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Neuroscience Perspectives on Disparities in School Readiness and Cognitive Achievement

Kimberly G. Noble, Nim Tottenham, and B. J. Casey

Summary

This article allows readers to look at racial and ethnic disparities in school readiness from a neuroscience perspective. Although researchers have traditionally measured gaps in school readiness using broad achievement tests, they can now assess readiness in terms of more specific brain-based cognitive functions. Three neurocognitive systems—cognitive control, learning and memory, and reading—are essential for success in school. Thanks to recent advances in brain imaging, it is now possible to examine these three systems, each located in specific areas of the brain, by observing them in action as children engage in particular tasks.

Socioeconomic status—already linked with how well children do on skills tests generally—is particularly closely linked with how well they perform on tasks involving these crucial neurocognitive systems. Moreover, children’s life experiences can influence their neurocognitive development and lead to functional and anatomical changes in their brains. Noting that chronic stress or abuse in childhood can impair development of the brain region involved in learning and memory, the authors show how the extreme stress of being placed in an orphanage leads to abnormal brain development and decreased cognitive functioning.

More optimistically, the authors explain that children’s brains remain plastic and capable of growth and development. Targeted educational interventions thus have the promise of improving both brain function and behavior. Several such interventions, for example, both raise children’s scores in tests of reading and increase activity in the brain regions most closely linked with reading. The brain regions most crucial for school readiness may prove quite responsive to effective therapeutic interventions—even making it possible to tailor particular interventions for individual children. The authors look ahead to the day when effective educational interventions can begin to close racial and socioeconomic gaps in readiness and achievement.

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Racial disparities in school readiness among America's preschoolers are strong and persistent. As elaborated elsewhere in this volume, many aspects of childhood experience, including health, parenting, stress, violence, and access to resources, contribute to these disparities. Many of these same experiences, including chronic stress and cognitive stimulation, also affect brain development in both animals and humans, suggesting a possible pathway between experience and ability.

To show how differences in brain development may ultimately link experience and academic achievement, we focus in this article on three core neurocognitive systems that are crucial for school readiness. Typical measures of school readiness such as achievement tests or even IQ tests are quite imprecise from the perspective of brain science.¹ These tests assess a diverse set of mental processes, involving many neural systems, without telling much about the specific systems of the child's mind and brain that are most involved in school readiness. Recent work in the field of cognitive neuroscience, however, has made it possible to assess the specific neurocognitive systems or brain regions involved in particular cognitive skills. Using new neuroimaging methods, researchers can design cognitive tests that assess a single system, enabling them to understand more precisely the cognitive processes and underlying brain regions whose development contributes to differences in achievement. Ultimately, specific neurocognitive systems might be differentially targeted by early educational interventions.

We begin by introducing the three neurocognitive systems, including the cognitive processes involved, the types of tests used for assessment, and the brain regions implicated.

We touch on the limited research into racial differences across these systems and discuss some links between socioeconomic background and neurocognitive performance. We then discuss research findings about how experience can influence development of these systems. We conclude by drawing implications for educational interventions on early brain and cognitive development in these systems.

Three Core Neurocognitive Systems

To illustrate how brain development can inform notions of readiness and achievement, we briefly describe three key neurocognitive systems involved in cognitive skills necessary for school success. Cognitive control, the ability to override inappropriate thoughts and behaviors, is associated with the prefrontal cortex, located in the front of the brain. Learning and memory involve the hippocampus, buried deep within the brain's temporal lobe. And reading (and its precursors in preliterate children) is associated with the temporo-parietal and temporo-occipital cortex, located on the left surface of the brain. Each of these brain regions changes and matures throughout childhood, and researchers are currently trying to understand how children's experiences influence such brain development. Scientists hope that this research will lead to insights that are promising for the design of specific educational interventions.

