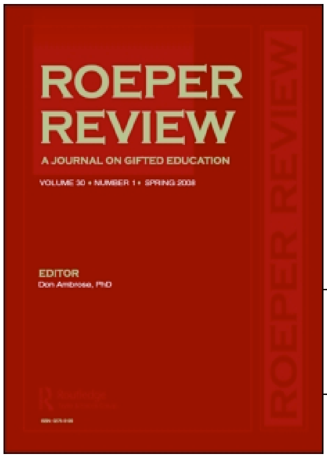

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Brain Imaging Studies of Intelligence and Creativity: What is the Picture for Education?

Richard J. Haier and Rex E. Jung

The goal of this article is to summarize current brain research on intelligence and creativity that may be relevant to education in the near future. Five issues are addressed: (a) Why is there a neuroscience interest in intelligence? (b) Can intelligence be located in the brain? (c) Why are some brains smarter than others? (d) What do we know about creativity and the brain? and (e) Can information about an individual's brain structure and function be useful to benefit his or her education? As we enter the 21st century, old controversies about measurement of intelligence are less relevant. Integrating neuroscience findings into education practices is a daunting challenge that will require educators to reexamine old ideas and acquire fundamental backgrounds in new areas.

As we enter the 21st century, neuroscience techniques will accelerate our understanding of how the brain works. Brain-imaging technologies are particularly helpful because they can identify brain areas, and the relationships among them, that underlie psychological processes central to education including learning, memory, attention, and reasoning. Moreover, there is a renewed interest in the neural basis for individual differences in these processes and for the complex integration of these processes that form the basis for most concepts of human intelligence. There is considerable progress in this area, as we summarize here.

In our view, understanding the neural basis for individual differences central to intelligence may present the single most important challenge to educators in the next decade, especially if it turns out that the neural basis of intelligence is amenable to educational strategies. Whether this is true is an empirical question yet to be answered and, as of now, there is relatively little investigation of this issue given its critical importance. Although research in cognitive psychology has advanced considerably in the last two decades, it is still not known why some people learn faster than others, or why some people have better memories or longer attention spans than other people, or why some people are much better at mathematical reasoning than at spelling, or why some people are more creative than others. Brain-imaging research is just beginning to address these questions; thus, educators do not yet have a strong empirical basis from neuroscience for tailoring one educational strategy or another for particular students. However, the results of this emerging research field likely will affect all students across the range of intellectual attainment from the lowest to the very highest.

In fact, even if neuroscience results offer educators potential advances, it is not clear that the education community is ready or prepared to listen. For example, there is no single concept more important in education than the concept of intelligence, but the very word is so controversial that it has all but disappeared from most educational discourse. One exception is the popular psychology notion of "multiple intelligences," but there is virtually no empirical support for it (see current debates: Gardner & Moran, 2006; Waterhouse, 2006a and b). The specialty field of gifted education is another notable exception where there is considerable interest in research identifying the neurobiology associated with very high mental ability levels (Haier & Benbow, 1995; Kalbfleisch, 2004, 2006, in press; O'Boyle et al., 2005). The more general disdain for intelligence is not because there is a lack of empirical data about the unbiased assessment of intelligence and the many biological and social correlates of such assessments. To the contrary, there is an enormous, scientifically robust research literature that is often ignored in discussions about education (Murray 2007a, 2007b, 2007c; Neisser et al., 1996). In part, this may derive from the vehement controversies about group differences in IQ that were well publicized in the late 1960s and were reignited with publication of *The Bell Curve* in the 1990s (Hernstein & Murray, 1994). There also is the

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common idea that all individuals have the same intellectual potential if only environments and opportunities were equal, although there are compelling reasons why this idea is not valid (Pinker, 2002).

Despite these controversies, it is time for educators to reexamine the current state of knowledge about intelligence (Jung & Haier, 2007; Neisser et al., 1996) so that new findings about the neural basis of intelligence, and the component processes of learning, memory, and attention, can be discussed and studied for relevance (if any) to education (Byrnes & Fox, 1998a and b; Geake, 2004; Geake & Cooper, 2003; Goswami, 2004). It also is important to note that attending to neuroscience data concerning intelligence does not preclude using any new data about important environmental influences, should such data become available and survive similar levels of scientific scrutiny.

