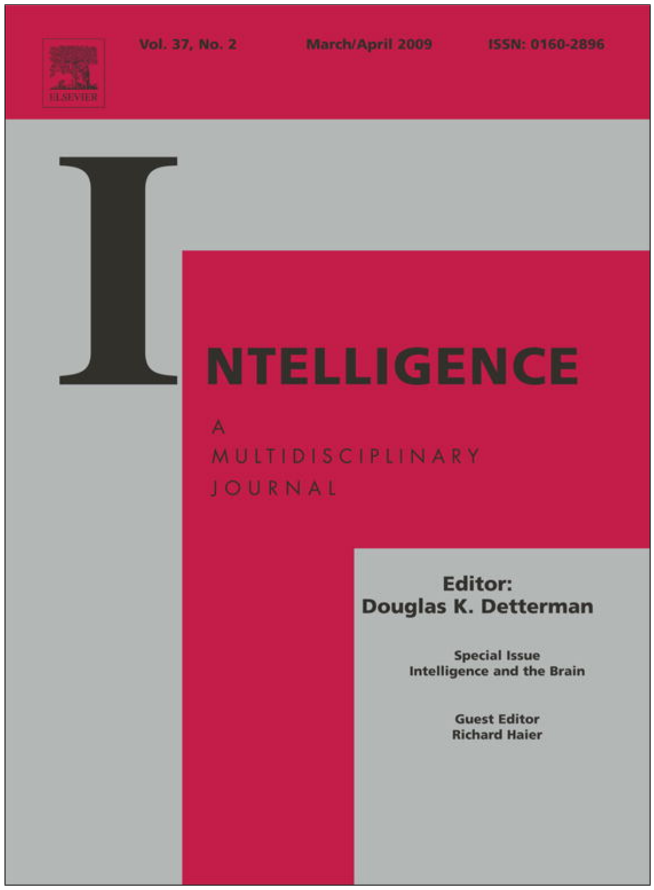
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Neuro-intelligence, neuro-metrics and the next phase of brain imaging studies

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ABSTRACT

Twenty years have passed since the first neuro-imaging study of intelligence. Researchers from around the world are now using a variety of imaging techniques to investigate the neural basis of intelligence, establishing the field of “neuro-intelligence”. The papers in this special issue help usher in the next phase of neuro-intelligence research. Among other issues, they illustrate some of the progress made in identifying key brain areas and in elucidating the concept of brain efficiency. Samples include children, adults, and seniors. Imaging includes structural assessments and functional determinations during cognitive tests of memory and processing speed. Intelligence measures address *g* and other factors. Some brain/intelligence relationships apparently differ for males and females. The data are intriguing. The field is maturing. The pace is quickening. As intelligence research engages 21st century neuroscience, new hypotheses and new controversies are inevitable. What a terrific time to work in this field.

Twenty years ago, we first used the new neuro-imaging technology of positron emission tomography (PET) to ask, “Where in the brain is intelligence?” Our experiment was simple, the results were surprising, and we have been working ever since to understand the data generated by subsequent studies. That first study combined functional brain imaging and psychometrics. It showed *inverse* correlations between glucose metabolism in areas distributed around the cortex and scores on the Raven's Advanced Progressive Matrices (RAPM), suggesting that high *g* was related to efficient brain function (Haier et al., 1988).

In the bigger picture, the demonstration that individual differences in psychometric scores are related to individual differences in brain function provided new validation for tests of intelligence. It also invigorated efforts to define a field of “neuro-intelligence” seeking to identify the neural basis of intelligence. These early findings also renewed interest in the older EEG concept of neuro-metrics—assessing intelligence by measuring brain parameters (Ertl & Schafer, 1969; Haier, 1993).

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We had hoped that the 1988 publication of these results in the then fledging journal *Intelligence* would encourage other researchers to pursue questions about brain/intelligence relationships with imaging technology not previously available. We recognized the challenges of working with new, complex, and extremely expensive technology, but we were hopeful that all psychology departments would someday have their own neuro-imaging facilities (Haier, 1990). It did not happen with PET, but the subsequent advent of functional MRI galvanized researchers in cognitive psychology and now neuro-imaging is a central resource in most psychology departments. Intelligence researchers have easier access and they are beginning to use neuro-imaging in greater numbers. Collaborations among psychometric researchers, neuropsychologists, experimental cognitive psychologists, and imaging experts are becoming more common.

