Neural Malleability

Neural plasticity facilitates healthy development across a vast continuum of rearing conditions and might help to account for resiliency even when children experience nonoptimal parenting or conditions of social and economic adversity. However, adaptive neural plasticity might also represent vulnerability under certain circumstances. In particular, there is increasing evidence that exposure to stress at levels that overwhelm the organism's ability to manage that stress may negatively affect brain development (P. A. Fisher & Gunnar, 2010).

For example, there is over half a century of research evidence involving animal models that stressful rearing environments are associated with changes in key neural regulatory systems (Levine, 2005). Evidence from parallel studies in human populations has documented similar effects. Research findings involving children reared in institutions in developing countries, which offer extremely neglectful early care, have shown long-term alterations in brain development (Pollak et al., 2010). Converging evidence has been obtained in studies of maltreated children (Cicchetti, Rogosch, Gunnar, & Toth, 2010) and foster children (P. A. Fisher, Gunnar, Dozier, Bruce, & Pears, 2006). Notably, stressful experiences do not have to be extreme to alter the course of brain development. Shonkoff, Boyce, and McEwen (2009) noted that one pathway for stress effects over time might be cumulative in nature (i.e., allostatic load) and that chronic exposure to moderate stressors might result in changes in the developing brain. In a review of the literature in this area, P. A. Fisher and Gunnar (2010) noted that the timing (especially in the first 24

months), duration, and severity of stress might require consideration by those examining the association between early adversity and alterations in brain development.

Intervention Efforts to Promote Neural Plasticity

If negative life events, such as early stress, can alter and remodel brain development, is the converse also true? Is it possible to leverage neural plasticity to promote healthy development and to remediate the effects of early stress via intervention efforts? Early evidence along these lines came from investigations of the effects of rearing rodents in enriched environments following exposure to early stress. In these studies, researchers have documented neuroanatomical changes after exposure to enriched environments, including increased brain weight and size, increased dendritic branching and length, changes in synaptic size and number, and behavioral improvements on long-term spatial memory tasks such as the Morris water maze and the T maze (see Nithianantharajah & Hannan, 2006; van Praag, Kempermann, & Gage, 2000). The two key components of an enriched environment seem to be complexity and novelty (Sale, Berardi, & Maffei, 2009).

Important questions arise, however, when attempting to apply these findings to humans. Certainly, the animal studies provide proof of concept that the brain is malleable in response to environmental intervention and that improved outcomes are possible following early stress. However, there is considerable cross-species variation in the rate of development. Moreover, the architecture of the human brain is vastly more complex than that of rodent brains, and the neural systems in which changes might be most desired in humans involve higher order cognitive processing. Thus, the limits, approaches, and effectiveness of interventions to promote positive neural plasticity in humans are uncertain.

It is worth highlighting the growing body of convergent animal and human literature that demonstrates beneficial changes in brain morphology and cognition after physical exercise. The findings from animal studies in rodents, for example, have consistently shown increased neurogenesis—the formation of new neurons—in the adult following induced or voluntary exercise.[2] Behavioral effects, such as improved acquisition and retention of spatial memory, have also been reliably observed in rodents after exercise (see van Praag, 2008); it should be noted, however, that there is insufficient evidence that the observed performance improvements result from exercise-induced neurogenesis (Hillman, Erickson, & Kramer, 2008; van Praag, 2008). Comparable effects of exercise on cognition have been found in human studies; in a recent review, Hillman et al. (2008) highlighted moderate but positive overall effects of physical activity on a range of child cognitive abilities, including academic performance. Similar findings in aging populations have shown beneficial relationships between exercise and various cognitive domains, particularly executive control (Colcombe & Kramer, 2003). Recent evidence indicates that exercise might also contribute to the continued plasticity of brain structures in old age. Erickson et al. (2011), for example, showed a gain in anterior hippocampus volume in a group of older adults who participated in a yearlong exercise regimen and a comparable loss in volume in those who practiced only stretching and toning. These changes in volume were positively related to changes in fitness level, blood levels of brain-derived neurotrophic factor (a putative mediator of neurogenesis), and improvements in a spatial memory task. Additionally, the results from functional neuroimaging studies have shown activation differences between physically fit individuals and their less fit peers in key control-related cortical areas (e.g., the dorsal lateral prefrontal cortex and anterior cingulate, areas implicated in the allocation of attention and conflict detection, respectively). Further, advancement in the field will no doubt be aided by the recent development of an in vivo imaging marker (cerebral blood volume) of exercise-induced neurogenesis in humans (Pereira et al., 2007). This literature is highlighted to illustrate an example of the profound neural and behavioral remodeling that can arise after accompanying environmental enrichment. Similar cortical plasticity is thought to occur following intense intervention or cognitive training regiments.

To capitalize on the adaptability of the brain, some of the earliest cognitive training researchers incorporated principles of cortical plasticity and basic neuroscience into their designs (e.g., the importance of competitive processes in driving change in neural networks). For example, basic research findings have implicated language-based learning impairments in children as a deficit in the temporal dynamics of auditory processing, so researchers devised a training program designed to improve basic perceptual processing (i.e., the spatiotemporal aspects of sounds) in young children diagnosed with language-based learning impairments. This program successfully improved speech discrimination and language comprehension abilities (Tallal et al., 1996). Similar plasticity-based training programs have proved effective at enhancing memory performance in older adults and verbal memory in individuals with schizophrenia (M. Fisher, Holland, Merzenich, & Finogradov, 2009; Mahncke et al., 2006).

Existing EF Training Paradigms

In this section, we review the major findings from brain and cognitive training and intervention studies to shed light on questions about the potential and limits of training the brain. In particular, we highlight training programs and findings focused on EF, the cognitive processes that allow for the flexible selection of behavior based on internal goals or rules (e.g., Koechlin & Summerfield, 2007; Zelazo,

[2] Exercise is just one way neurogenesis can be promoted; other factors implicated in regulating new cell growth in adults include exposure to enriched environments and exposure to hippocampal-dependent learning (e.g., spatial navigation tasks).

Müller, Frye, & Marcovitch, 2003).[3] These processes include related but separate components such as updating representations in working memory, shifting between mental representations (cognitive flexibility), and inhibiting competing, prepotent representations or responses (Huizinga, Dolan, & van der Molen, 2006; Miyake, Friedman, Emerson, Witzki, & Howerter, 2000). The anatomical basis of EF has been intricately linked to the prefrontal cortex in humans (Miller & Cohen, 2001). The development of EF follows a protracted course, with EF components emerging in infancy, exhibiting pronounced changes during the preschool period, and reaching full competency in adolescence or young adulthood (Carlson, 2005; Huizinga et al., 2006; Zelazo, Carlson, & Kesek, 2008). We chose to focus on EF for a number of reasons. First, EF deficits are one of the chief effects manifested in relation to early adversity. For example, researchers working with foster children (Lewis, Dozier, Ackerman, & Sepulveda-Kozakowski, 2007; Pears, Kim, & Fisher, 2008) and low-income children (Hackman & Farah, 2009) have found poorer performance on EF tasks in these high-risk samples. Second, the development of EF is clearly important to healthy adjustment in the context of family, school, peers, and community. Proficient EF capabilities play a critical role in a multitude of other domains, including theory of mind (Carlson & Moses, 2001), self-regulation (Blair, 2002), and long-term memory retrieval (Levy & Anderson, 2002). Additionally, EF deficits appear to be at the core of developmental psychopathologies such as autism (Ozonoff, 1995), ADHD (Pennington & Ozonoff, 1996), and substance abuse disorders (Giancola & Tarter, 1999). Thus, EF might be particularly susceptible to disruption yet amendable via training.