As the concept of intelligence has divided and perplexed many educators and parents, interest in creativity has increased. However, there are few neuroscience studies of creativity or of the creative process. This is most likely due to the difficulties of defining creativity and the lack of psychometric means of assessing it, problems largely addressed and overcome in research on intelligence. Nonetheless, there may well be a neural basis for creativity. If so, it will be important to distinguish how this concept differs from and/or overlaps the neural basis of intelligence. To this end, we will summarize some theoretical and brain-imaging efforts in this direction.

It is our goal in this article to bring to the reader's attention some of the current brain research that may be relevant to education in the near future. The remainder of this article is organized to address the following questions:

1. Why is there a neuroscience interest in intelligence?
2. Can intelligence be located in the brain?
3. Why are some brains smarter than others?
4. What do we know about creativity and the brain?
5. Can information about an individual's brain structure and function be useful to benefit his/her education?

WHY IS THERE INTEREST IN BRAIN CORRELATES OF INTELLIGENCE?

Psychometric intelligence testing is the subject of debate and controversy, but there is overwhelming data that such assessments have considerable construct and predictive validity (Gottfredson, 1997). This is true for several concepts of intelligence including the *g*-factor, crystallized intelligence, fluid intelligence, and intelligence in general. There are substantial individual differences among people on intelligence measures and much of this variance can be attributed to genetic factors (Bouchard, 1999, 1998). Since genes always work through biology, there must be a biological basis to intelligence, and so there is a logical focus on understanding how biological and genetic variables influence the brain. There is no controversy about the importance of understanding these influences for Alzheimer's disease, mental illness, mental retardation, learning disabilities, and many other serious problems. Surely, there are biological and genetic influences on the cognitive processes that underlie intelligence in the absence of neurological problems and a major neuroscience effort to understand these influences is warranted.

It is important to note that there is a common misconception that anything that has a biological or genetic basis, even in part, is relatively difficult to change compared to something with a largely environmental basis. Just the opposite may be true. Every time you visit a physician it is with the expectation that broken biology can be fixed. In the 21st century, we are beginning to have innovative techniques to alter the neurobiology of the brain; these include new drugs and targeted delivery into specific brain areas, electrical stimulation of deep brain structures with implanted electrodes, genetic engineering, and even surgical interventions including tissue transplantation in the brain. Currently, this research and funds that support it target neurological and psychiatric problems, but as progress continues there is every reason to expect that new knowledge can be applied to understanding intelligence. For example, if there are drugs developed to dramatically improve memory in Alzheimer's disease (AD) patients, how will such drugs affect college students studying for exams? Such a "miracle" drug for treating AD is a goal for many determined researchers and a major effort in neuroscience. Since memory is a key component of intelligence (Colom, Rubio, Chun Shih, & Santacreu, 2006), there undoubtedly will be controversial issues about using such drugs in people without AD to optimize learning or mathematical ability or reading speed or any other cognitive process. This debate will be vigorous with or without participation from educators, who may wish to argue that intelligence is an inexact or irrelevant concept.

There already is serious concern about parents seeking a diagnosis of ADD so that their child can receive medication or have additional time during SAT testing (a *de facto* intelligence test; Frey & Detterman, 2004) and anecdotal reports of students taking a wide range of drugs (e.g., modafinil) with or without prescriptions to "augment" performance during studying and/or examination in high school and college. Thus, even with limited neuroscience knowledge about the details of individual differences in intelligence, there is growing interest in using drugs developed to treat diseases and disorders to improve normal cognitive performance relative to peers in educational settings.

CAN INTELLIGENCE BE LOCATED IN THE BRAIN?

