What Does a Smart Brain Look Like?

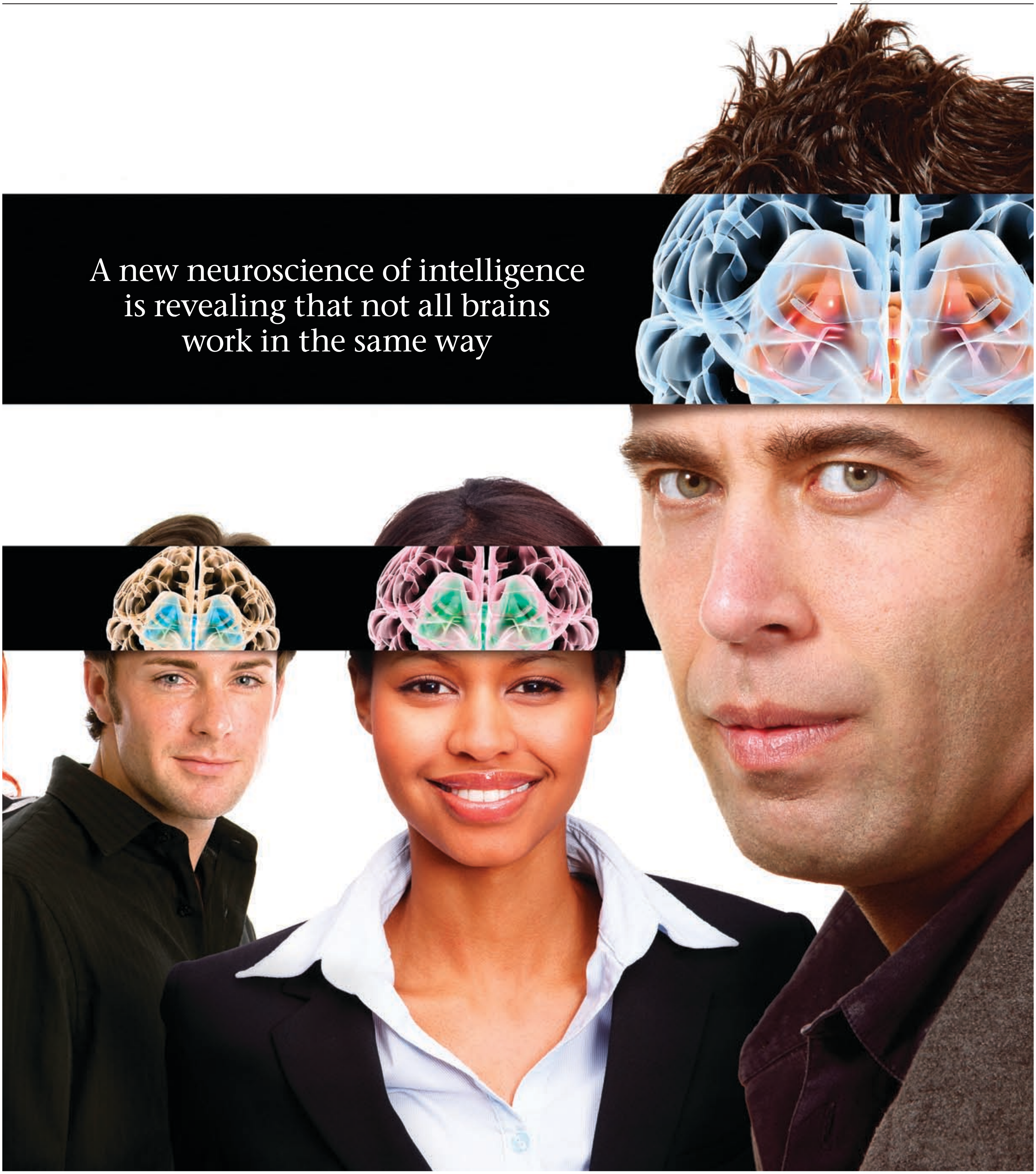
By Richard J. Haier

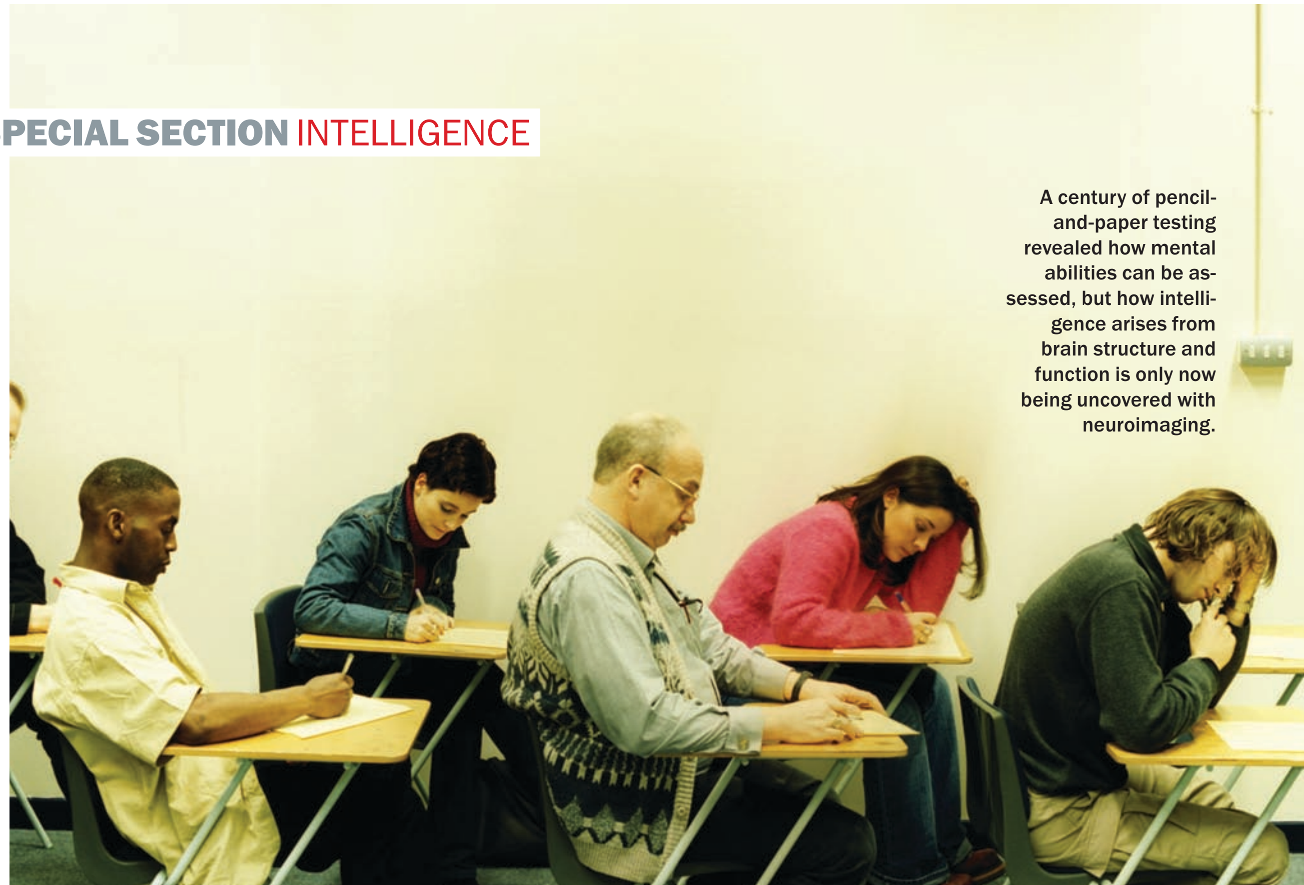
We all know someone who is not as smart as we are—and someone who is smarter. At the same time, we all know people who are better or worse than we are in a particular area or task, say, remembering facts or performing rapid mental math calculations. These variations in abilities and talents presumably arise from differences among our brains, and many studies have linked certain very specific tasks with cerebral activity in localized areas. Answers about how the brain as a whole integrates activity among areas, however, have proved elusive. Just what does a "smart" brain look like?

AARON GOODMAN (*photoillustration*); PASIEKA/SPL/PHOTO RESEARCHERS, INC. (*brain images*)

Now, for the first time, intelligence researchers are beginning to put together a bigger picture. Imaging studies are uncovering clues to how neural structure and function give rise to individual differences in intelligence. The results so far are confirming a view many experts have had for decades: not all brains work in the same way. People with the same IQ may solve a problem with

A new neuroscience of intelligence is revealing that not all brains work in the same way





A century of pencil-and-paper testing revealed how mental abilities can be assessed, but how intelligence arises from brain structure and function is only now being uncovered with neuroimaging.

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equal speed and accuracy, using a different combination of brain areas. [For more on IQ and intelligence, see "Rational and Irrational Thought: The Thinking That IQ Tests Miss," by Keith E. Stanovich, on page 34.]