Cognitive Control

Cognitive processes attributed to the prefrontal cortex include the ability to allocate attention, to hold something "online" in memory, and to withhold an inappropriate response.² Such processes, collectively known as cognitive control, are important developmentally, as they underlie cognitive and social skills essential to academic success,

such as the ability to ignore distracting events inside and outside the classroom. In the laboratory, researchers can design behavioral tasks to assess a child's ability to inhibit an inappropriate response. For example, a widely used paradigm known as the Go–No Go task presents a child with many “go” stimuli that require a rote button-press response, along with an occasional “no go” stimulus that requires the child to *withhold* a response.³

Now, thanks largely to developments in imaging methods, like magnetic resonance imaging (MRI), researchers can study cognitive skills in the developing human brain. More than a decade ago, Kenneth Kwong, Seji Ogawa, and others showed that magnetic resonance is sensitive to blood oxygenation changes in the brain that may reflect changes in blood flow and neuronal activity.⁴ The discovery that MRI can assess activity in the human brain without the need for radioactive tracers required by other forms of brain imaging opened a new era in the study of human brain development and behavior. Since then, numerous functional magnetic resonance imaging (fMRI) studies have examined children engaged in cognitive control tasks and have found a characteristic age-related pattern in the development of neural activity in the prefrontal cortex.⁵ In young children, cognitive control tasks are associated with diffuse patterns of prefrontal cortex activity, whereas by adolescence the pattern of activity is both more focal and more intense. In adulthood, activity remains focal, but somewhat less intense. Because increasing age is also linked with accuracy in performing a task, with experience, and with learning, one possible interpretation of these findings is that the age-related decrease in brain activity could reflect reduced recruitment of brain tissue as the task becomes easier. But studies that have matched children and adults on accuracy on

the Go–No Go task show that prefrontal activity differences represent maturational change, not difference in ability.⁶

Memory and Learning

The development of memory and learning is also clearly important to academic success. One aspect of learning is the ability to form new associations among events. In laboratory tasks that test the learning of new memories, children typically see or hear lists of words, stories, or scenes and then try to recollect the presented stimuli.⁷ For very young children,

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for whom a nonverbal memory assessment is preferable, researchers first familiarize the child with a stimulus and then present him or her with test trials pairing the familiar stimulus with a new one. Infants' known preference for novelty allows researchers to infer that an infant who spends a longer time looking at the new stimulus recognizes the familiar one.⁸

The ability to learn and remember is supported in part by the hippocampus, located deep inside the brain's temporal lobe.⁹ A child's hippocampus increases in size with age, with a particularly sharp increase before the age of two.¹⁰ During the course of those two years, a child's ability to learn and re-

member associations matures in terms of both how much information is remembered and how long it is retained.¹¹ Although research into the link between a child's memory and the functional neuroanatomical development of the hippocampus is still in its early stages, a recent imaging study showed that in both children and adults, the speed of learning a new association was correlated with hippocampal activity.¹² Interestingly, as with cognitive control and the prefrontal cortex, the activity associated with forming and remembering new associations was more diffuse and less focal in children than it was in adults.

Language and Reading

Both cognitive control and memory and learning are general cognitive abilities that a child brings to the academic environment. A more specific cognitive ability—one that is key to understanding the gap in school readiness—is reading, along with the precursor language skills that are critical for the development of reading. Ample evidence has shown that phonological awareness, or an understanding of the sounds of language, is crucial for reading.¹³ Not only do preliterate children with better phonological awareness learn to read more quickly than children with less such awareness, but kindergarten phonological awareness predicts teenage reading ability better than kindergarten reading skill does.¹⁴ Phonological awareness is measured behaviorally by tasks such as rhyming, blending sounds, and word-sound games that assess the ability to manipulate syllables or smaller units of speech known as phonemes.

A large swath of cortex known as the perisylvian region stretches along the left side of the brain and underlies most language functioning. Within this larger area, two regions are primarily responsible for the normal development of reading.¹⁵ The first region, the supe-

rior temporal gyrus, is involved in phonological processing in normally reading adults and children.¹⁶ Later childhood brings anatomical maturation of this region as measured by size, symmetry, and connectivity.¹⁷ The second region, the fusiform gyrus, located along the bottom-left side of the brain, has been associated with the ability of skilled readers to perceive automatically a written word. Activity in the fusiform gyrus is positively correlated with both reading ability and age.¹⁸ The two regions are functionally linked in that the development of the fusiform gyrus is thought to be influenced by phonological processing in the preliterate child.¹⁹

This sketch of these three neurocognitive systems illustrates how researchers have begun to understand the developmental course of several cognitive processes and their neural underpinnings. The challenge is to understand how an individual child's experiences, many of which may vary according to racial, ethnic, or socioeconomic background, may affect the developing brain. Focusing on these specific neurocognitive systems, rather than on the multiple systems measured by achievement tests, may make it possible both to understand the link between experience and brain development and to address the racial gap in school readiness by directly targeting the specific systems with interventions.