In the last 20 years, over 40 brain-imaging studies using a variety of techniques have identified specific areas related to various measures of intelligence (including crystallized, fluid, *g*, and others). A fundamental question has been whether there is one main intelligence area or whether there are several areas distributed throughout the brain. We recently reviewed this literature and found a rather striking consensus across these studies (Jung & Haier, 2007). In our view, the evidence clearly favors a distributed network model, including regions within the parietal and frontal lobes linked by discrete white matter tracts, underlying performance on measures of intelligence, reasoning, and even games of strategy such as chess and Go. We call this model the Parieto-Frontal Integration Theory of intelligence, or P-FIT. Following is a brief summary from our review of how we think it works and the specific brain areas involved (denoted as Brodmann areas [BA], standard classification system of brain areas; Broadman, 1912; see Figure 1).

The P-FIT recognizes that our species gathers and processes information predominantly through auditory and/or visual means, usually in combination; thus, particular brain regions within the temporal and occipital lobes are critical to early processing of sensory information: the extrastriate cortex (BAs 18, 19) and fusiform gyrus (BA 37), involving recognition and subsequent imagery and/or elaboration of visual input, and Wernicke's area (BA 22), involving analysis and/or elaboration of syntax of auditory information. This basic sensory processing is then fed forward to the parietal cortex, predominantly the supramarginal (BA 40), inferior parietal (BA 7), and angular (BA 39) gyri, wherein structural symbolism and/or abstraction of the current set to alternative cognitive sets are generated and elaborated. The parietal cortex interacts with frontal regions (i.e., BAs 6, 9, 10, 45–47), which serve to hypothesis test various solutions to a given problem. Once the best solution emerges, the anterior cingulate (BA 32) is engaged to constrain response selection as well as inhibition of other competing responses. This process is critically dependent upon the fidelity of underlying white matter needed to facilitate rapid and error-free transmission of data from posterior to frontal brain regions.

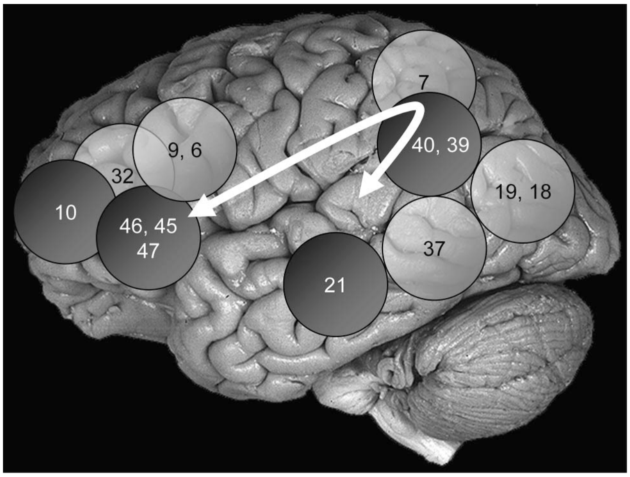

FIGURE 1 Brain regions by Brodmann area (BA) associated with better performance on measures of intelligence and reasoning that define the P-FIT model. Numbers represent BAs; dark circles = predominant left hemisphere associations; light circles = predominant bilateral associations; white arrow = arcuate fasciculus.

Does this model help educators? Not yet, but identifying the specific brain areas necessary for intelligence (as defined by the tests used in these studies) is an important step for understanding the properties that help integrate their functioning into networks. Whether the P-FIT is confirmed in whole or in part by future research, once the areas and their properties are known, interventions can be imagined, as discussed in the subsection on usefulness to education later in this article. Already, this kind of research has provided strong validation evidence for psychometric assessments of intelligence since there is clear evidence that such scores are associated with specific brain characteristics. In the near future, a major hypothesis to test is whether any combinations of the areas in the P-FIT predict something useful for education. For example, take two individuals with the same IQ but different patterns of gray matter volume in a subset of the P-FIT areas (for example, one student has more tissue in fusiform visual integration regions, the other more tissue in the Wernicke's language area). Should both individuals take the same courses taught in the same way? Imagine an educational research project to determine particular brain strengths and subsequently apply more visual hands-on approaches for the former student and a more classic (i.e., auditory-verbal) approach for the latter. We must emphasize that even if such brain-based knowledge becomes available, this does not preclude the importance of environmental, social, or cultural factors to the extent that they are shown to be relevant.