Men and women show group average differences on neuroimaging measures, as do older and younger groups, even at the same level of intelligence. But newer studies are demonstrating that individual differences in brain structure and function, as they relate to intelligence, are key—and the latest studies have exposed only the tip of the iceberg. These studies hint at a new definition of intelligence, based on the size of certain brain areas and the efficiency of information flow among them. Even more tantalizing, brain scans soon may be able to reveal an individual's aptitude for certain academic subjects or jobs, enabling accurate and useful education and career counseling. As we learn more about intelligence, we will better understand how to help individuals fulfill or perhaps enhance their intellectual potential and success.

For 100 years intelligence research relied on pencil-and-paper testing for metrics such as IQ. Psychologists used statistical methods to characterize the different components of intelligence and how they change over people's lifetimes. They determined that virtually all tests of mental ability, irrespective of content, are positively related to one another—that is, those who score high on one test tend to score high on the others. This fact implies that all tests share a common factor, which was dubbed *g*, a general factor of intelligence. The *g* factor is a powerful predictor of success and is the focus of many studies. [For more on *g*, see "Solving the IQ Puzzle," by James R. Flynn; Scientific American Mind, October/November 2007.]

In addition to the *g* factor, psychologists also have established other primary components of intelligence, including spatial, numerical and verbal factors, reasoning abilities known as fluid intelligence, and knowledge of factual information, called crystallized intelligence. But the brain mechanisms and structures underlying *g* and the other factors could not be inferred from test scores or even individuals with brain damage and thus remained hidden.

FAST FACTS

Smart Brains Revealed

1» **Brain structure and metabolic efficiency may underlie individual differences in intelligence, and imaging research is pinpointing which regions are key players.**

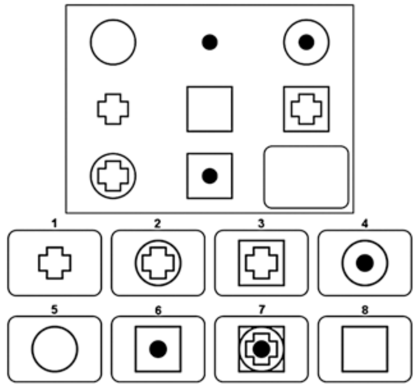
2» **Smart brains work in many different ways. Women and men who have the same IQ show different underlying brain architectures.**

3» **The latest research suggests that an individual's pattern of gray and white matter might underlie his or her specific cognitive strengths and weaknesses.**

The advent of neuroscience techniques about 20 years ago finally offered a way forward. New methods, particularly neuroimaging, now allow a different approach to defining intelligence based on physical properties of the brain. In 1988 my colleagues and I at the University of California, Irvine, conducted one of the first studies to use such techniques. Using positron-emission tomography (PET), which produces images of metabolism in the brain by detecting the amount of low-level radioactive glucose used by neurons as they fire, we traced the brain's energy use while a small sample of volunteers solved nonverbal abstract reasoning problems on a test called the Raven's Advanced Progressive Matrices [*see illustration at right*].

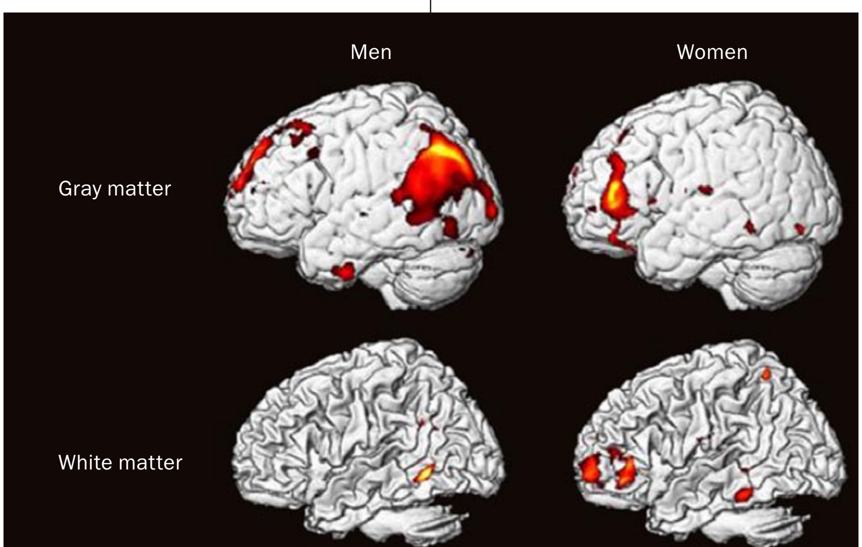
This test is known to be a good indicator of *g*, so we were hoping to answer the question of where general intelligence arises in the brain by determining which areas showed increased activation while solving the test problems. To our surprise, greater energy use (that is, increased glucose metabolism) was associated with *poorer* test performance. Smarter people were using less energy to solve the problems—their brains were more efficient.