The current EF training methods generally involve two approaches: laboratory-based training and neurobiologically informed ecological interventions. Improvements on psychosocial, behavioral, and/or physiological measures have been demonstrated with both strategies, and each strategy has specific advantages, limitations, and implicit assumptions.

Laboratory-Based Training

Laboratory-based training approaches often involve repeated performance, typically computer-based, on speeded-choice tasks. These approaches tend to target a particular cognitive domain (often labeled a *specific process* or *direct intervention*) rather than take a *domain-general* approach aimed at improving overall psychosocial well-being, reducing behavioral problems, or reducing clinical symptomatology.

Improving working memory capacity, for example, has been the goal of several recent training studies in typically developing and developmentally delayed child populations. Targeting working memory ability, especially in children, is a naturally attractive goal, given the relationship between individual differences on measures of working memory and fluid intelligence in adults (Engle & Kane, 2004) in addition to the relationship seen between working memory scores and scholastic performance in children (Gathercole, Brown, & Pickering, 2003). Early researchers investigating training on working memory, however, found marginal improvements at best in working memory capacity (Kristofferson, 1972) or highly task specific improvements (Ericcson, Chase, & Faloon, 1980). However, perhaps owing to the recent development of more precise intervention techniques and/or measurement methods, promising results have begun to emerge. The results of these studies, as well as those targeting other EF domains, are summarized in Table 1. (Direct comparison of effect sizes from different designs and statistics in Tables 1–4 is cautioned against; Morris & DeShon, 2002. See supplemental materials for procedures and formulas for calculating effect sizes, additional demographics, and additional details on the studies listed in Tables 1–4.) As shown in Table 1, laboratory-based training intervention methods excel at enhancing specific neurobehavioral processes (or highly related processes) of interest, and some produce broader transfer of training effects. Further, the rigorous methodological considerations in these studies limit nuisance or confounding variables. Given the specificity of the processes targeted for improvement, the design and objectives of these studies are driven by relatively precise neurobehavioral theoretical bases.

The laboratory nature of the training in these studies inevitably raises questions of ecological or external validity and the generalizability of improvements. At present, there is only limited evidence that training on computerized, laboratory-based tests of specific cognitive abilities generalizes to real-world situations. Understanding of the degree to which cognitive improvement from such training applications enhances daily cognitive functioning is clearly needed. Similarly, little is known of the long-term effects of these training paradigms. Retest improvements have been shown over a matter of months in several studies (Holmes, Gathercole, & Dunning, 2009; Klingberg et al., 2005), but an understanding of the long-term efficacy of these methods is clearly needed to move beyond the proof-of-concept phase.

Moreover, questions remain as to how effective such training is for the extreme ends of the impaired EF spectrum. Although some researchers have investigated training effects with developmentally delayed populations, such as children with ADHD (see Table 1), little is known about the effectiveness of such training methods in populations demonstrating more severe behavioral, cognitive, or emotional deficits.

[3] Several of the studies reviewed here target the training of attention. On the surface, attention training might not seem to fit into the EF category; however, various types of attention have been hypothesized, including executive attention. The studies reviewed here contain components that can be categorized as training this type of attention and/or control over the allocation of attention and thereby broadly fitting the EF construct.

Table 1
Laboratory-Based EF Training Studies in Children

						Effect sizes					
Study	N_C	N_E	Age	Sample	Training domain	Category	Stat	Source	Type	Effect	Size
Rueda et al. (2005)	25[a]	24	4	Typically developing	Attention	IG p-p	*d*	C	N	small ↑ frontal ERP amplitude	
						IG p-p	*d*	C	F	↑ reasoning	0.82[b]
						IG p-p	*d*	C	F	↑ IQ	0.63[b]
Rueda et al. (2005)	12	12	6	Typically developing	Attention	IG p-p	*d*	C	N	↑ frontoparietal ERP amplitude	
						IG p-p	*d*	C	F	↑ vocabulary	
Thorell et al. (2009)	30[a]	17	4–5	Typically developing	Visuospatial WM	IG p-p	*d*	C	N	↑ spatial WM	0.41
						IG p-p	*d*	C	F	↑ verbal WM	1.40
						IG p-p	*d*	C	F	↑ attention	0.65
Karbach & Kray (2009)	42	14	8–10	Typically developing	Task switching	RM	*d*	R	N	↓ switch costs	~1.20
						IG p-p	*d*	C	N	↑ inhibitory control	0.44
						IG p-p	*d*	C	N	↑ working memory	0.60[c]
						IG p-p	*d*	C	F	↑ reasoning	0.49
Stevens et al. (2008)	13	9	6–8	Typically developing	Language via attention	IG p-p	*d*	C	N	↑ receptive language	1.43
						IG p-p	*d*	C	F	↑ attentional ERP amplitude	1.76
Stevens et al. (2008)	13	7	6–8	Specific language impairment	Language via attention	IG p-p	*d*	C	N	↑ receptive language	3.91
						IG p-p	*d*	C	F	↑ attentional ERP amplitude	6.73
Holmes et al. (2009)	20	22	8–11	Low WM	Verbal and visuospatial WM	IG p-p	*d*	C	N	↑ verbal WM	1.06[c,d]
						IG p-p	*d*	C	N	↑ visuospatial WM	1.20[c,d]
						RM	*d*	R	F	↑ math at follow-up	0.49[c,e]
Mackey et al. (2011)	11	17	7–9	Low SES	Fluid reasoning	IG p-p	*d*	C	N	↑ reasoning	1.32
						IG p-p	*d*	C	F	↑ WM	0.88
Kerns et al. (1999)	7	7	7–11	ADHD	Attention	RM	*d*	C	N	↑ attention	2.64[c]
						RM	*d*	C	N	↓ interference	3.06
						RM	*d*	C	F	↑ math	1.94
Klingberg et al. (2002)	7	7	7–15	ADHD	Verbal and visuospatial WM	IG p-p	*d*	C	N	↑ visuospatial WM	4.66[c]
						IG p-p	*d*	C	F	↑ reasoning	1.89
						IG p-p	*d*	C	F	↓ ADHD	1.44

Table 1 (*continued*)