WHY ARE SOME BRAINS SMARTER THAN OTHERS?

Between 1988 and 2000, we were among the first to use modern brain-imaging with PET to address this type of question. PET scanning is based on injecting a small amount of radioactive sugar into a person. This sugar goes to the brain where it is used by neurons. The more a neuron fires, the more sugar it uses. After the injection, in our first study we had normal male volunteers work on a difficult test of abstract reasoning, the Raven's Advanced Progressive Matrices (RAPM; Haier et al., 1988). This is a nonverbal test and scores are highly corrected to IQ scores; the RAPM also loads high on the *g*-factor (i.e., the common factor among all mental abilities as defined originally by Spearman, 1904). As each person reasoned his way though 36 items, the areas of his brain working the hardest had the most neurons firing and the most radioactive sugar went to those areas. The scanning revealed the distribution of the radioactive sugar throughout the brain, so we could determine which brain areas were working the hardest while solving the problems. A control group also was scanned while each performed a simple test of attention with no problem-solving required. The results identified several areas that showed more activation while problem-solving. But, the surprise was that *more* activation in these areas was correlated to *lower* scores on the problem-solving test. Thus, the people with the highest scores on the reasoning test used less brain energy to solve the problems. We interpreted this finding as evidence that intelligence was associated with a more efficient brain rather than with a brain working harder.

There has been much subsequent research on the relationship between brain efficiency and intelligence and the performance of complex cognitive tasks (Neubauer & Fink, 2003; Neubauer, Fink, & Schrausser, 2002; Neubauer, Grabner, Freudenthaler, Beckmann, & Guthke, 2004). We continued this line of research by asking whether learning made the brain more efficient. To do so, we used PET scanning again to study more male volunteers the first time they played the computer game Tetris (Haier, Siegel, MacLachlan, et al., 1992), which involves making rapid visual-spatial decisions about placing different shapes together like a linear jigsaw puzzle. Not only was this game new at the time (and virtually unknown), but there were very few home computers yet, so we were able to easily find subjects unfamiliar with this visual-spatial game. Subjects were scanned the very first time they played and then scanned again after about 50 days of practice. As they got better and better during the practice period, the game grew harder and harder because each correct response increased the speed of the game. Nonetheless, the second scan showed decreases in brain function. We interpreted this as evidence that learning resulted in greater brain efficiency and speculated that during the learning period, the brain determined which areas not to use, reducing overall brain activity, whereas during the first scan when the game was novel, many brain areas were recruited inefficiently. We also showed that the subjects in this study who had the highest scores on the RAPM showed the greatest brain decreases in function after the practice period. This suggested that the smartest people became the most brain efficient most rapidly (Haier, Siegel, Tang et al., 1992).

We also used PET to study sex differences in mathematical reasoning ability (Haier & Benbow, 1995). Contrary to the brain efficiency idea, men showed greater brain activity in the temporal lobes the better they did on an SAT-M test. Women did not show this effect and women showed no brain areas where there was a relationship between activity and SAT-M score. This was one of the first demonstrations with functional imaging that men and women may use different areas to accomplish the same cognition. Subsequently, there are now several studies of intelligence that show clear sex differences in the brain, both in children and adults (Haier, Jung, Yeo, Head, & Alkire, 2005; Jung et al., 2005; Kimura & Harshman, 1984; Schmithorst & Holland, 2006; Yurgelun-Todd, Killgore, & Young, 2002).

Do these brain differences have no consequences for education? This is unlikely, but new ideas and research are needed to show how education could take advantage of such differences to optimize learning. Note that sex differences in the brain are statistical and while they may characterize either group in general, no statement can be made about any individual. This means that any potential application of knowledge about sex differences in the brain and how they may influence learning must be determined on a person-by-person basis. The fact that males and females have different brains may not be surprising, but the implication is quite important because it means that not all brains think the same way. This simple fact could be revolutionary for education because it demands a neuroscience approach that recognizes the importance of individual differences and the necessity to evaluate each student as an individual (Haier, 2007).