The next obvious question was



Which of the eight options correctly completes the matrix? This type of abstract reasoning problem is similar to those on the Raven's test, a good indicator of general intelligence. (The answer is number 7.)

whether energy efficiency can arise through practice. In 1992 we used PET before and after subjects learned the computer game Tetris (a fast paced visuospatial puzzle), and we found less energy use in several brain areas after 50 days of practice and increased skill. The data suggest that over time the brain learns what areas are not necessary for better performance, and activity in those areas diminishes—leading to greater overall efficiency. Moreover, the individuals in the study with high *g* showed more brain efficiency after practice than the people with lower *g*.



The structural roots of intelligence may differ by gender. In women higher IQ scores are associated with more gray and white matter in frontal language areas, whereas in men higher IQ correlates with more gray matter in posterior sensory integration areas.

COURTESY OF RACHAEL GRAZIOPLENE (*top*); SCIENTIFIC AMERICAN MIND; SOURCE: R. E. JUNG ET AL. IN *NEUROIMAGE*, VOL. 26, NO. 3; 2005 (*bottom*)

By the mid-1990s we were focusing on efficiency as a key concept for understanding intelligence. But then, in 1995, we discovered a difference in the way male and female brains work, giving us our first clue to what we know today: the concept of efficiency depends on the type and difficulty of tasks involved, and there are individual and group differences in brain function during problem solving, depending on who is doing the thinking. In the 1995 study we tested a specific mental ability—mathematical reasoning. We selected college students with either very high or average SAT-Math scores and used PET to investigate their brain function while they solved mathematical reasoning problems. Unlike the *g* studies, this study showed the people with high math ability using *more* brain energy in a certain region (the temporal lobes), but this was true only for the men and not for the women—even though both men and women performed at the same level on the test.

Gender Matters

These observations have now been replicated by us and other researchers, especially in studies using advanced electroencephalographic (EEG) mapping techniques. In addition to these experiments showing differences in brain function, brain *structure* also seems to play a role—studies have suggested that other gender differences in cognition, such as the tendency for men to have better visuospatial ability, may be rooted in architecture.

For example, in a series of papers published in *NeuroImage* starting in 2004, we used structural MRI scans to investigate correlations between gray and white matter volume and scores on intelligence tests. Gray matter, made up of neuron cell bodies, does the computa-

(The Author)

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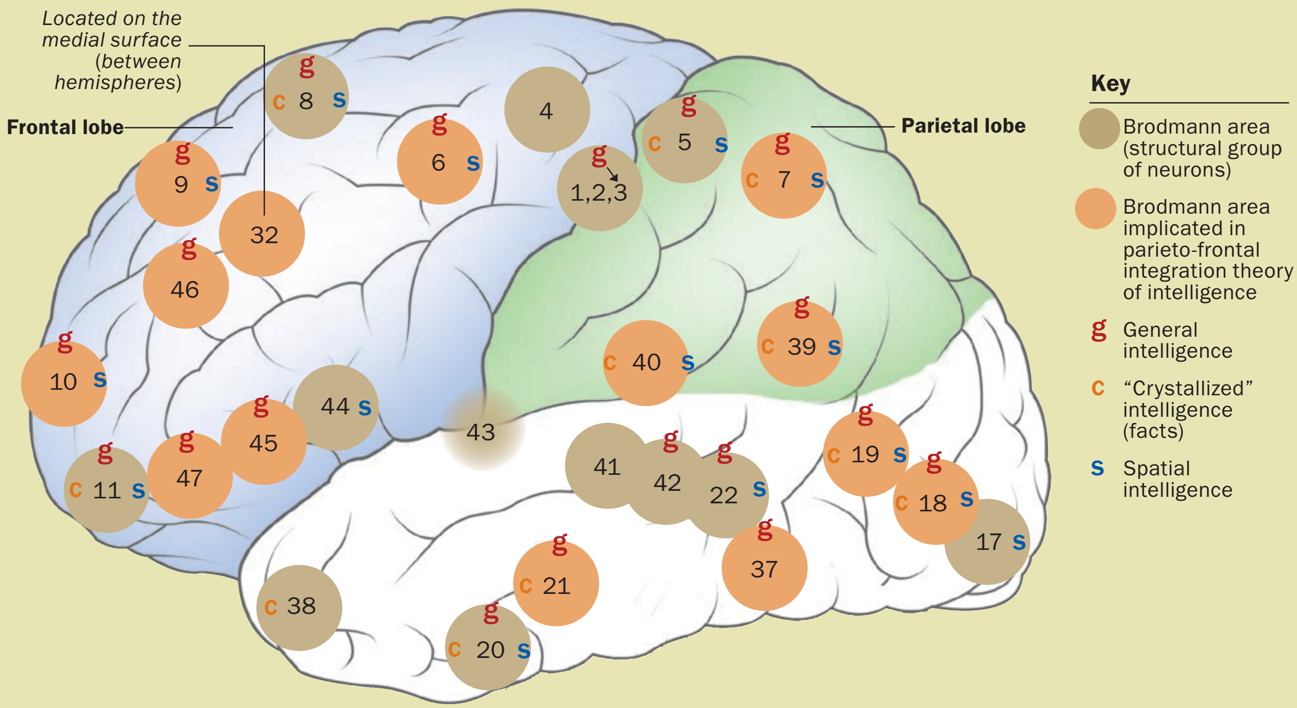
The Neural Roots of Intelligence