Racial and Socioeconomic Disparities in Neurocognitive Performance

Few researchers as yet have examined racial disparities in academic achievement in terms of specific neurocognitive systems. In fact, few studies of cognitive development explicitly examine race at all. One notable recent exception, a study of cognitive control, investigated a child's ability to suppress an inappropriate response as measured in a labora-

tory task.²⁰ The study found that children from higher socioeconomic backgrounds generally performed better on the test. It also found, after controlling for socioeconomic status, that African American and Hispanic children resisted the interference of competing demands better than white children did. Although this study needs to be replicated to confirm its findings, a preliminary interpretation might be that racial disparities in achievement, or at least in cognitive control, are in fact mediated by socioeconomic differences (and with associated differences in access to resources).

The suggestion that socioeconomic differences underlie racial differences in academic performance is supported by the fact that minorities are at much greater risk for growing up in poverty.²¹ As detailed elsewhere in this volume, children from impoverished backgrounds are at heightened risk for poor academic readiness and achievement because of differences in their physical health, the quality of the cognitive and emotional stimulation they receive at home, their parenting, and their early childhood education.²² Thus, although work on racial differences in cognitive development is limited as yet, researchers are beginning to examine the link between socioeconomic status (SES) and neurocognitive achievement.

So far this research has documented a strong and persistent connection between socioeconomic status—most commonly measured using education, occupation, and income—and childhood cognitive ability and achievement as measured by IQ, achievement test scores, and functional literacy.²³ In one study, for example, socioeconomic status accounted for some 20 percent of the variation in childhood IQ.²⁴ Another found that disparities in achievement due to socioeconomic status in-

crease with age: a child's cognitive ability at age ten is more closely linked to his socioeconomic status at age two than to his cognitive ability at age two.²⁵ But despite extensive work on the connection between socioeconomic status and cognitive performance as measured by standardized testing, researchers are only beginning to focus on the specific brain functions that link childhood experience and cognitive performance.

To address this gap in research, we recently examined the neurocognitive functioning of African American kindergartners from different socioeconomic backgrounds, using tasks

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from the cognitive neuroscience literature to explore how childhood SES helps account for the normal variance in performance across different neurocognitive systems.²⁶ We recruited thirty middle-SES children and thirty low-SES children from public kindergarten classes in Philadelphia to participate in a battery of behavioral tasks, each specific to a particular neurocognitive system. The tasks were designed to assess the language, cognitive control, and memory systems, along with several others. The systems we selected were relatively independent of one another, had correspondingly distinct locations in the

brain, and had substantial roles in cognition and school performance. We found that socioeconomic status was generally correlated with the children's performance on the battery of tasks as a whole, thus replicating the well-documented socioeconomic gap in global measures of cognitive performance. But we also found that socioeconomic status was disproportionately correlated with performance in certain systems. Specifically, children's performance in tasks tapping the left perisylvian (language) system and the

Socioeconomic status accounted for a good portion of the variance in performance in different aspects of cognitive control and in tasks involving several other systems, including learning and memory.

prefrontal (cognitive control) system varied widely according to their socioeconomic status, while their performance in tasks involving other systems showed either no differences or nonsignificant trends. The effects on the language and cognitive control systems were quite large. For the left perisylvian (language) system, the mean score of the group of middle-class children was 1.1 standard deviations higher than the mean score of the poorer children; for the prefrontal (cognitive control) system, the difference was 0.68 standard deviation.

When we replicated our preliminary study in a larger sample of 150 multiracial children,

we largely confirmed our original findings.²⁷ Socioeconomic status accounted for the most variance in performance in the language system. It also accounted for a good portion of the variance in performance in different aspects of cognitive control and in tasks involving several other systems, including learning and memory.