This idea was reinforced to us in a surprising PET finding. We reported that scores on the RAPM were correlated to brain activity even during a passive non-reasoning task (Haier, White, & Alkire, 2003). These correlations were in posterior visual processing areas and suggested that smarter people process incoming stimulation differently even before reasoning about the information occurs. If this finding is corroborated in future studies, it may have important implications for education because it means that not all brains work the same way as they process information even before reasoning occurs. Surely, educational strategies can be developed and targeted to individual students based on an empirical assessment of how their brain processes stimuli, although this will require considerable effort.

It should be said at this point that PET studies are difficult to interpret. Usually the sample sizes are quite small because of the high cost per scan and because each task used during the uptake of the radioactive sugar will have its own pattern of activity. Although we have found some consistencies across PET studies of intelligence and across fMRI studies (a different way of assessing brain function without any radioactive component), we decided to undertake a series of new studies using structural MRI to measure brain structures, especially the amount of gray matter and white matter. The technique of voxel-based morphometry allowed us to look at gray and white matter distributions throughout the brain and correlate them to intelligence test scores voxel by voxel (the voxel is the smallest unit of a brain image).

These findings show that more gray and white matter in several areas is associated with higher intelligence scores (Haier, Jung, Yeo, Head, & Alkire, 2004). These areas are different in young and older adults (Haier et al., 2004) and different in men and women (Haier et al., 2005), so how these areas or subsets of these areas relate to the P-FIT is not yet known. Also, the more *g*-loaded the test, the more brain areas have correlations between gray matter and test scores (Colom, Jung, & Haier, 2006a, 2006b). We speculate that having more gray matter in these key areas results in having more resources to work a problem and this results in those areas working less hard or more efficiently.

More and more imaging studies are becoming available and interesting results continue to accumulate about the factors that account for why some brains are better than others for memory (Rypma, Berger, & D'Esposito, 2002; Rypma & D'Esposito, 1999), learning (Breitenstein et al., 2005; Chein & Schneider, 2005; Kelly, Hester, Foxe, Shpaner, & Garavan, 2006; Little & Thulborn, 2005; Shelton & Gabrieli, 2004), intelligence (Geake & Hansen, 2005; Jung et al., 2005; Lerch et al., 2006; Schmithorst & Holland, 2006; Shaw et al., 2006), and other abilities like writing (Xue, Chen, Jin, & Dong, 2006) and reading (Leonard, Eckert, Given, Virginia, & Eden, 2006). In our view, there is not yet any educational use of these observations but they support the idea that individual differences in brain function and structure are related to individual differences in specific cognitive abilities and to intelligence. Surely, this idea will have educational implications, as discussed later in this article.

WHAT DO WE KNOW ABOUT CREATIVITY AND THE BRAIN?

The most common definition of creativity is something both *novel* and *useful* (Sternberg & Lubart, 1999). One readily can appreciate that mere novelty does not equal creativity: random splashes of color on a canvas or the neologisms of schizophrenia are certainly novel but not useful. To be truly creative there must be some inherent utility in the product, whether it be for aesthetic consumption (e.g., modernism), to fill a technological need (e.g., the Internet), or to push our understanding of nature forward (e.g., theory of relativity). One of the first models of the creative process was put forth by Wallas (1926), based in part on the previous work of Helmholtz (1826), who described a five-stage process comprised of *preparation* (the acquisition of skills), *incubation* (where the problem is internalized), *intimation* (where a feeling occurs that a solution is on the way), *illumination* (or a sudden burst of insight), and *verification* (where the idea is checked against reality and applied). Early psychometric researchers (e.g., Guilford, 1950) attempted to distinguish linear and logical thought processes (i.e., convergent thinking) from more diffuse and impressionistic thought patterns (i.e., divergent thinking, James, 1890), a major conceptual dichotomy that survives to this day and is manifested in psychometric measures of deliberate creative acts (Guilford, 1968; Torrance, 1974). Thus, the notion of creativity has been distilled from centuries of thought, and discrete measures have been developed from which theories might be experimentally tested. However, the psychometric properties of creative measures are in their infancy as compared to the 100+ years of research devoted to intelligence measures.