SCIENTIFIC AMERICAN MIND; SOURCES: R. E. JUNG AND R. J. HAIER IN *BEHAVIORAL AND BRAIN SCIENCES*, VOL. 30, NO. 2; 2007, AND K. MARTINEZ AND R. COLOM IN *PERSONALITY AND INDIVIDUAL DIFFERENCES*, VOL. 46; 2009

Brain-imaging studies reveal many areas in which the amount of gray matter (neuron bodies) correlates with intelligence test scores. The color patches above indicate the approximate location of the Brodmann areas—structural groupings of neurons numbered according to historical tradition. The letters on each Brodmann area indicate which intelligence factors it is associated with: general (g); spatial (s); and crystallized (c), or factual knowledge. Every individual has a unique pattern of gray matter in these areas [*see graph on opposite page*], giving rise to different cognitive strengths and weaknesses.

Fourteen of the Brodmann areas (*colored orange above*) are consistently implicated in studies of intelligence-related brain structure and function. Neuropsychologist Rex E. Jung of the University of New Mexico and I reviewed the studies and identified this network, calling it the parieto-frontal integration theory (P-FIT) because areas in the parietal (*green*) and frontal (*blue*) lobes were consistent across the most studies. Most of the P-FIT areas are involved in computation (frontal areas) and sensory integration (parietal areas), the processing and conscious understanding of sensory information. —*R.J.H.*

tional work of the brain. White matter enables communication among regions of gray matter via axons, brain cells' long, wirelike appendages. Our studies point to a network of areas distributed throughout the brain where more gray or white matter is related to higher IQ scores. The specific areas in this network are different in men and women, suggesting there are at least two different brain architectures that produce equivalent performance on IQ tests. In general, we found that in women more gray and white matter in frontal brain areas, especially those associated with language, was correlated with IQ scores; in men IQ scores correlated with gray matter in frontal areas and, especially, in posterior areas that integrate sensory information [*see bottom illustration on preceding page*].

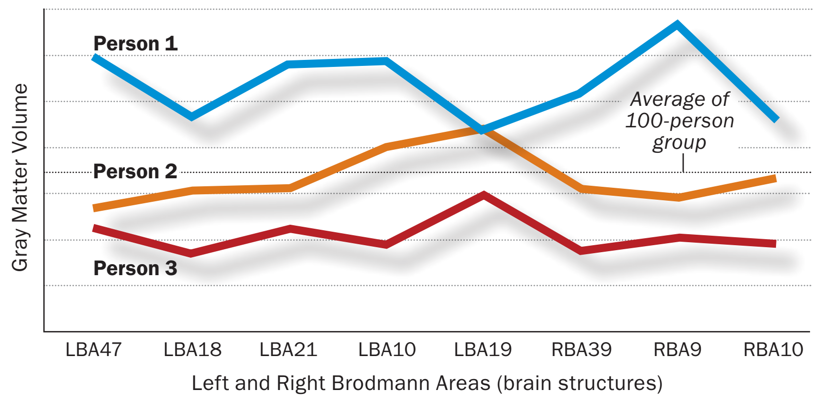
Children also show different developmental brain patterns related to IQ, depending on their gender. In a series of imaging studies with large samples, published from 2006 to 2008, neuroscientist Vincent J. Schmithorst of the Cincinnati Children's Hospital Medical Center and his colleagues found that as girls age they show increasing organization—that is, well-defined paths between disparate brain regions—in their right hemisphere. Boys, in contrast, show this developmental trend in their left hemisphere. We do not yet know how these findings relate to behavioral or learning differences, but the research points the way for future studies to determine how brain development relates to boys' and girls' cognition and academic achievement. [For more on gender differences, see "Sex, Math, and Scientific Achievement," by Diane F. Halpern, Camilla P. Benbow, David C. Geary, Ruben C. Gur, Janet Shibley Hyde and Morton Ann Gernsbacher;

Scientific American Mind, December 2007/January 2008.]