These two studies are the first ever to compare directly the extent to which socioeconomic factors account for the variance in children's performance on tasks involving different neurocognitive systems. Both found that the effect of socioeconomic status was not uniform, that it differs from system to system. In some systems, the effect was negligible. Effects were greatest on variations in language skills, but socioeconomic status also accounts for some of the variation in other systems, including cognitive control and possibly learning and memory, among others.

Because of the exceptional importance of reading skill for academic and life achievement, we were particularly interested in examining how socioeconomic status affects that particular aspect of language development. Correlations between socioeconomic background and word reading ability are typically fairly strong (they fall within the range of 0.3 to 0.7, with 1 being a perfect correlation).²⁸ Often, researchers attribute this close relationship to the link between socioeconomic status and reading-related experiences, such as the home literacy environment, degree of early print exposure, and quality of early schooling.²⁹ But, as noted, a largely separate line of research has provided abundant evidence that phonological awareness is causally related to reading development.³⁰ Despite independent work showing that socioeconomic background and phonological awareness are each associated with

reading achievement, surprisingly few studies have explored how socioeconomic status relates to phonemic awareness in predicting individual differences in reading ability.³¹

We investigated this question and found that on several different types of reading tasks, socioeconomic status and phonological awareness each accounted for unique variance in skill.³² Furthermore, in certain cases, we found that SES actually seemed to *modulate* the relationship between phonological awareness and reading. That is, at the highest levels of phonological awareness, children were on average reading well regardless of socioeconomic background. In contrast, at lower levels of phonological skill, a disparity emerged such that higher-SES children continued to read relatively well, whereas lower-SES children began to struggle.

Together, these findings imply that the relationship between socioeconomic background and reading does not simply reflect differences in the development of phonological awareness skills. In contrast, multiple factors play complex roles in the development of reading and in predicting whether a child will acquire this crucial skill easily or with difficulty. Put simply, disparate causes may lead to the same cognitive difficulties. Two different children may have similar problems in learning to read, but one may have inherently poor phonological awareness skills, while the other may be growing up in an environment with scant access to literacy materials and instruction. Is it possible then, that a child who struggles with reading in the context of a low-literacy environment might have difficulties that are fundamentally different from those of a child who struggles *despite* access to a higher-literacy environment? Might these two children respond differently to different types of intervention?

This brings us to a key application for neuroimaging. If similar low levels of performance in a skill such as reading may have different causes, then imaging the brain may help to tease such effects apart, extending our knowledge beyond the limits of behavioral data. It is now possible to examine whether similar behavioral profiles resulting from different causes could be rooted in different effects on brain development. It may be differences in brain development, rather than differences in behavioral performance, that ultimately predict an individual child's response to intervention. In the next section, we examine how differences in experience influence the development of neurocognitive systems crucial for academic success.

Experience and Brain Development

Thus far, we have focused on the developmental course of several core cognitive processes and their neural underpinnings, as well as on how cognitive achievement is associated with socioeconomic background and perhaps race. The next challenge is to understand how a child's experiences—many of which may reflect his or her socioeconomic, racial, or ethnic background—may affect the developing brain. Understanding how experience influences behavioral and brain development may make it possible to design educational curriculums to target the specific brain regions that underlie cognitive skills important for academic success.

Experience shapes brain development at many levels of organization, from molecules to larger brain systems.³³ Variations in such types of experience as cognitive stimulation and early life stress lead to functional and anatomical changes throughout the brain in both animals and people. Scientists can, for example, cause broad neural changes in ani-

mals by manipulating the laboratory environment, enriching or depriving the animals' experience in various ways.³⁴ In humans, stress has garnered much attention as one particular experience that may affect cognitive and academic achievement. Stressful life conditions have been associated with low socioeconomic status, and differences in emotional support in the home account for a significant portion of the variance in children's verbal, reading, and math skills, even when maternal education, family structure, prenatal care, infant health, nutrition, and mother's age are taken into account.³⁵ Such cognitive differences may be caused in part by biological responses to stress.