Study	N_C	N_E	Age	Sample	Training domain	Effect sizes					
						Category	Stat	Source	Type	Effect	Size
Klingberg et al. (2005)	24	20	7–12	ADHD	Verbal and visuospatial WM	IG p-p	*d*	C	N	↑ verbal WM	0.68[d]
						IG p-p	*d*	C	N	↑ visuospatial WM	0.66[d]
						IG p-p	*d*	C	N	↓ interference	0.25
						IG p-p	*d*	C	F	↑ reasoning	0.18
						IG p-p	*d*	C	F	↓ ADHD	0.90[d]
Shalev et al. (2007)	16	20	6–13	ADHD	Attention	IG p-p	η^2	R	F	↑ academic achievement	0.15[c]
						IG p-p	η^2	R	F	↓ ADHD	0.29[c]

Note. Age is given in years. See supplemental materials for definitions and procedures for determining the effect sizes based on the parameters given in the original studies. EF = executive function; N_C = sample size of the control group; N_E = sample size of the experimental/training group; Stat = the effect size statistic given; IG p-p = independent groups, pre–post; *d* = Cohen's *d*; C = effect size value calculated; N = near (improvement on trained tasks or nontrained, structurally similar tasks); ERP = event-related potential; F = far (improvement on structurally dissimilar tasks); WM = working memory; RM = repeated measures, change within group; SES = socioeconomic status; ADHD = attention-deficit/hyperactivity disorder; R = effect size value as reported in the original study; η^2 = eta squared.
[a] Multiple control groups used, combined *N* given. [b] See note in supplemental materials for calculation of these effect sizes. [c] Average effect size calculated from multiple dependent variables measuring the same construct. [d] Effect stable at follow-up test. [e] Effect reported from follow-up test.

Neurobiologically Informed Ecological Interventions

Numerous researchers conducting more traditional, contextually based school- and family-centered prevention and intervention studies have demonstrated evidence of brain training via changes in behavioral and psychosocial functioning. Such ecological approaches acknowledge the importance of understanding the neural underpinnings of behavior, especially nonnormative behavior, as a critical factor in designing and implementing prevention and intervention paradigms. In discussing the rationale for these approaches, Blair (2002) argued that the extent to which children successfully navigate the transition to primary school depends on a set of social–emotional skills that are based in the EF neural substrates. These skills include self-regulation, effortful control, and working memory. Ecological interventions that target these domains typically integrate high rates of employing EF-based skills in school or family settings. Several of these interventions have resulted in impressive findings (see Table 2).

Ecological intervention approaches have a number of advantages over the laboratory-based training methods, in particular, real-world applicability. They are relatively easy to implement and require no special equipment. Moreover, because these approaches are conducted in real-world settings, the skills learned might be more likely to generalize to similar real-world contexts. In addition, these approaches appear to be effective with multiproblem children who might have fairly large deficits in the targeted intervention areas.

Despite these potential advantages, these approaches tend to be more intensive, longer lasting, and more costly than the laboratory-based training methods. In addition, inasmuch as many of these interventions consist of multiple components, it can be challenging to deconstruct and distill the effective components. In addition, these approaches are typically less specific with regard to the targeted brain systems. Although neural and biological indices of functioning are acquired, precise theories of how the interventions affect the underlying neural circuitry are often less well articulated. Isolating particular neurocognitive systems affected by such interventions is difficult in the context of these studies, in part because of their domain-general, multimodal natures. As such, one goal of future ecological interventions targeting EF is to more adequately identify the targeted neurocognitive systems.

A Promising New Approach

Given the limitations of the aforementioned approaches, we propose a third possible approach to brain training in this area: strengthening compensatory processes. Rather than being aimed only at restoring neurocognitive functions that are not operating optimally, this method is aimed at leveraging other neural systems to accomplish complementary cognitive and behavioral outcomes. As is shown below, this is not a novel concept in of itself; however, to our knowledge, this type of approach has not been employed as

Table 2
Neurobiologically Informed Ecological Interventions

Study	N_C	N_E	Age	Sample	Intervention	Effect sizes					
						Category	Stat	Source	Type	Effect	Size
Diamond et al. (2007)	62	85	5	Low SES	Self-regulation, play, memory, attention, and listening skills	IG post			N	↑ inhibitory control	
						IG post[a]			N	↑ EF	
							r	R	F	EF correlation with academic scores	0.41[b]
Raver et al. (2009)	218	231	3–5	Low SES	Teacher training: clear rules, monitoring, and positive reinforcement	IG p-p	*d*	R	F	↓ internalizing	0.76[b]
						IG p-p	*d*	R	F	↓ externalizing	0.59[b]
Tominey & McClelland (2011)	37	28	4–5	½ low SES	Playgroup games: attention, memory, and inhibitory control	IG post	*d*	C	N	↑ inhibitory control	0.69[c]
						IG p-p	*d*	C	F	↑ reading	0.44
Bruce et al. (2009)	24[d]	10	5–7	Foster care	Parent training and therapeutic playgroup	IG post	η_p^2	R	F	↑ feedback-related ERP amplitude	0.25

Note. Age is given in years. See supplemental materials for definitions and procedures for determining the effect sizes based on the parameters given in the original studies. N_C = sample size of the control group; N_E = sample size of the experimental/training group; Stat = the effect size statistic given; SES = socioeconomic status; IG post = independent groups, post; N = near (improvement on trained tasks or nontrained, structurally similar tasks); EF = executive function; *r* = Pearson's product–moment correlation; R = effect size value as reported in the original study; F = far (improvement on structurally dissimilar tasks); IG p-p = independent groups, pre–post; *d* = Cohen's *d*; C = effect size calculated; η_p^2 = partial eta squared.
[a] Measure not administered to control group. [b] Average effect size calculated from multiple dependent variables measuring the same construct. [c] Effect found in subset with low initial executive function scores. [d] Multiple control groups used, combined *N* given.

a therapeutic intervention for remedying EF deficits and other neurocognitive deficits in children.

Numerous neurorehabilitation therapies for patients with traumatic brain injuries are aimed at improving cognitive functioning by using strategic training techniques to offset rather than restitute lost functionality. In these approaches, the underlying neural systems supporting a given function are generally assumed to be damaged beyond repair. These approaches thus target dormant, complementary neural systems (i.e., redundant pathways) unaffected by the brain insult or wholly different brain systems capable of carrying out functions formerly handled by damaged brain regions. The conceptual models driving these approaches involve rerouting the neural circuitry so individuals learn new methods of handling old problems or goals. In general, these compensatory approaches target specific cognitive deficits incurred after brain damage (e.g., attentional, memorial, or visual abilities; see Table 3).