A New Definition

Gender differences were merely the first indication that not all brains work the same way. In 2003 we investigated whether we could observe functional variations during passive mental activity without a task assigned. Again we used PET in two groups of volunteers selected for high or average scores on the Raven's test. Both groups watched the same videos passively with no problem solving or other task demands. The group with high test scores showed different brain activations in posterior visual-processing areas as compared with the average group. The data suggest that early stages of information processing are more engaged in individuals with higher intelligence, perhaps suggesting that the smarter people in the study were not watching the videos "passively" after all—they were actively processing what they were seeing.

How Brains Stack Up



Brain profiles of three individuals show the amount of gray matter each has in areas associated with intelligence, called P-FIT areas [*for more information about these brain areas, see box on opposite page*]. The person who scored the highest in the 100-person study group on tests of general intelligence, or *g*, has far more than the group's average amount of gray matter in every area (*blue line*). The other two individuals (*red* and *orange lines*) had identical, average *g* scores, but their pattern of gray matter differs. Further research could reveal how such differences correspond to an individual's cognitive strengths and weaknesses.

Every individual uses some combination of intelligence-related brain areas in a unique way.

Although more and more evidence shows that problem solving and even passive sensory processing does not look exactly the same in every brain, we still are able to identify a network of areas that seem to give rise to intelligence in general. In fact, defining the crucial regions and connections will help us delineate exactly how each person's brain works—every individual uses some combination of these areas in a unique way.

In 2007 neuropsychologist Rex E. Jung of the University of New Mexico and I reviewed the 37 neuroimaging studies on intelligence that existed at that point. In the journal *Behavioral and Brain Sciences*, we identified salient brain areas found in both structural and functional studies with some consistency. The 14 areas are distributed throughout the brain, refuting the long-held notion that the frontal lobes alone are the primary location for intelligence. In particular, parts of the parietal lobes, located under the crown of the head and known to be involved in sensory integration, play a significant role. Because areas in the parietal and frontal lobes were most represented across the studies we reviewed, we called our theory of intelligence based on this network the parieto-frontal integration theory (P-FIT). The 14 P-FIT areas are involved in attention, memory, language and sensory processing [*see box on opposite page*].

Identifying the P-FIT network implies a new definition of general intelligence based on the brain's measurable characteristics. Both the amount of gray matter in certain P-FIT areas and the rate of information flow among these areas are likely to play key roles in intelligence. Earlier this year studies at University Medical Center Utrecht in the Netherlands and the Chinese Academy of Sciences in Beijing used functional MRI to determine the efficiency of connections throughout the brain, pinpointing P-FIT areas where connectivity was especially associated with IQ scores. The findings support the idea that general intelligence not only arises from gray matter volume but also depends to a large extent on the white matter connections between crucial gray matter areas. More efficient connections allow information to flow faster—and quick processing times seem to go hand in hand with a high IQ.

Everyone Is Unique

But IQ scores do not tell the whole story—not even close. Intelligence seems to arise from varying combinations of the P-FIT brain areas in different people, which may explain each person's individual strengths and weaknesses. The challenges of identifying these patterns are well illustrated by the extremely rare cases of autistic savants. Daniel Tammet, for example, is an autistic young adult with uncommonly high IQ scores. He sees numbers as colors and shapes, which allowed him to memorize the value of pi to 22,514 digits. He also learned to converse fluently in Icelandic after only sev-

SCIENTIFIC AMERICAN MIND; SOURCE: COURTESY OF RICHARD J. HAIER

en days of instruction. Tammet leads an independent life and wrote a best-selling autobiography describing his extraordinary numerical and language ability. What would his "brain profile" show? [For more on Daniel Tammet, see "Think Better: Tips from a Savant," by Jonah Lehrer; SCIENTIFIC AMERICAN MIND, April/May/June 2009.]