Children raised in chronically stressful or abusive situations demonstrate increased or irregular production of stress hormone.³⁶ In animals, such abnormal levels of stress hormone lead to adverse brain development, particularly in the hippocampus.³⁷ Reduced hippocampal volume has also been found in human adults in a variety of stress-related conditions, including post-traumatic stress disorder and major depression.³⁸ Given the critical role of the hippocampus in learning and memory, it is not surprising that changes in hippocampal activity caused by prolonged exposure to elevated stress hormone may lead to deficits in learning.³⁹

Developmental studies of maltreated children find generalized intellectual and academic impairments, as measured by IQ or achievement tests.⁴⁰ Studies applying more specific neurocognitive methods suggest that these children also show deficits in cognitive control.⁴¹ MRI studies of children suffering from post-traumatic stress disorder caused by maltreatment have found not only that their brains are smaller overall than those of children who have not been maltreated, but also

that their frontal lobe structure is abnormal.⁴² These studies, however, cannot draw causal relationships between maltreatment and brain changes.

To sort out these findings, we have begun to examine how one extreme form of chronic childhood stress—being placed in an orphanage—affects a child's developing brain. Researchers have recognized for some time that both a child's age at placement and the duration of the placement affect the child's development.⁴³ We have recruited and collected preliminary data on fourteen children between the ages of five and eleven who spent time in an orphanage. The children were adopted between the ages of six months and five years, except for one boy, who was adopted at age eight. They were placed in the orphanage between birth and age two, with the exception of the same boy, who was placed at age five.

Of the fourteen children, seven have at least one clinical psychiatric diagnosis. Strikingly, the older the children were at adoption, the more likely they are to have symptoms, and ultimately a diagnosis. The healthiest children were placed in the orphanage young and adopted young, and they spent relatively less time in the orphanage overall.

Most of the children's general cognitive ability scores fell within the average range, but their estimated full-scale IQ scores were negatively correlated with time spent in the orphanage (see figure 1). The children who lived there a shorter time tended to have higher IQ scores.

To assess cognitive control in these children, we used the Go-No Go test.⁴⁴ The performance of the adopted children on the test differed from that of twelve age-matched con-

Figure 1. Time Spent in Orphanage and IQ

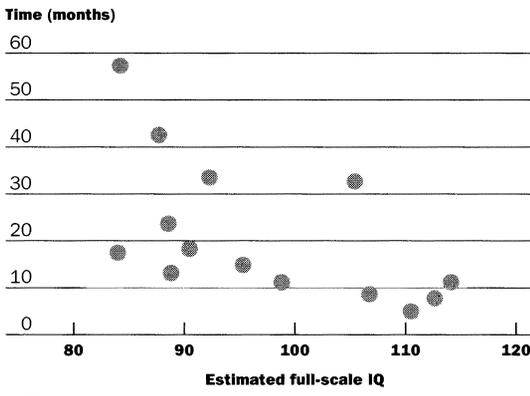
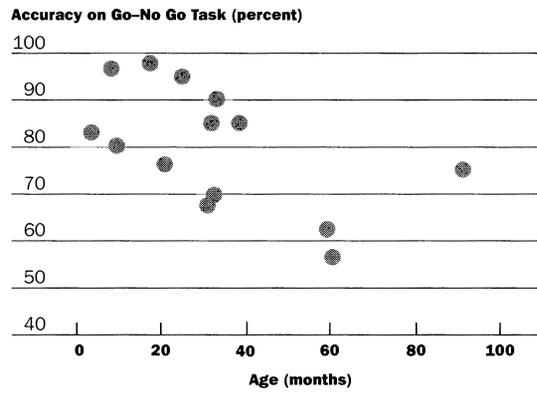


Figure 2. Cognitive Control and Age at Adoption



trols in overall accuracy. Performance was negatively correlated with age of adoption: children adopted at a younger age tended to score higher on the test (see figure 2). Thus stress associated with institutionalization appears to be linked with decreased cognitive ability as measured both by general intelligence tests and by specific measures of cognitive control. These findings are in line with those noted earlier, that traumatized children show abnormal maturation of prefrontal function.