Other examples of compensatory processing are more spontaneous in nature. Recruitment of right hemisphere areas, homologous to left hemisphere language centers, has been shown to aid individuals with aphasia in recovering language function. It has been suggested that these right hemisphere activations reflect the recruitment of additional processes to support language recovery rather than the restoration of language functions per se (see Raymer et al., 2008). Similarly, neuroimaging researchers conducting aging studies have shown overactivation patterns (i.e., more diffuse activity) in the brains of older than of young adults during complex cognitive tasks. This distributed pattern in older adults is often seen as bilateral activity, often in the prefrontal cortex, homologous to the unilateral activity seen in young adults, and positive correlations between additional activity and performance have been reported. Such overactivation patterns have been demonstrated even when performance levels between groups were matched. The claim that increased activation is necessary for improved performance is supported by a pair of transcranial magnetic stimulation (TMS) studies. In one study, older adults performed more poorly when deactivating TMS was applied to either prefrontal hemisphere during a recognition memory task (older adults normally show bilateral activation in this task), whereas younger adults performed more poorly when deactivating TMS was applied to only one hemisphere (Rossi et al., 2004). Conversely, in a subgroup of low-performing older adults, activating TMS increased task performance. Moreover, the functional magnetic resonance imaging (fMRI) activation patterns in this low-performing group were more unilateral before and more bilateral after the activating TMS (Solé-Padullés et al., 2006), which is consistent with improved performance. Taken together, this evidence supports the *compensation account* of overactivation: Increased activation reflects neural processes that aid older adults during task performance (see Table 4; see Reuter-Lorenz & Lustig, 2005). However, bilateral activity during performance on inhibitory tasks has also been linked to poorer performance in older adults, suggesting that overactivation patterns might not universally indicate the presence of compensatory processing (Colcombe, Kramer, Erickson, & Scalf, 2005).

As is shown in Tables 3 and 4, compensatory or strategic processes can be effective remedies for ameliorating lost or degraded cognitive functioning. As such, this form of brain training should be further explored as a potential model to consider for application with vulnerable populations. One such compensatory strategy, broadly defined, might involve teaching self-verbalization strategies (i.e., using one's inner voice to stay on task) to children with attention or inhibitory control deficits. This strategy is based on the Vygotskian hypothesis that inner language helps to guide action, particularly during development, and on recent empirical evidence supporting the role of self-verbalization in the performance of demanding EF situations like task switching (Bryck & Mayr, 2005; Emerson & Miyake, 2003).

Valuable lessons can be gleaned from the aforementioned compensatory rehabilitation techniques when addressing severe early adversity (e.g., childhood physical and emotional trauma and neglect), which can greatly impact neurodevelopment. The results from neuroscience research are increasingly demonstrating the existence of redundant and complementary neural systems, making it plausible that similar compensatory systems could be tapped in children who have endured similar alterations in neural functioning. Much work is needed to tailor these training programs to meet the specific needs and impairments of vulnerable childhood populations and to design clinical trial examinations of the effectiveness of compensatory training in young and/or at-risk populations. Despite this, the compensatory processes brain-training approach is worth exploring, especially for individuals who are less responsive to more traditional intervention approaches.

Discussion

The findings from research on neural plasticity provide the impetus for interventions designed to reverse the effects of early adverse environments on child brain development, in particular with regard to EF. Although experimental evaluations of the impact of interventions on EF neural plasticity are relatively new, the research findings to date are promising. Laboratory-based training and neurobiologically informed ecological interventions have been shown to be efficacious and have great promise for improving outcomes for high-risk children. Moreover, enhanced outcomes may be obtained by hybridizing these two approaches.

Compensatory processes brain training has not yet been applied to prevention and intervention programs for high-risk children, despite its analogues in neural rehabilitation research. Such methods might prove to be efficacious on their own or as supplementary components appended to emerging methods with documented efficacy. It is clear that the structure and components involved in such approaches should be specified and evaluated.

In addition, there is a need for parallel development of innovative measurement methodologies. For example, examining fMRI activation on tasks known to recruit EF

Table 3
Neurorehabilitation Strategy/Compensatory Training Studies

Study	N_C	N_E	Age	Sample	Deficit	Strategy	Effect sizes			
							Category	Stat	Effect	Size
Niemeier (1998)	15	16	45–77	Stroke	Visual inattention/neglect	Visual imagery (sweeping eye movements)	RM	*d*	↓ visual search errors	0.91
							IG p-p	*d*	↑ attention	1.04
Kerkhoff et al. (1994)		22	16–77	Stroke	Homonymous visual field defects[a]	Compensatory eye saccades and visual search strategies	RM		↓ visual search errors	
							RM		↑visual search	
							RM		↑ activities of daily living	
Pambakian et al. (2004)		29	24–75	Stroke	Homonymous visual field defects[a]	Visual search	RM		↓ visual search time	
							RM		↑ activities of daily living	
Kaschel et al. (2002)	12	9	20–60	TBI	Memory	Visual imagery mnemonics	IG p-p	*d*	↑ delayed recall	1.17[b]
							IG p-p	*d*	↑ everyday memory	0.73[b]
Berg et al. (1991)	11	17	19–58	TBI	Memory	Making associations, organizing, and matching encoding and retrieval contexts	IG p-p	f^2	↑ acquisition memory	0.04[c]
							IG p-p	f^2	↑ delayed recall	0.06[c]
Fasotti et al. (2000)	10	12	18–45	TBI	Mental slowness	Decision planning, task management, and delineating tasks hierarchically	IG p-p	*d*	↑ memory	0.40
							IG p-p	*d*	↑ attention	0.52
van Heugten et al. (1998)		33	39–91	Stroke	Apraxia	Verbalizing the steps in an action	RM	*d*	↑ activities of daily living	1.30
							RM	*d*	↑ motor functioning	0.57
							RM	*d*	↓ apraxia symptoms	0.59

Note. Age is given in years. See supplemental materials for definitions and procedures for determining the effect sizes based on the parameters given in the original studies. All effect sizes were calculated. N_C = sample size of the control group; N_E = sample size of the experimental/strategy group; Stat = the effect size statistic given; RM = repeated measures, change within group; *d* = Cohen's *d;* IG p-p = independent groups, pre–post; TBI = traumatic brain injury; f^2 = Cohen's f^2.
[a] A loss of visual perception in one half of the field of vision. [b] Effect stable at follow-up test. [c] Effect reported from follow-up test.

Table 4
Overactivation Patterns of Activity in Senior Participants Reflect Compensatory Processing

Study	N_C	N_E	Age	Tasks	Results
Morcom et al. (2003)	14	14	63–74	Memory	Successful encoding activates left prefrontal cortex in young adults but homologous left and right prefrontal cortex in older adults
Cabeza et al. (2004)	20	20	70 (*M*)	Working memory and attention	In both tasks, older adults showed greater bilateral prefrontal cortex activity (compensation) and less occipital activity (sensory decline) than young adults did
Rossi et al. (2004)	37	29	50–80	Memory	↓ memory retrieval in older adults with disruptive TMS at the left or right prefrontal cortex and ↓ memory retrieval in young adults with disruptive TMS only at the right prefrontal cortex
Solé-Padullés et al. (2006)	19	20	67 (*M*)[a]	Memory	Preactivating TMS: unilateral activity. Postactivating TMS: ↑ bilateral activity and ↑ memory

Note. Age is given in years. Due to the complexity and descriptive nature of these effects, effects sizes are not reported. N_C = sample size of the control group; N_E = sample size of the experimental/senior group; TMS = transcranial magnetic stimulation.
[a] Participants demonstrated low memory scores at pretesting.

neural systems before and after the application of strategy training could be applied as a useful tool in determining whether, where, and how much compensatory processing has occurred as a result of the training. Similarly, employing measures of connectivity among regions of interest, in terms of both resting-state and task-related functional connectivity, is likely to be highly promising (see Fair et al., 2007). The hypothesis that compensatory mechanisms can be recruited to overcome early deficits in children with early adversity is an exciting and potentially highly rewarding avenue that necessitates exploration.