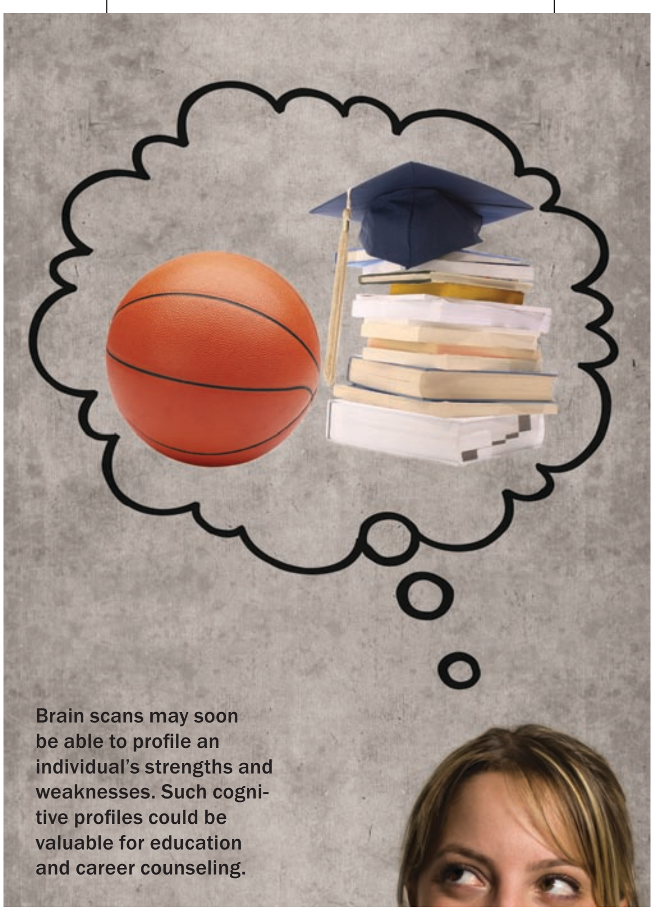
Although we are not currently able to deduce from a scan of Tammet's brain how his extraordinary abilities arise, the most recent wave of neuroimaging studies has given us clues to how we might one day do exactly that. New studies have found correlations between gray matter in certain areas and specific intelligence factors.

A learning program could be tailored based on an individual student's brain characteristics.

In March psychologist Roberto Colom of the Autonomous University of Madrid and his collaborators (including me) reported on the relation between gray matter volume and different intelligence factors in 100 young adults. Each person completed a battery of nine cognitive tests known to indicate different intelligence factors, including *g*, fluid intelligence, crystallized intelligence and a spatial factor. We found a positive correlation between scores on the *g* factor and the amount of gray matter in several areas predicted by P-FIT. And once we accounted for the common *g* factor, we found that gray matter volume in certain brain areas was related to the other specific intelligence factors. For details of which areas are connected to each factor, see the box on page 30.

One of the most tantalizing ideas to come out of this recent research is the possibility of matching an individual's gray and white matter pattern to his or her *g* and to other specific intelligence factors. In other words, the tissue in P-FIT areas may predict a person's unique pattern of cognitive strengths and weaknesses across a range of mental abilities. These differing brain profiles may explain why two people with an identical IQ score may show very different cognitive abilities. The data from Madrid illustrate this idea nicely [*see illustration on preceding page*]. The person in our volunteer group with the highest *g* score showed far more gray matter than the group's average amount in several P-FIT areas—perhaps not surprisingly. But it is interesting to note that two people with identical *g* scores of 100, the average for the group tested in the study, exhibited different cognitive profiles, suggesting different cognitive strengths and weaknesses.

The idea that we all have our own pattern of variations in brain areas that contribute to different intelligence factors is underscored dramatically by a structural MRI study in March of 241 patients with brain lesions. Psychologist Jan Gläscher of the California Institute of Technology and his colleagues showed that the site of each lesion was correlated with specific factor scores. For example, perceptual organization suffered—patients had trouble consciously understanding raw information from their senses—when their right parietal lobe was damaged.



Brain scans may soon be able to profile an individual's strengths and weaknesses. Such cognitive profiles could be valuable for education and career counseling.

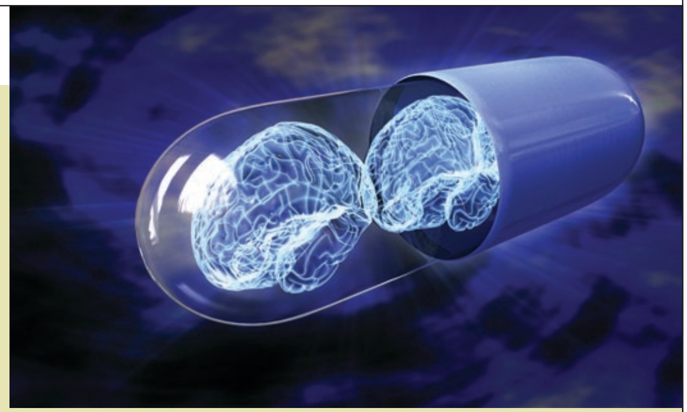
A Smarter Future

These most recent studies suggest that neuroimaging could one day become a supplement or even a substitute for traditional paper-and-pencil intelligence testing. An individual brain profile could be valuable. In education, for example, a learning program could be tailored for an individual student, at any age, based on that student's brain characteristics. Perhaps vocational success could also be predicted—are there patterns of gray matter across some areas, for example, that make for the best teachers, fighter pilots, engineers or tennis players? People seeking a better life with vocational and career consultation certainly will want the choice of having a brain assessment if there are data to support its usefulness.

