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

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Abstract

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 paper, 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

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? Lastly, are there circumstances under which we should be concerned about potential iatrogenic effects of intervention or training programs?

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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 policy makers focused on allocating funding/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 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: by early childhood, the human brain has reached approximately 90% of its adult weight and changes very little in size after age 5 (Durstun 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. Grey 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 mature the earliest in development, with higher level association and multimodal areas (such as the dorsolateral prefrontal cortex and the superior temporal gyrus) reaching adult levels the latest (Giedd, 2005; Gogtay

¹It should be noted that many of these products lack a solid neuroscience framework upon which they are based; further, empirical evidence supporting the efficacy of some of these programs has recently been called into question (Owen et al., 2010)

et al., 2004; Riess 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 grey matter and increases in white matter has been postulated to reflect both synaptic pruning (loss of grey 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.

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 4 weeks to 3 months) corresponds to a period of preprogrammed ocular dominance column formation, in which alternating bands form in the primary visual cortex that are preferentially sensitive to input from either eye. In the case of monocular deprivation, however, profound visual impairment was seen after reopening the deprived eye. However, these effects were not seen if the deprivation occurred later (i.e., age 3–4 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 hard-wired 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 congenitally deaf individuals exhibit an early attention effect compared to participants with normal hearing 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) by congenitally deaf rather than by hearing participants when tracking motion. Similar results have been obtained with congenitally blind individuals in response to auditory stimuli (Röder et al., 1999). Individuals who are deaf have also been shown to have superior tactile ability compared to nondeprived control samples; further, the primary visual cortex has been shown to be activated when blind participants 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 other 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. Specifically, 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 need to be considered when 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, then 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 van Praag, Kempermann, & Gage, 2000; Nithianantharajah & Hannan, 2006). 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 rodents, 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. (2010) 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 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 seniors who participated in a year-long exercise regimen and a comparable *loss* in volume in those who only practiced stretching and toning. Critically, 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 PFC 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 following intense intervention or cognitive training regimens.

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 (specifically, 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 proven effective at enhancing memory performance in older adults and verbal memory in schizophrenic patients (M. Fisher, Holland, Merzenich, & Finogradov, 2009; Mahncke et al., 2006).

²Exercise 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).

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, 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 (PFC) in humans (Miller & Cohen, 2001). The development of EF follows a protracted course, with EF components first emerging in infancy, exhibiting pronounced changes occurring during the preschool period, with 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 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,

³Several 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, and the studies reviewed here contain components that can be categorized as training this type of attention and/or control over the allocation of attention, thereby broadly fitting the EF construct.

found marginal improvements at best in working memory capacity (Kristofferson, 1972) or highly task specific improvements (Ericsson, Chase, & Faloan, 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 [Morris & DeShon, 2002]. See Supplementary Material 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/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 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 understanding 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.

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 non-normative 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. These approaches can be relatively easily implemented and require no special equipment. Moreover, because they are conducted in real-world settings, the skills learned might be more likely to generalize to other, 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 component(s). Similarly, 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 at only 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 a therapeutic intervention for remedying EF 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 reconstitute 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. Generally, these compensatory approaches target specific cognitive deficits incurred after brain damage such as 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 senior compared to young adult participants during complex cognitive tasks. This distributed pattern in seniors is often seen as activity in homologous regions in the prefrontal cortex to the unilateral activity seen in young adults and positive correlations between activation 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 were impaired when deactivating TMS was applied to only one hemisphere (Rossi et al., 2004). Conversely, in a subgroup of low performing seniors, activating TMS increased task performance. Moreover, the 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 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, particularly regarding 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 analogs 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. Clearly, the structure and components involved in such approaches need to be specified and evaluated.

In addition to the development of novel intervention methods, there is a need for parallel development of innovative measurement methodologies. For example, examining fMRI activation on tasks known to recruit EF 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, both in terms of 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/functions that might only benefit a subset of the targeted population.

Additionally, much of the work to date has been on preschool- and kindergarten-aged 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 is needed to determine whether booster sessions would be appropriate. The efficacy of such booster sessions would need to be evaluated as well.