Limitations and Assumptions of Current Methods

There are consistent limitations seen across the methods of brain training reviewed here. Foremost among these is that a training regimen designed for a particular group or population can have limited success in dissimilar populations. The most straightforward solution is to tailor interventions or training protocols to the population of interest. Similarly, within any population, a large degree of variation in the deficits observed is likely, and there are inherent challenges in targeting particular skills or functions that might benefit only a subset of the targeted population.

Additionally, much of the work to date has been on preschool- and kindergarten-age children. Given the considerable behavioral and neural changes throughout the course of development, more work is needed to understand whether interventions of this nature (especially after services have ceased) are efficacious throughout development. The existing evidence to this end is limited. More data on the long-term persistence of these effects are needed to determine whether booster sessions would be appropriate. The efficacy of such booster sessions would require evaluation as well.

When considering the intended beneficial effects of these approaches for high-risk children, one must also examine the implicit assumptions made by each methodology. Laboratory-based approaches are generally aimed at improving functioning within one cognitive domain. Such research findings suggest that improvements in a given domain can mediate real-world improvements in classroom behavior and achievement or reduce psychopathology symptoms. The implicit assumptions are that strengthening a specific cognitive process via laboratory training allows for more efficient use of this pathway when it is called upon in ecological settings and that the given neural pathway has been strengthened. The problem with these assumptions is that few of the laboratory-based training studies have tested the potential positive effects of training outside of the laboratory, although some exceptions exist (e.g., Holmes et al., 2009; Klingberg et al., 2005; Klingberg, Forssberg, & Thomson, 2002; Shalev, Tsal, & Mevorach, 2007; Stevens, Fanning, Coch, Sanders, & Neville, 2008). Future training studies in children should include pre–post measures of academic achievement and teacher reports of classroom behavior to allow for an assessment of the potential broad effects training might induce in ecologically valid contexts.

The assumption that neural processing is somehow strengthened after training has been examined previously. For example, Olesen, Westerberg, and Klingberg (2004) found increased prefrontal activity resulting from working memory training in adults. Additionally, Rueda, Rothbart, McCandliss, Saccomanno, and Posner (2005) and Stevens et al. (2008) demonstrated evidence of enhanced neural processing after training via changes in event-related potential attentional components. However, more evidence is needed from neuroimaging studies to delineate the mechanisms behind these observed changes; for example, it is unclear whether training

results in stronger connectivity between regions, the recruitment of more diffuse neural areas, and more available cognitive resources or whether neural processing in a given pathway becomes more efficient after training. Collecting a full range of neural indices, such as resting-state connectivity patterns, electroencephalogram power and source localization analyses, fMRI activation, and regional connectivity analyses before and after training paradigms are implemented, could help answer such questions.

It might appear that neurobiologically based ecological interventions and laboratory-based training interventions make opposing assumptions because the generality of the former typically prevents defining the precise systems affected. For example, although EF deficits are thought to contribute heavily to classroom behavioral regulation problems and poorer academic performance, many interventions lack appropriate or well-defined markers of such deficits or the potential for improving them. Incorporating a working memory task known to activate the EF systems targeted by many of these interventions, for example, would allow for a pre–post estimation of EF change. Such a marker—particularly if it is a neural index—would support the claim that these systems are enhanced or might show that these systems are affected differently after the intervention than in normal populations (e.g., through the use of compensatory pathways to achieve the same result). Regardless, such knowledge is critical for developing efficacious brain training techniques.

A recent study, Mackey, Hill, Stone, and Bunge (2011; see Table 1), took a unique approach to training by incorporating aspects of laboratory-based and of ecologically based intervention methods. Computerized and noncomputerized games that required relational integration, the simultaneous processing of multiple relations between stimuli, were chosen. Relational integration is thought to be integral to fluid reasoning ability, which is a strong predictor of school performance. In this study, the children (age seven–nine; low socioeconomic status) participated in an eight-week session of fluid reasoning training or of processing speed training in a classroom setting where games were played individually and in groups. The children in the reasoning group showed significant improvement in the number of matrix reasoning problems, a measure of fluid intelligence, completed after training. This large effect is particularly impressive, given the widely held belief that fluid reasoning is a static trait that is not amendable to training (cf. Jaeggi, Buschkuehl, Jonides, & Perrig, 2008, for a similar training effect on fluid reasoning in adults). These results provide a first step toward integrating ecologically valid approaches with rigorous laboratory-tested methodologies to achieve promising changes in mental abilities.

Summary

Training the brain, specifically in at-risk populations, is a difficult undertaking with many factors to consider, including the program type for a given population, the skills or abilities to target, and the program cost and duration. Given the difficulties and the limitations involved in effective brain training, we advocate for a more collaborative effort. Continued advancements in neuroscience will allow greater insight into the neural processes underlying learning and training, particularly in brains having undergone damage, insult, or abnormal development. Such advances will continue to inform intervention, prevention, and training efforts as to the specific deficits affected and the particular brain systems to target in differing populations. Understanding the neural mechanisms affected will also advance our understanding of the most malleable brain systems for training or intervention. Conversely, intervention science will continue to make advancements regarding the best means of implementing training and applications for real-world contexts. With regard to effective policy, the most critical factor will undoubtedly be the ability of neuroscientists and intervention scientists to listen, communicate, and collaborate with each other.

REFERENCES

Bavelier, D., Tomann, A., Hutton, C., Mitchell, T., Corina, D., Liu, G., & Neville, H. (2000). Visual attention to the periphery is enhanced in congenitally deaf individuals. *Journal of Neuroscience, 20*(17), 1–6. Retrieved from http://www.jneurosci.org

Berg, I. J., Koning-Haanstra, M., & Deelman, B. G. (1991). Long-term effects of memory rehabilitation: A controlled study. *Neuropsychological Rehabilitation, 1,* 97–111. doi:10.1080/09602019108401384

Blair, C. (2002). School readiness: Integrating cognition and emotion in a neurobiological conceptualization of children's functioning at school entry. *American Psychologist, 57,* 111–127. doi:10.1037/0003-066X.57.2.111

Bruce, J., McDermott, J. M., Fisher, P. A., & Fox, N. A. (2009). Using behavioral and electrophysiological measures to assess the effects of a preventive intervention: A preliminary study with preschool-aged foster children. *Prevention Science, 10,* 129–140. doi:10.1007/s11121-008-0115-8

Bryck, R. L., & Mayr, U. (2005). On the role of verbalization during task set selection: Switching or serial order control? *Memory & Cognition, 33,* 611–623. doi:10.3758/BF03195328