Within discussions of creativity, there still exist two major schools of thought, primarily separated by the notion of whether creativity is a subset of intelligence (Guilford & Christensen, 1973) or distinct from intelligence and social factors such as *common sense* (Gardner, 1985; Sternberg & O'Hara, 1999). Most researchers agree that creativity and intelligence are correlated with one another up to a certain threshold (around an IQ of 120), after which they tend to vary independently (Barron & Harrington, 1981), although others have found no association between IQ and creativity (Herr, Moore, & Hasen, 1965; Simonton, 1994). What all researchers tend to agree upon is that intelligence, and particularly the acquisition of domain-specific skills and knowledge (i.e., *preparation*) stored within the posterior part of the brain (Heilman, Nadeau, & Beversdorf, 2003), is necessary for the creative process to occur but not sufficient to ensure its manifestation. We make the distinction between convergent cognitive processes, which arrive at one correct answer, and divergent thinking, wherein multiple correct responses are possible. The psychometric analogs of these constructs are standardized intelligence tests (e.g., Ravens Progressive Matrices Test; Raven, 2000) and tests of divergent thinking (e.g., Multiple Uses Test; Torrance, 1971). Again, whether the brain structures, organization, and networks underlying intelligence and creativity are distinct, common, or substantially overlap is an empirical question. We have described (above) a discrete brain network associated with intelligence across myriad neuroimaging paradigms (Jung & Haier, 2007); thus, testing hypotheses regarding the relative overlap of creative brain processes with "intelligence" and other networks associated with higher cognitive functioning (Cabeza & Nyberg, 2000) is within our grasp and potentially of high import to the education field.

Some strive to be creative by force of will, while others experience creative insight (i.e., illumination) as if from out of the blue; most experience their creative thoughts as sometimes spontaneous, other times deliberate. The major distinction regarding the cognitive networks associated with these experiences revolves around the notion of explicit, or rule-based, systems associated with cognitive awareness and implicit, or experienced-based, systems inaccessible to conscious awareness (Graf & Schacter, 1985; Schacter & Buckner, 1998). Neurological distinctions have been made based on whether the frontal lobes are engaged or whether more posterior brain regions (Heilman et al., 2003) or subcortical structures (e.g., basal ganglia) are more predominant (Dietrich, 2004). As the "final common pathway" to such higher cognitive functions as sustained attention, working memory, and integration of sensory processes, the frontal lobes must be a major region of inquiry regarding the neuroscience of creativity (Dietrich, 2004).

Indeed, to the extent that creativity is the result of deliberate and methodical problem-solving, discrete frontal brain regions—particularly the dorsolateral prefrontal cortex (DLPFC)—would be expected to constrain the creative product. Neuroimaging data support the notion that the DLPFC is recruited during working memory, semantic retrieval, episodic encoding and retrieval, priming, and explicit categorization (Cabeza & Nyberg, 2000), all critical to deliberate creative acts. However, the specific role of the DLPFC in creativity, particularly whether more or less DLPFC activation is associated with higher creative quality and output (analogous to the neural efficiency model of intelligence; Haier et al., 1992; Neubauer et al., 2004) is unknown.

Brain processes associated with spontaneous creativity also are largely unexplored, although several reports suggest that rest/relaxation, meditation, sleep, and dreams are a major source of creative ideas (Dietrich, 2004; Hobson, 1988). Indeed, several lines of evidence, particularly from electroencephalography (EEG) experiments wherein electrical impulses arising from neuronal firing are measured at the scalp (Jausovec & Jausovec, 2000; Petsche, 1996), would suggest that a more distributed network associated with lower levels of cortical arousal (Martindale & Hasenfus, 1978), diminished prefrontal activity, and even frontal inactivity during sleep (Braun et al., 1997) might be associated with spontaneous creative output (Heilman et al., 2003). Cajal (1897) advised young scientists "If a solution fails to appear after all of this…try resting for awhile." This notion of "rest" has garnered significant interest within the cognitive neurosciences. Defined as "an organized, baseline default mode of brain function that is suspended during specific goal-directed behaviors" (Raichle et al., 2001, pp. 676–682), this lowered level of brain activity has undergone intense scrutiny associated with the brain's readiness to respond to changes in the external and internal environment (Fransson, 2005). Moreover, the default mode has been linked to alpha-level activity (brain waves observed when individuals are awake with their eyes closed) during EEG acquisition (Laufs et al., 2006), the significance to creativity research of which will be described below.