When considering the intended beneficial effects of these approaches for high-risk children, it is also critical to 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/achievement or reduce psychopathology symptoms, the implicit assumptions being that strengthening a specific cognitive process via laboratory training allows for more efficient use of this pathway when 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, though some exceptions exist: Klingberg et al. (2002; 2005); Holmes et al. (2009); Shalev, Tsal, and Mevorach (2007); and Stevens, Fanning, Coch, Sanders, and 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 (ERP) 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, EEG 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 make opposing assumptions compared to laboratory-based training interventions 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 these deficits or their potential for improvement. 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 et al. (in press; see Table 1) took a unique approach to training by incorporating aspects of both laboratory based and ecologically based intervention methods. They selectively chose computerized and noncomputerized games that required relational integration, the simultaneous processing of multiple relations between stimuli. This ability is thought to be integral to fluid reasoning ability, which is a strong predictor of school performance. In this study, the children (aged 7–9; low SES) participated in an 8-week session of either fluid reasoning training or 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 wide-held belief that fluid reasoning is a static trait that is not amendable to training (c.f., Jaeggi, Buschkuhl, Jonides, & Perrig [2008] for a similar training effect on fluid reasoning in adults). These results provide a first step towards 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. Regarding effective policy, the most critical factor will undoubtedly be the ability of neuroscientists and intervention scientists to listen, communicate, and collaborate with each other.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Table 1

Laboratory-Based EF Training Studies in Children

First author (year)	N _C	N _E	Age	Sample	Training domain	Effect Sizes					
						Category	Stat	Source	Type	Effect	Size
Rueda (2005)	25 ^a	24	4	Typically developing	Attention	IG p-p	<i>d</i>	C	N	small ↑ frontal ERP amplitude	—
						IG p-p	<i>d</i>	C	F	↑ reasoning	0.82 ^d
						IG p-p	<i>d</i>	C	F	↑ IQ	0.63 ^d
Rueda (2005)	12	12	6	Typically developing	Attention	IG p-p	<i>d</i>	C	N	↑ frontoparietal ERP amplitude	—
						IG p-p	<i>d</i>	C	F	↑ vocabulary	—
Thorell (2009)	30 ^a	17	4–5	Typically developing	Visuospatial WM	IG p-p	<i>d</i>	C	N	↑ spatial WM	0.41
						IG p-p	<i>d</i>	C	F	↑ verbal WM	1.40
						IG p-p	<i>d</i>	C	F	↑ attention	0.65
Karbach (2009)	42	14	8–10	Typically developing	Task-switching	RM	<i>d</i>	R	N	↓ switch costs	~1.2
						IG p-p	<i>d</i>	C	N	↑ inhibitory control	0.44
						IG p-p	<i>d</i>	C	N	↑ working memory	0.60 ^b
						IG p-p	<i>d</i>	C	F	↑ reasoning	0.49
Stevens (2008)	13	9	6–8	Typically developing	Language via attention	IG p-p	<i>d</i>	C	N	↑ receptive language	1.43
						IG p-p	<i>d</i>	C	F	↑ attentional ERP amplitude	1.76
Stevens (2008)	13	7	6–8	Specific language impairment	Language via attention	IG p-p	<i>d</i>	C	N	↑ receptive language	3.91
						IG p-p	<i>d</i>	C	F	↑ attentional ERP amplitude	6.73
Holmes (2009)	20	22	8–11	Low WM	Verbal and visuospatial WM	IG p-p	<i>d</i>	C	N	↑ verbal WM	1.06 ^{b,c}
						IG p-p	<i>d</i>	C	N	↑ visuospatial WM	1.20 ^{b,c}
						RM	<i>d</i>	R	F	↑ math at follow-up	0.49 ^{b,e}
Mackey (in press)	11	17	7–9	Low SES	Fluid reasoning	IG p-p	<i>d</i>	C	N	↑ reasoning	1.32
						IG p-p	<i>d</i>	C	F	↑ WM	0.88
Kems (1999)	7	7	7–11	ADHD	Attention	RM	<i>d</i>	C	N	↑ attention	2.64 ^b
						RM	<i>d</i>	C	N	↓ interference	3.06
						RM	<i>d</i>	C	F	↑ math	1.94

First author (year)	N _C	N _E	Age	Sample	Training domain	Category	Stat	Source	Type	Effect Sizes	
										Effect	Size
Klingberg (2002)	7	7	7–15	ADHD	Verbal and visuospatial WM	IG p-p	<i>d</i>	C	N	↑ visuospatial WM	4.66 ^b
						IG p-p	<i>d</i>	C	F	↑ reasoning	1.89
						IG p-p	<i>d</i>	C	F	↓ ADHD	1.44
Klingberg (2005)	24	20	7–12	ADHD	Verbal and visuospatial WM	IG p-p	<i>d</i>	C	N	↑ verbal WM	0.68 ^c
						IG p-p	<i>d</i>	C	N	↑ visuospatial WM	0.66 ^c
						IG p-p	<i>d</i>	C	N	↓ interference	0.25
Shalev (2007)	16	20	6–13	ADHD	Attention	IG p-p	<i>d</i>	C	F	↑ reasoning	0.18
						IG p-p	<i>d</i>	C	F	↓ ADHD	0.90 ^c
						IG p-p	η^2	R	F	↑ academic achievement	0.15 ^b
						IG p-p	η^2	R	F	↓ ADHD	0.29 ^b

Note: Age is given in years. See Supplementary Material for definitions and procedures for determining the effect sizes (Stat) based on the parameters given in the original studies.