Cabeza, R., Daselaar, S. M., Dolcos, F., Prince, S. E., Budde, M., & Nyberg, L. (2004). Task-independent and task-specific age effects on brain activity during working memory, visual attention and episodic retrieval. *Cerebral Cortex, 14,* 364–375. doi:10.1093/cercor/bhg133

Carlson, S. M. (2005). Developmentally sensitive measures of executive function in preschool children. *Developmental Neuropsychology, 28,* 595–616. doi:10.1207/s15326942dn2802_3

Carlson, S. M., & Moses, L. J. (2001). Individual differences in inhibitory control and children's theory of mind. *Child Development, 72,* 1032–1053. doi:10.1111/1467-8624.00333

Cicchetti, D., Rogosch, F. A., Gunnar, M. R., & Toth, S. L. (2010). The differential impacts of early physical and sexual abuse and internalizing problems on daytime cortisol rhythm in school-aged children. *Child Development, 81,* 252–269. doi:10.1111/j.1467-8624.2009.01393.x

Colcombe, S., & Kramer, A. (2003). Fitness effects on the cognitive function of older adults: A meta-analytic study. *Psychological Science, 14,* 125–130. doi:10.1111/1467-9280.t01-1-01430

Colcombe, S. J., Kramer, A. F., Erickson, K. I., & Scalf, P. (2005). The implications of cortical recruitment and brain morphology for individual differences in cognitive performance in aging humans. *Psychology and Aging, 20,* 363–375. doi:10.1037/0882-7974.20.3.363

Diamond, A., Barnett, W. S., Thomas, J., & Munro, S. (2007, November 30). Preschool program improves cognitive control. *Science, 318,* 1387–1388. doi:10.1126/science.1151148

Durston, S., Hulshoff Pol, H. E., Casey, B. J., Giedd, J. N., Buitelaar, J. K., & van Engeland, H. (2001). Anatomical MRI of the developing human brain: What have we learned? *Journal of the American Academy of Child & Adolescent Psychiatry, 40,* 1012–1020. doi:10.1097/00004583-200109000-00009

Emerson, M. J., & Miyake, A. (2003). The role of inner speech in task switching: A dual-task investigation. *Journal of Memory and Language, 48,* 148–168. doi:10.1016/S0749-596X(02)00511-9

Engle, R. W., & Kane, M. J. (2004). Executive attention, working memory capacity, and a two-factor theory of cognitive control. In B. H. Ross (Ed.), *The psychology of learning and motivation* (pp. 145–199). New York, NY: Academic Press.

Ericcson, K. A., Chase, W. G., & Faloon, S. (1980, June 6). Acquisition of a memory skill. *Science, 208,* 1181–1182. doi:10.1126/science.7375930

Erickson, K. I., Voss, M. W., Prakash, R. S., Basak, C., Szabo, A., Chaddock, L., . . . Kramer, A. F. (2011). Exercise training increases size of hippocampus and improves memory. *Proceedings of the National Academy of Sciences, USA, 108,* 3017–3022. doi:10.1073/pnas.1015950108

Fair, D. A., Dosenbach, N. U. F., Church, J. A., Cohen, A. L., Brahmbhatt, S., Miezin, F. M., . . . Schlaggar, B. L. (2007). Development of distinct task control networks through segregation and integration. *Proceedings of the National Academy of Sciences, USA, 104,* 13507–13512. doi:10.1073/pnas.0705843104

Fasotti, L., Kovacs, F., Eling, P. A. T. M., & Brouwer, W. H. (2000). Time pressure management as a compensatory strategy training after closed head injury. *Neuropsychological Rehabilitation, 10,* 47–65. doi:10.1080/096020100389291

Fisher, M., Holland, C., Merzenich, M. M., & Finogradov, S. (2009). Using neuroplasticity-based auditory training to improve verbal memory in schizophrenia. *American Journal of Psychiatry, 166,* 805–811. doi:10.1176/appi.ajp.2009.08050757

Fisher, P. A., & Gunnar, M. R. (2010). Early life stress as a risk factor for disease in adulthood. In E. Vermetten, R. Lanius, & C. Pain (Eds.), *The impact of early life trauma on health and disease* (pp. 133–141). Cambridge, England: Cambridge University Press.

Fisher, P. A., Gunnar, M. R., Dozier, M., Bruce, J., & Pears, K. C. (2006). Effects of a therapeutic intervention for foster children on behavior problems, caregiver attachment, and stress regulatory neural systems. In B. M. Lester, A. Masten, & B. McEwen (Eds.), *Annals of the New York Academy of Sciences: Vol. 1094. Resilience in children* (pp. 215–225). doi:10.1196/annals.1376.023

Gathercole, S. E., Brown, L., & Pickering, S. J. (2003). Working memory assessments at school entry as longitudinal predictors of National Curriculum attainment levels. *Educational and Child Psychology, 20,* 109–122.

Giancola, P. R., & Tarter, R. E. (1999). Executive cognitive functioning and risk for substance abuse. *Psychological Science, 10,* 203–205. doi:10.1111/1467-9280.00135

Giedd, J. N. (2004). Structural magnetic resonance imaging of the adolescent brain. Adolescent brain development: Vulnerabilities and opportunities. In R. E. Dahl & L. P. Spear (Eds.), *Annals of the New York Academy of Sciences: Vol. 1021. Adolescent brain development: Vulnerabilities and opportunities* (pp.77–85). doi:10.1196/annals.1308.009

Giedd, J. N., Blumenthal, J., Jeffries, N. O., Castellanos, F. X., Liu, H., Zijdenbos, A., . . . Rappoport, J. L. (1999). Brain development during childhood and adolescence: A longitudinal MRI study. *Nature Neuroscience, 2,* 861–863. doi:10.1038/13158

Gogtay, N., Giedd, J. N., Lusk, L., Hayashi, K. M., Greenstein, D., Vaituzis, A. C., . . . Thompson, P. M. (2004). Dynamic mapping of human cortical development during childhood through early adulthood. *Proceedings of the National Academy of Sciences, USA, 101,* 8174–8179. doi:10.1073/pnas.0402680101

Hackman, D. A., & Farah, M. J. (2009). Socioeconomic status and the developing brain. *Trends in Cognitive Sciences, 13,* 65–73. doi:10.1016/j.tics.2008.11.003

Hillman, C. H., Erickson, K. I., & Kramer, A. F. (2008). Be smart, exercise your heart: Exercise effects on brain and cognition. *Nature Reviews Neuroscience, 9,* 58–65. doi:10.1038/nrn2298

Holmes, J., Gathercole, S. E., & Dunning, D. L. (2009). Adaptive training leads to sustained enhancement of poor working memory in children. *Developmental Science, 12,* F9–F15. doi:10.1111/j.1467-7687.2009.00848.x

Hubel, D. H., & Wiesel, T. N. (1970). The period of susceptibility to the physiological effects of unilateral eye closure in kittens. *Journal of Physiology, 206,* 419–436.