But it is worth remembering that, contrary to older dogma,

BURAK PEKAKCAN *iStockphoto (thought bubble)*; GETTY IMAGES *(basketball)*; SHARON DOMINICK *iStockphoto (books and mortarboard)*

Boosting Healthy Brains



The latest research into the neural roots of intelligence may lead to better drugs and tools for cognitive enhancement. In the future, drugs may enhance the neurotransmitters that regulate communication among the salient brain areas underlying general intelligence or more specific mental abilities. Other drugs could stimulate gray matter growth or white matter integrity in relevant areas. Certainly such advances would be welcome as potential treatments for mental retardation and developmental disabilities. They may also be welcome by any individual looking for more intelligence.

If an effective "IQ pill" becomes available, are the societal and ethical issues the same as for performance-enhancing drugs in sports, or is there a moral imperative that more intelligence is always better than less? Apparently, many scientists agree with the latter. An online survey of 1,427 scientists conducted in 2008 by *Nature* found that 20 percent of respondents already use prescription drugs to enhance "concentration" rather than for treating a medical condition. Almost 70 percent of 1,258 respondents who answered the question said they would be willing to risk mild side effects to "boost their brainpower" by taking cognition-enhancing drugs. Eighty percent of all the scientists who responded—even those who did not use these drugs—defended the right of "healthy humans" to take them as work boosters, and more than half said their use should not be restricted, even for university entrance exams. More than a third said that they would feel pressure to give their children such drugs if they knew other kids at school were also taking them. Few appear to favor the "ignorance is bliss" position.

Intelligence is a critical resource for the development of civilization. As the global economy evolves and small countries compete with larger countries, assessing, developing and even enhancing intellectual talent may well become the neuroscience challenge for the 21st century. *—R.J.H.*

the brain is not set in stone or in genetic immutability. Exactly the opposite is true. The brain is plastic—it changes. A brain profile detailing a person's strengths would offer a guide rather than a prescription—perhaps suggesting ways to practice skills or improve education so that a person could become better suited for the activities or careers he or she is most interested in. Fascinating recent studies show that learning to juggle increases the amount of gray matter in brain areas relevant to motor activity. When the training stops, the additional gray matter disappears. Because regional gray matter is related to intelligence, can training beyond conventional education approaches be directed at specific brain areas to increase intelligence? We do not yet know, but the prospect is exciting.

The next phase of neurointelligence research may include studies designed to answer such questions, including education experiments to determine whether different strategies produce specific brain changes and whether students selected on the basis of their individual brain characteristics are more likely to maximize learning in a particular subject with one educational strategy versus another. The goal would be to enhance current educational decision making by adding customized information about each student's brain. How any specific brain characteristic develops and how it may be influenced are critical, but separate, questions for research.

Whether everyone agrees on precisely the same definition of intelligence or not, progress in neuroscience is inexorable. We will continue to discover how the brain manages the complex information processing that undoubtedly underlies all notions of intelligence. Given the ravages of brain disease, aging, the technical needs of modern societies, the challenges of education and the joy of experiencing the world through intellect, there is some urgency to understand how smart brains work. It is not too early for discussion about the implications of the search for neurointelligence and our willingness to go where the data lead. M

(Further Reading)

- **Why Aren't More Women in Science?** Stephen J. Ceci and Wendy M. Williams. American Psychological Association, 2006.
- **The Parieto-Frontal Integration Theory (P-FIT) of Intelligence: Converging Neuroimaging Evidence.** Rex E. Jung and Richard J. Haier in *Behavioral and Brain Sciences,* Vol. 30, No. 2, pages 135–187; 2007.
- **Brain Imaging Studies of Intelligence and Creativity: What Is the Picture for Education?** Rex E. Jung and Richard J. Haier in *Roeper Review,* Vol. 30, No. 3, pages 171–180; 2008.
- **Gray Matter Correlates of Fluid, Crystallized, and Spatial Intelligence: Testing the P-FIT Model.** Roberto Colom, Richard J. Haier, Kevin Head, Juan Álvarez-Linera, María Ángeles Quiroga, Pei Chun Shih and Rex E. Jung in *Intelligence,* Vol. 37, No. 2, pages 124–135; March-April 2009.

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