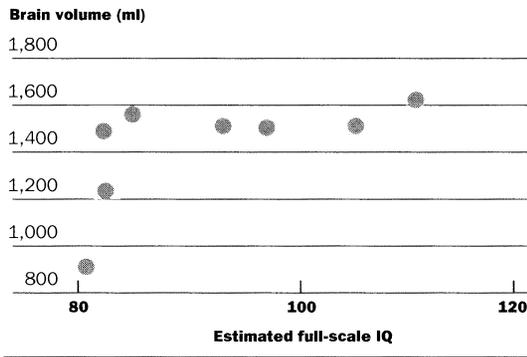
How do these cognitive changes relate to brain changes? We examined the effects of institutionalization on brain development using magnetic resonance imaging on a subset of eight of these children. As seen in figure 3, MRIs of those children showed an association between total brain volume and estimated IQ, a trend that has been repeatedly demonstrated elsewhere.⁴⁵ The MRIs also showed a moderate association between the length of time a child spent in an orphanage and the child's prefrontal volume (after overall brain volume had been taken into account).

Because the hippocampus is implicated in memory and learning and because it is vul-

nerable to stress, we tested for a link between its volume and the length of time a child lived in the orphanage. As figure 4 shows, the volume decreased as a function of time spent in the institution. (We controlled for current age and overall brain volume.) These results, too, are in line with those noted in adults with post-traumatic stress disorder. Not surprisingly, we found that previously institutionalized children perform poorly on learning and memory tasks. Preliminary findings from our laboratory showed that these children were significantly slower than the control group to learn new stimulus-response associations and override old ones, an ability that correlates with hippocampal activity.⁴⁶ Hippocampal volume was also correlated with time spent with the adopted family: the longer a child lived with a stable family, the greater his or her hippocampal volume. This finding suggests a powerful effect of the positive experience of adoption from orphanage to home.

Although most research on stress and humans has focused on extreme—and rare—cases such as institutionalization, milder daily elevations in stress may have long-term effects as well. In children of low socioeco-

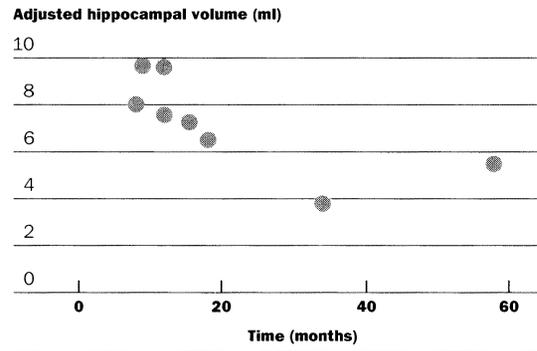
Figure 3. Brain Volume and IQ



conomic status, for example, Sonia Lupien and her colleagues found increased levels of salivary cortisol, which were linked with depression in their mother.⁴⁷ This research is potentially quite relevant to understanding the biological and neural underpinnings of the achievement gap between children of different socioeconomic backgrounds.

As is evident from the effect of adoption in our study of children placed in an orphanage, experience need not be negative to shape a developing brain. On the contrary, positive differences in experience can quite powerfully lead to functional reorganization of the brain. One often-cited example is learning a second language. As has long been recognized, the older a person is when exposed to a second language, the less likely he or she is to be able to develop true, accent-free fluency. Recent neuroimaging studies have begun to elucidate the neurobiological basis for this experience.⁴⁸ Typically, the studies present children with written or spoken words in both their first and their second languages and examine differences in brain activity in response. In bilingual children who learn a second language before they turn seven, brain activity in response to the two languages is similar and takes place in overlapping regions of the left side of the brain. But in children

Figure 4. Hippocampal Volume and Time Spent in Orphanage



who learn a second language later, brain activity in response to the two languages occurs in nonoverlapping regions. In particular, the first language typically elicits the usual left-sided pattern of activity, whereas the second often causes a more variable pattern that is more likely to be localized to the right side. Although the brain retains plasticity for learning a second language, the specific pattern of plasticity appears to depend on the age when that language is learned, which may also reflect ultimate fluency.