Neurological inquiries of creativity in normal cohorts is sparse, yet a handful of EEG studies provided tantalizing support that imaging of the creative experience is both possible and informative to understanding the interactions of distributed neural networks. For example, early EEG studies demonstrated that highly creative individuals differed from normal controls in: (a) greater activity within right parieto-temporal areas, (b) higher alpha activity during analogs of "inspiration," and (c) greater tendency to present physiological overresponse (Martindale & Greenough, 1973; Martindale & Hasenfus, 1978; Martindale & Hines, 1975). A second group has shown greater dimensional complexity in subjects when undertaking tasks of divergent thinking (compared to convergent thinking tasks) over central and parietal cortices, which they interpret as "loosened attentional control during creative thinking" (Molle et al., 1996, p. 61). Similarly, one study that compared gifted, intelligent, creative, and average individuals (Jausovec, 2000) found lower levels of mental activity in highly creative subjects when compared to average individuals when engaged in the solution of creative problems. This same group (Jausovec & Jausovec, 2000) found that, when 115 normal individuals were stratified across measures of creativity and intelligence, EEG coherence (during "rest" with eyes open) was significantly related to creativity scores, particularly across the right hemisphere. Finally, a recent group studied 31 normal controls, finding lower levels of cortical arousal during creative problem-solving and stronger alpha synchronization in centroparietal cortices associated with more original responses (Fink & Neubauer, 2006). This same group used a pre-post within-subjects design to show that training on creativity tasks resulted in higher frontal alpha wave synchronization post training, which they interpret as "selective top-down inhibition of external input" during task performance (Fink, Grabner, Benedek, & Neubauer, 2006). Taken together, these studies point to the importance of posterior brain regions, as well as more diffuse frontal activation, during performance of creativity tasks.

Finally, the neurobiology of creativity has been addressed using regional cerebral blood flow (rCBF), single photon emission computerized tomography (SPECT), positron emission tomography (PET), and functional magnetic resonance imaging (fMRI), all of which infer neuronal activity through measurement of either blood flow or uptake of radioactive isotopes. The first study (Carlsson, Wendt, & Risberg, 2000) was undertaken in 12 healthy male subjects stratified by either high or low scores on a creativity test. Blood flow measures were compared during performance of verbal fluency and divergent thinking task. The highly creative group was characterized by bilateral frontal activation during the divergent thinking task compared to predominantly left hemisphere activation in the low creative group. Interestingly, better performance on the creative task was negatively correlated with higher activity within superior frontal regions, suggestive of neuronal efficiency (Haier et al., 1992; Neubauer et al., 2004). SPECT was used to study 12 highly creative subjects while performing figural and verbal creativity tasks. These authors found a positive relationship between the creativity index and cerebral blood flow throughout various regions of the brain, representing a "highly distributed brain system" underlying creativity (Chavez, Graff-Guerrero, Garcia-Reyna, Vaugier, & Cruz-Fuentes, 2004). PET was used to study normal subjects as they performed verbal creativity tasks, with brain activations observed in the left parieto-temporal brain regions (Brodmann areas 39 and 40) considered to be "crucial" to the creative process (Bechtereva et al., 2004). Only one fMRI study exists that attempts to localize creative story generation within the brains of a cohort of 8 normal subjects (Howard-Jones, Blakemore, Samuel, Summers, & Claxton, 2005). When creative story generation was contrasted to uncreative story generation, significant activations were observed within bilateral medial frontal gyri (BAs 9, 10) and the left anterior cingulate (BA 32). Across studies, no clear consensus emerges as to whether frontal or more posterior brain regions are more central to the creative process and whether more or less activation induces creativity, although the results beg for further research that might be subsequently translated into the classroom.