Huizinga, M., Dolan, C. V., & van der Molen, M. W. (2006). Age-related change in executive function: Developmental trends and a latent variable analysis. *Neuropsychologia, 44,* 2017–2036. doi:10.1016/j.neuropsychologia.2006.01.010

Huttenlocher, P. R. (1990). Morphometric study of human cerebral cortex development. *Neuropsychologia, 28,* 517–527. doi:10.1016/0028-3932(90)90031-I

Jaeggi, S. M., Buschkuehl, M., Jonides, J., & Perrig, W. J. (2008). Improving fluid intelligence with training on working memory. *Proceedings of the National Academy of Sciences, USA, 105,* 6829–6833. doi:10.1073/pnas. 0801268105

Karbach, J., & Kray, J. (2009). How useful is executive control training? Age differences in near and far transfer of task-switching training. *Developmental Science, 12,* 978–990. doi:10.1111/j.1467-7687.2009.00846.x

Kaschel, R., Della Sala, S., Cantagallo, A., Fahlböck, A., Laaksonen, R., & Kazen, M. (2002). Imagery mnemonics for the rehabilitation of memory: A randomised group controlled trial. *Neuropsychological Rehabilitation, 12,* 127–153. doi:10.1080/09602010143000211

Kerkhoff, G., Münssinger, U., & Meier, E. K. (1994). Neurovisual rehabilitation in cerebral blindness. *Archives of Neurology, 51,* 474–481.

Kerns, K. A., Eso, K., & Thomson, J. (1999). Investigation of a direct intervention for improving attention in young children with ADHD. *Developmental Neuropsychology, 16,* 273–295. doi:10.1207/S15326942DN1602_9

Klingberg, T., Fernell, E., Olesen, P. J., Johnson, M., Gustafsson, P., Dahlström, K., . . . Westerberg, H. (2005). Computerized training of working memory in children with ADHD: A randomized, controlled trial. *Journal of the American Academy of Child & Adolescent Psychiatry, 44,* 177–186. doi:10.1097/00004583-200502000-00010

Klingberg, T., Forssberg, H., & Westerberg, H. (2002). Training of working memory in children with ADHD. *Journal of Clinical and Experimental Neuropsychology, 24,* 781–791. doi:10.1076/jcen.24.6.781.8395

Koechlin, E., & Summerfield, C. (2007). An information theoretical approach to prefrontal executive function. *Trends in Cognitive Science, 11,* 229–235. doi:10.1016/j.tics.2007.04.005

Kristofferson, M. W. (1972). Effects of practice on character-classification performance. *Canadian Journal of Psychology/Revue canadienne de psychologie, 26,* 54–60. doi:10.1037/h0082415

Levänen, S., & Hamdorf, D. (2001). Feeling vibrations: Enhanced tactile sensitivity in congenitally deaf humans. *Neuroscience Letters, 301,* 75–77. doi:10.1016/S0304-3940(01)01597-X

LeVay, S., Wiesel, T. N., & Hubel, D. H. (1980). The development of ocular dominance columns in normal and visually deprived monkeys. *Journal of Comparative Neurology, 191,* 1–51. doi:10.1002/cne.901910102

Levine, S. (2005). Stress: An historical perspective. In T. Steckler, N. H. Kalin, & J. M. H. M. Reul (Eds.), *Handbook on stress and the brain* (pp. 3–23). Amsterdam, the Netherlands: Elsevier Science.

Levy, B. J., & Anderson, M. C. (2002). Inhibitory processes and the control of memory retrieval. *Trends in Cognitive Sciences, 6,* 299–305. doi:10.1016/S1364-6613(02)01923-X

Lewis, E. E., Dozier, M., Ackerman, J., & Sepulveda-Kozakowski, S. (2007). The effect of placement instability on adopted children's inhibitory control abilities and oppositional behavior. *Developmental Psychology, 43,* 1415–1427. doi:10.1037/0012-1649.43.6.1415

Mackey, A. P., Hill, S. S., Stone, S. I., & Bunge, S. A. (2011). Differential effects of reasoning and speed training in children. *Developmental Science, 14,* 582–590.

Mahncke, H. W., Connor, B. B., Appelman, J., Ahsanuddin, O. N., Hardy, J. L., Wood, R. A., . . . Merzenich, M. M. (2006). Memory enhancement in healthy older adults using a brain plasticity-based training program: A randomized, controlled study. *Proceedings of the National Academy of Sciences, USA, 103,* 12523–12528. doi:10.1073/pnas.0605194103

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience, 24,* 167–202. doi:10.1146/annurev.neuro.24.1.167

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., & Howerter,

A. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41,* 49–100. doi:10.1006/cogp.1999.0734

Morcom, A. M., Good, C. D., Frackowiak, R. S. J., & Rugg, M. D. (2003). Age effects on the neural correlates of successful memory encoding. *Brain, 126,* 213–229. doi:10.1093/brain/awg020

Morris, S. B., & DeShon, R. P. (2002). Combining effects size estimates in meta-analysis with repeated measures and independent-groups designs. *Psychological Methods, 7,* 105–125. doi:10.10371082-989X.7.1.105

National Scientific Council on the Developing Child. (2007). *The timing and quality of early experiences combine to shape brain architecture* (Working Paper No. 5). Retrieved from http://developingchild.harvard-.edu/library/reports_and_working_papers/working_papers/wp5/

Neville, H. J., & Lawson, D. (1987). Attention to central and peripheral visual space in a movement detection task: An event-related potential and behavioral study: II. Congenitally deaf adults. *Brain Research, 405,* 268–283. doi:10.1016/0006-8993(87)90296-4

Niemeier, J. P. (1998). The lighthouse strategy: Use of a visual imagery technique to treat visual inattention in stroke patients. *Brain Injury, 12,* 399–406. doi:10.1080/026990598122511

Nithianantharajah, J., & Hannan, A. J. (2006). Enriched environments, experience-dependent plasticity and disorders of the nervous system. *Nature Reviews Neuroscience, 7,* 697–709. doi:10.1038/nrn1970

Olesen, P. J., Westerberg, H., & Klingberg, T. (2004). Increased prefrontal and parietal activity after training of working memory. *Nature Neuroscience, 7,* 75–79. doi:10.1038/nn1165

Owen, A. M., Hampshire, A., Grahn, J. A., Stenton, R., Dajani, S., Burns, A. S., . . . Ballard, C. G. (2010, June 10). Putting brain training to the test. *Nature, 465,* 775–778. doi:10.1038/nature09042

Ozonoff, S. (1995). Executive functions in autism. In E. Schopler & G. B. Mesibov (Eds.), *Learning and cognition in autism: Current issues in autism* (pp. 199–219). New York, NY: Plenum Press.