Finally, discussions of experience-related plasticity in cognitive ability and brain development often evoke the issue of genetics. What is the role of genes in the development of cognitive abilities? Researchers have long agreed that both genes and experience influence cognitive outcomes. For instance, twin studies have shown that even when genetic effects are taken into account, violence in the home is linked with lower IQ.⁴⁹ Conversely, both genes and environment affect cognitive resilience to the effects of low socioeconomic status.⁵⁰ Adoption studies have also shown that the socioeconomic backgrounds of both biological and adoptive parents are independent predictors of adopted children's IQ, reflecting genetic and experiential influences on the child, respectively.⁵¹

But the nature-nurture question is more nuanced than merely being a matter of where the balance of influence lies. Researchers now recognize that genes and experience are not truly independent predictors, but that in many cases nature is in part *moderated* by nurture. Animal research, for example, has shown that naturally occurring variations in maternal care can alter the expression of genes that regulate the response to stress and that early social attachment relationships can modify the heritability of aggressive behavior.⁵² Human research has drawn similar conclusions. Of particular relevance to understanding the gap in school readiness is a recent study showing that among families of lower socioeconomic status, variation in IQ is far more environmental than genetic in origin, whereas the converse holds in families of higher socioeconomic status.⁵³ That is, an impoverished child's background and experiences can so heavily influence his or her degree of achievement that his genetic makeup is nearly irrelevant in predicting his academic success. Optimistically, such a powerful role for experience suggests that intervention may be particularly successful among disadvantaged children.

Brain-Targeted Interventions

In this final section, we look ahead to the role that brain plasticity may play in developing and testing cognitive interventions in the three neurocognitive systems on which we have focused: memory and learning, cognitive control, and reading. It is premature to recommend specific interventions on the basis of brain evidence, but preliminary research in this nascent field is promising.

Researchers in brain plasticity have as yet done little work on memory training in humans. Although animal research has repeatedly shown that training on memory para-

digms can lead to improved learning and problem solving that is directly related to hippocampal plasticity, it is not yet clear whether similar effects could be observed in children.⁵⁴

Cognitive control has received somewhat more attention. Several studies have shown not only that young children with attention deficit hyperactivity disorder (ADHD) can benefit from repeated training on laboratory tasks known to involve prefrontal function, but also that training on such tasks can improve performance on untrained tasks involving similar regions.⁵⁵ These studies did not directly measure brain function, relying instead on tasks already shown to engage prefrontal regions. Recently, however, M. R. Rueda and colleagues showed that four-year-olds who attended seven sessions of attention training showed significant improvement on abstract reasoning skills relative to children who received a control intervention of watching videos. Furthermore, during a cognitive control task administered after their training was complete, the children showed brain activity that was more adult-like than that of the control group.⁵⁶ These preliminary results suggest the possibility of designing broader educational interventions that specifically target cognitive control, which a recent study found to be the single best predictor of resilience among high-risk children, even controlling for age, gender, negative life events, chronic strain, abuse, nonverbal IQ, self-esteem, parental monitoring, and emotional support.⁵⁷ Of course, the feasibility of any intervention program must be assessed outside the laboratory before being implemented on a larger scale.

Reading has attracted by far the most attention from those scientists investigating intervention-related brain plasticity.⁵⁸ Many studies have provided behavioral evidence that

children with mild to severe reading impairments can benefit from interventions that explicitly support phonological awareness and provide training in the alphabetic decoding skills necessary to convert print to sound.⁵⁹ Recent examinations of the neural effects of such behavioral studies provide a better understanding of how such programs improve skills, with the ultimate goal of targeting intervention to individual children's needs. Several investigators have used neuroimaging techniques to follow brain changes in children over the course of an intervention. One investigation found decreased brain activity in the left superior temporal gyrus region in eight children with reading difficulties, as compared with nonimpaired children.⁶⁰ Following a two-month intervention involving eighty hours of phonological processing work with one of two commercial packages (*Phono-Graphics* and *Lindamood Phoneme Sequencing*), the reading-impaired children's mean standardized reading scores improved from the 5th percentile to the 50th percentile. The children also showed increases in left superior temporal gyrus activity (as well as a decrease in right-sided activity). The eight nonimpaired children who did not participate in the intervention demonstrated stable brain responses over the same time span. Importantly, the study included no reading-impaired control group, making it impossible to tell whether changes were specific to the intervention or simply the result of generic tutoring or even schooling effects. Another interpretive difficulty was that before the intervention, the reading-impaired children showed very low accuracy in performing the task measured by the brain scanner. The changes in brain activity following the intervention, therefore, could have been due not to a change in brain function *per se* but rather to the children's engagement in a task to which they had previously not attended.