CAN INFORMATION ABOUT AN INDIVIDUAL'S BRAIN STRUCTURE AND FUNCTION BENEFIT HIS OR HER EDUCATION?

In our view, the main findings from the neuroimaging studies we have summarized are that: (a) not all brains work the same way, (b) some optimal combination of tissue density and activation in frontal and more posterior brain regions appear to underlie both intelligence and creativity, and (c) in some cases *less is more* best characterizes neuroimaging results in terms of efficiency (with regard to intelligence) and disengagement (with respect to creativity). These results likely comport well with most everyday intuition and experience of teachers, but the neuroscience findings now point to ways of assessing the strengths and weaknesses of individual brains so that education can be more precisely targeted to individual students. For example, MRI scans are noninvasive, with minimal risk, and relatively inexpensive (less than a psychological test battery). Suppose a person can have a 20-minute structural MRI scan to determine his or her pattern of gray and white matter in the areas salient for intelligence, like those proposed in the P-FIT. Will this pattern predict either the best subjects for this person to focus on or the best educational strategies to help this person learn a specific subject? Research studies to test these ideas are possible today if there was sufficient funding to test large, diverse samples such as that described recently articulating developmental brain processes associated with intelligence (Shaw et al., 2006).

On an even more speculative note, neuroscience research suggests that there may be neural factors that increase the growth of regional gray matter or white matter. If such factors exist, drugs can be developed to stimulate them. Whether such drugs would work best during childhood or perhaps even in the adult brain is an empirical question. Suppose they work better in men or women. Clearly, if such drugs can be targeted to the salient areas for intelligence, creativity, or specific cognitive abilities (e.g., mathematical reasoning, learning a second language, etc.), a host of ethical issues will need careful consideration by educators, parents, and society at large. Such issues expand on current concerns regarding the drugs now used on an as-wanted but unapproved basis to augment attention and concentration in normal high school and college students. Better drugs for this purpose will be available and, much like the drug augmentation debates in sports, we need to examine the issues very carefully for education.

Finally, and perhaps the least potentially controversial, if we know how the brain of an individual learns or remembers or creates, can we envision a unique educational strategy or intervention to maximize this person's potential? Educators try to do this now, but wouldn't brain data for each student provide an empirical way to optimize this process? Concerns that using such brain data in education may result in wrong and even harmful decisions are legitimate. An alternate perspective, however, might include whether using brain data results in better decisions and fewer harmful mistakes than the current methods used in education. The question is whether brain information in general and for specific individuals can improve education from the baseline of current practices, not whether it is perfect in all cases. Educators must work with brain researchers to design the proper studies to establish how new neuroscience information can translate into the classroom.

Research developments could come rather quickly. Educators may well find themselves on the cutting edge of applying new knowledge about the brain and how it works during the learning and education processes. This is a challenge that will require a reexamination of old ideas and continuing education about new research techniques so that our deliberations and good intentions are informed by the best science available (Goswami, 2006). Given the history of modern educational controversies (e.g., Humes, 2007) and the general lack of advanced technical training about research and statistical methods that typifies many educational degree programs, there is no obvious reason for optimism that this challenge can be met. Neuroscience is advancing inexorably, so sooner or later, educators must engage these issues with expertise that is not easy to obtain. There are some resources concerning basic neuroscience and education available, but for the most part, they either ignore intelligence as a topic (Blakemore & Frith, 2005) or assert that there is no scientific definition of intelligence (Organization for Economic Co-operation and Development, OECD, 2007). Someday, we believe that our educational system will be informed by neuroscience knowledge, especially concerning intelligence, but how we get from here to there remains unclear.

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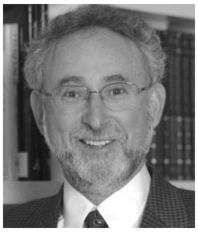

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