Pambakian, A. L. M., Mannan, S. K., Hodgson, T. L., & Kennard, C. (2004). Saccadic visual search training: A treatment for patients with homonymous hemianopia. *Journal of Neurology, Neurosurgery & Psychiatry, 75,* 1443–1448. doi:10.1136/jnnp.2003.025957

Pascual-Leone, A., Amedi, A., Fregni, F., & Merabet, L. B. (2005). The plastic human brain cortex. *Annual Review of Neuroscience, 28,* 377–401. doi:10.1146/annurev.neuro.27.070203.144216

Pears, K. C., Kim, H. K., & Fisher, P. A. (2008). Psychosocial and cognitive functioning of children with specific profiles of maltreatment. *Child Abuse & Neglect, 32,* 958–971. doi:10.1016/j.chiabu.2007.12.009

Pennington, B. F., & Ozonoff, S. (1996). Executive functions and developmental psychopathology. *Journal of Child Psychology and Psychiatry, 37,* 51–87. doi:10.1111/j.1469-7610.1996.tb01380.x

Pereira, A. C., Huddleston, D. E., Brickman, A. M., Sosunov, A. A., Hen, R., McKhann, G. M., . . . Small, S. A. (2007). An in vivo correlate of exercise-induced neurogenesis in the adult dentate gyrus. *Proceedings of the National Academy of Sciences, USA, 104,* 5638–5643. doi:10.1073/pnas.0611721104

Pollak, S. D., Nelson, C. A., Schlaak, M. F., Roeber, B. J., Wewerka, S. S., Wiik, K. L., . . . Gunnar, M. R. (2010). Neurodevelopmental effects of early deprivation in postinstitutionalized children. *Child Development, 81,* 224–236. doi:10.1111/j.1467-8624.2009.01391.x

Raver, C. C., Jones, S. M., Li-Grining, C., Zhai, F., Metzger, M. W., & Solomon, B. (2009). Targeting children's behavior problems in preschool classrooms: A cluster-randomized controlled trial. *Journal of Consulting and Clinical Psychology, 77,* 302–316. doi:10.1037/a0015302

Raymer, A. M., Beeson, P., Holland, A., Kendall, D., Maher, L. M., Martin, N., . . . Rothi, L. J. G. (2008). Translational research in aphasia: From neuroscience to neurorehabilitation. *Journal of Speech, Language, and Hearing Research, 51,* S259–S275. doi:10.1044/1092-4388(2008/020)

Reiss, A. L., Abrams, M. T., Singer, H. S., Ross, J. L., & Denckla, M. B. (1996). Brain development, gender and IQ in children: A volumetric imaging study. *Brain, 119,* 1763–1774. doi:10.1093/brain/119.5.1763

Reuter-Lorenz, P. A., & Lustig, C. (2005). Brain aging: Reorganizing discoveries about the aging mind. *Current Opinion in Neurobiology, 15,* 245–251. doi:10.1016/j.conb.2005.03.016

Röder, B., Teder-Sälejärvi, W., Sterr, A., Rösler, F., Hillyard, S. A., & Neville, H. J. (1999, July 8). Improved auditory spatial tuning in blind humans. *Nature, 400,* 162–166. doi:10.1038/22106

Rossi, S., Miniussi, C., Pasqualetti, P., Babiloni, C., Rossini, P. M., & Cappa, S. F. (2004). Age-related functional changes of prefrontal cortex in long-term memory: A repetitive transcranial magnetic stimulation study. *Journal of Neuroscience, 24,* 7939–7944. doi:10.1523/JNEUROSCI.0703-04.2004

Rueda, M. R., Rothbart, M. K., McCandliss, B. D., Saccomanno, L., & Posner, M. I. (2005). Training, maturation, and genetic influences on the development of executive attention. *Proceedings of the National Academy of Sciences, USA, 102,* 14931–14936. doi:10.1073/pnas.0506897102

Sale, A., Berardi, N., & Maffei, L. (2009). Enrich the environment to empower the brain. *Trends in Neurosciences, 32,* 233–239. doi:10.1016/j.tins.2008.12.004

Shalev, L., Tsal, Y., & Mevorach, C. (2007). Computerized progressive attentional training (CPAT) program: Effective direct intervention for children with ADHD. *Child Neuropsychology, 13,* 382–388. doi:10.1080/09297040600770787

Shonkoff, J. P., Boyce, W. T., & McEwen, B. S. (2009). Neuroscience, molecular biology, and the childhood roots of health disparities: Building a new framework for health promotion and disease prevention. *JAMA, 301,* 2252–2259. doi:10.1001/jama.2009.754

Solé-Padullés, C., Bartrés-Faz, D., Junqué, C., Clemente, I. C., Molinuevo, J. L., Bargalló, N., . . . Valls-Solé, J. (2006). Repetitive transcranial magnetic stimulation effects on brain function and cognition among elders with memory dysfunction: A randomized sham-controlled study. *Cerebral Cortex, 16,* 1487–1493. doi:10.1093/cercor/bhj083

Stevens, C., Fanning, J., Coch, D., Sanders, L., & Neville, H. (2008). Neural mechanisms of selective auditory attention are enhanced by computerized training: Electrophysiological evidence from language-impaired and typically developing children. *Brain Research, 1205,* 55–69. doi:10.1016/j.brainres.2007.10.108

Tallal, P., Miller, S. L., Bedi, G., Byma, G., Wang, X., Nagarajan, S., . . . Merzenich, M. M. (1996, January 5). Language comprehension in language-learning impaired children improved with acoustically modified speech. *Science, 271,* 81–84. doi:10.1126/science.271.5245.81

Thorell, L. B., Lindqvist, S., Nutley, S. B., Bohlin, G., & Klingberg, T. (2009). Training and transfer effects of executive functions in preschool children. *Developmental Science, 12,* 106–113. doi:10.1111/j.1467-7687.2008.00745.x

Tominey, S. L. M., & McClelland, M. M. (2011). *Red light, purple light: Findings from a pilot intervention using classroom games to improve behavioral self-regulation.* Manuscript submitted for publication.

van Heugten, C. M., Dekker, J., Deelman, B. G., van Dijk, A. J., Stehmann-Saris, J. C., & Kinebanian, A. (1998). Outcome of strategy training in stroke patients with apraxia: A phase II study. *Clinical Rehabilitation, 12,* 294–303. doi:10.1191/026921598674468328

van Praag, H. (2008). Neurogenesis and exercise: Past and future directions. *Neuromolecular Medicine, 10,* 128–140. doi:10.1007/s12017-008-8028-z

van Praag, H., Kempermann, G., & Gage, F. H. (2000). Neural consequences of environmental enrichment. *Nature Reviews Neuroscience, 1,* 191–198. doi:10.1038/35044558

Wiesel, T. N., & Hubel, D. H. (1963). Single-cell responses in striate cortex of kittens deprived of vision in one eye. *Journal of Neurophysiology, 26,* 1003–1017.

Zelazo, P. D., Carlson, S. M., & Kesek, A. (2008). Development of executive function in childhood. In C. A. Nelson & M. Luciana (Eds.), *Handbook of developmental cognitive neuroscience* (pp. 553–574). Cambridge, MA: MIT Press.

Zelazo, P. D., Müller, U., Frye, D., & Marcovitch, S. (2003). The development of executive function: Cognitive complexity and control—revised. *Monographs of the Society for Research in Child Development, 68,* 93–119. doi:10.1111/j.0037-976X.2003.00266.x