Similarly, Elise Temple and colleagues measured changes in functional activity in a group of reading-impaired children in whom pre-intervention functional magnetic resonance imaging indicated reduced activity in reading-related regions relative to children in a control group.⁶¹ After the children in the experimental group participated in a six-week, forty-five-hour intervention, including a commercial computer-based training program (*Fast ForWord Language*) and a special school curriculum for children with dyslexia, their reading improved significantly. Changes in their post-test functional MRI results were widespread, extending to fourteen brain regions, some of which also changed in the non-impaired group. Most of the regions undergoing change are thought to be typically involved in reading; several are not. The size of changes in regions associated with reading was correlated with improvements in oral language, but not with reading improvements. Again, this study is difficult to interpret because it lacked a reading-impaired control group randomized to a different intervention. To make interpretation even more complicated, in a separate randomized controlled study, more than 200 children in an urban school district received *Fast ForWord* but made no gains in reading compared with a control group of reading-impaired children who did not receive the program.⁶² This finding underscores the need for a reading-impaired control group in imaging studies and suggests that the strict adherence to an intervention required in the laboratory setting may be unrealistic in the classroom.

Finally, a recent study followed a group of children who received an experimental intervention consisting of fifty minutes a day of individual tutoring focused on phonological awareness and the alphabetic principle and contrasted it with a "community interven-

tion” group that received normal school-based remedial reading instruction.⁶³ The children were tested before and after eight months of intervention and were also compared with a control group of nonimpaired readers. Following the intervention, children in the experimental group had made significantly greater gains in reading fluency than had those in the community intervention group. They also showed brain activity during reading that looked remarkably similar to that of children in the nonimpaired control group—and they maintained this more typical pattern of activity for at least one year. The community intervention group showed less activity in the typical reading-related areas than did the other two groups.

Together, these three studies suggest that brain regions involved with reading in typically developing readers may prove to be quite malleable in response to effective therapeutic interventions. Brain activation patterns in these regions can change dramatically over the course of relatively short-lived interventions. As noted, successful interpretation of study results requires the rigorous use of control groups to examine both the behavioral efficacy and neural specificity of any intervention effects. In addition, improvements must be followed over time to verify that gains persist. Finally, interventions that succeed in the laboratory must be tested in real classroom environments before they can be widely implemented. Although it would be premature at this time to recommend a specific program for use, we are becoming more confident of the efficacy of combined training in phonological awareness and the alphabetic principle, as laboratory tests of that particular combination often show both

improved reading skills and patterns of brain activity that look more like those seen in typically developing readers.

But it is not enough for an intervention to improve reading skills on average. Ultimately, the goal is to tailor particular interventions for individual children. If, as we believe, similar low levels of reading performance—or any other neurocognitive skill—may result from different causes, then imaging the brain may help to tease such effects apart, extending our knowledge beyond the limits of behavioral data. We now have the ability to examine whether similar behavioral profiles associated with disparate risk factors might be rooted in different effects on brain development. In fact, it may be differences in brain development, rather than in behavioral performance, that ultimately predict an individual child’s response to intervention.

Tantalizing preliminary evidence for this suggestion comes from a study showing that both socioeconomic status and a particular neuroanatomical measure (left-right asymmetry of the planum temporale in the temporal lobe) independently predicted reading ability.⁶⁴ The study suggests that researchers can predict a child’s reading achievement levels better by using a combination of information about the brain and about social background than by using either type of information alone. By using both types of information, they might one day be able to design interventions that meet an individual child’s needs in ways that simple behavioral measures alone cannot. Indeed, by thus honing the tools of intervention, they may ultimately reduce the gap in achievement so often observed for underserved groups.

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