NC = sample size of the control group; NE = sample size of the experimental/training group; WM = working memory; IG p-p = independent groups, pre-post; RM = repeated measures, change within group; Stat = the effect size statistic given; *d* = Cohen's *d*; η^2 = Eta-squared; C = effect size value calculated; R = effect size value as reported in the original study; N = near (improvement on trained tasks or nontrained, structurally similar tasks); F = far (improvement on structurally dissimilar tasks).

^aMultiple control groups used, combined *N* given.

^bAverage effect size calculated from multiple dependent variables measuring the same construct.

^cEffect stable at follow-up test.

^dSee note in Supplemental Material for calculation of these effect sizes.

^eEffect reported from follow-up test.

Table 2

Neurobiologically Informed Ecological Interventions

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

Note. Age is given in years. See Supplementary Material for definitions and procedures for determining the effect sizes (Stat) based on the parameters given in the original studies.

NC = sample size of the control group; NE = sample size of the experimental/training group; IG p-p = independent groups, pre-post; IG post = independent groups, post; Stat = the effect size statistic given; *d* = Cohen's *d*; η_p^2 = Partial Eta-squared; *r* = Pearson's product moment correlation; C = effect size calculated; R = effect size value as reported in the original study; N = near (improvement on trained tasks or nontrained, structurally similar tasks); F = far (improvement on structurally dissimilar tasks).

^a Average effect size calculated from multiple dependent variables measuring the same construct.

^b Measure not administered to control group.

^c Effect found in subset with low initial executive function scores.

^d Multiple control groups used, combined *N* given.

Table 3

Neurorehabilitation Strategy/Compensatory Training Studies

First author (year)	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	<i>d</i>	↓ visual search errors	0.91
Kerkoff (1994)	—	22	16–77	Stroke	Homonymous visual field defects ^a	Compensatory eye saccades and visual search strategies	IG p-p	<i>d</i>	↑ attention	1.04
Pambakian (2004)	—	29	24–75	Stroke	Homonymous visual field defects ^a	Visual search	RM	—	↑ visual search	—
Kaschel (2002)	12	9	20–60	TBI	Memory	Visual imagery mnemonics	IG p-p	<i>d</i>	↑ activities of daily living	—
Berg (1991)	11	17	19–58	TBI	Memory	Making associations, organization, and matching encoding and retrieval contexts	IG p-p	<i>f</i> ²	↑ acquisition memory	0.04 ^c
Fasotti (2000)	10	12	18–45	TBI	Mental slowness	Decision planning, task management, and delineating tasks hierarchically	IG p-p	<i>f</i> ²	↑ delayed recall	0.06 ^c
van Heugten (1998)	—	33	39–91	Stroke	Apraxia	Verbalizing the steps in an action	IG p-p	<i>d</i>	↑ attention	0.52
							RM	<i>d</i>	↑ activities of daily living	1.30
							RM	<i>d</i>	↑ motor functioning	0.57
							RM	<i>d</i>	↓ apraxia symptoms	0.59

Note. Age is given in years. See Supplementary Material for definitions and procedures for determining the effect sizes (Stat) based on the parameters given in the original studies. All effect sizes were calculated.

NC = sample size of the control group; NE = sample size of the experimental/strategy group; TBI = traumatic brain injury; IG p-p = independent groups, pre-post; RM = repeated measures, change within group; Stat = the effect size statistic given; *d* = Cohen's *d*; *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.

Effect reported from follow-up test.

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

First author (year)	N _C	N _E	Age	Tasks	Results
Morcom (2003)	14	14	63–74	Memory	Successful encoding: activates left prefrontal cortex in the young but homologous left and right prefrontal cortex in seniors
Cabeza (2004)	20	20	70 (M)	Working memory and attention	In both tasks: seniors showed greater bilateral prefrontal cortex activity than young (compensation), and seniors showed less occipital activity than young (sensory decline)
Rossi (2004)	37	29	50–80	Memory	↓ memory retrieval in seniors with disruptive TMS at the left or right prefrontal cortex and ↓ memory retrieval in the young with disruptive TMS <i>only</i> at the right prefrontal cortex
Solé-Padullés (2006)	19	20	67 (M) ^a	Memory	Pre-activating TMS: unilateral activity. Post-activating 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.

NC = sample size of the control group; NE = sample size of the experimental/senior group; TMS = transcranial magnetic stimulation.

^aParticipants demonstrated low memory scores at pretesting.