In the last twenty years, about 40 studies have correlated structural and functional brain parameters assessed with various neuro-imaging techniques to various measures of intelligence. We recently reviewed most of these in detail (Jung & Haier, 2007) and derived a neuro-anatomic theory of intelligence called the parieto-frontal integration theory (PFIT). We also noted that, in our view, the set of studies we reviewed marked the end of the first phase of neuro-intelligence studies (Haier & Jung, 2007). As part of our response to commentators on our review, we anticipated that the next phase of research would have much larger samples (males and females, young and old), more sophisticated experimental designs, and more detailed, hypothesis-driven analyses about *g* and other components of intelligence.

On the 20th anniversary of our 1988 PET/RAPM study, it is fitting that a special issue of *Intelligence* is focused on neuro-imaging studies that, in our view, exemplify the next phase of neuro-intelligence research. We thank Doug Detterman for suggesting this issue. The eleven reports come a long way from our first PET study. They represent some of the most recent worldwide efforts to understand how brain structure and function relate to intelligence. Imaging studies like these will form the empirical basis for new thinking about neuro-intelligence and potential neuro-metrics.

Roberto Colom and colleagues set out to test the Jung & Haier PFIT model with structural MRI data from a new sample of 100 young adults in Madrid, Spain (Colom et al., 2009-this issue). They all completed a battery of 9 tests selected to yield core intelligence factors including *g*. Gray matter in several PFIT areas was correlated to *g*-factor scores. This study used sophisticated psychometric methods to define *g* and other factors whereas most previous studies used individual tests with high *g*-loadings like the Raven's Progressive Matrices or full-scale IQ scores. In another paper, we report on a new sample of 40 young adults tested in New York who completed a different battery of tests and their *g*-scores were correlated to gray matter assessed with MRI. Surprisingly, these results (Haier et al., 2009-this issue) did not correspond very well with those from the Madrid sample for *g*-scores, but they did correspond for scores on a spatial factor. This lead us to wonder whether *g*-factors derived from different batteries were not unitary on the neuro-anatomical level even if they were unitary on the psychometric level. In other words, is there a single neuro-*g*?

Karama and colleagues also derived *g*-scores from WAIS subtests in a representative sample of 216 children and adolescents (age 6–18 years) studied in a multicenter collaborative project (Karama et al., 2009-this issue). They assessed cortical thickness from MRI scans and found correlations with *g*-scores also consistent with some PFIT areas. These three papers, based on structural MRIs, agree that the areas related to intelligence are distributed throughout the brain and not localized only in the frontal lobes. Luders and colleagues at UCLA address this issue in their comprehensive review paper and come to the same conclusion (Luders, Narr, Thompson, & Toga, 2009-this issue).

As more and more imaging studies of adults clarify the neuroanatomy of intelligence, questions about the developmental trajectories of the key areas become increasingly interesting, as shown in the paper by Karama et al. Schmithorst and colleagues have published a remarkable series of imaging studies on intelligence and here, he reports new data on more than 100 children and adolescents aged 5–18 (Schmithorst, 2009-this issue). The focus is specifically on sex differences in white matter tracts assessed with the MRI technique of diffusion tensor imaging (DTI). The findings show significant sex by IQ interactions, consistent with other studies in adults showing different intelligence/brain structure relationships. Moreover, he reports some evidence that *less* white matter in a specific tract may be related to higher IQs in older males. Results like these underscore the critical importance not only of large samples, but also the necessity to investigate males and females separately across wide age ranges.

Several researchers in China are using neuro-imaging to study intelligence. Here, Yu and colleagues report DTI assessment of white matter in patients with tuberous sclerosis complex, a disease often marked by low intellectual ability. They find correlations with IQ, consistent with other reports that damage to white matter may underlie low intellectual ability (Yu, Lin, Zhao, Ye, & Qin, 2009-this issue).

Given the data on gray and white matter correlates of intelligence, the paper by Van Leeuwen and colleagues in the Netherlands takes a further step by combing genetic analysis and imaging (van Leeuwen et al., 2009-this issue). In this paper, they studied 112 twin pairs who were 9 years old and found phenotypic correlations between IQ and gray and white matter volumes. Consistent with earlier studies, they conclude that brain volumes and intelligence share some common genes.

Genes, of course, require biochemical processes. My colleague Rex Jung and his team at the MIND Institute in Albuquerque, New Mexico are pioneers in applying the MRI technique of proton magnetic resonance spectroscopy to investigations of brain chemistry and intelligence. Here they report one chemical marker of neuron density and integrity, NAA, shows negative correlations with VIQ in the anterior gray matter (stronger in males) and positive correlations with PIQ in posterior gray matter ($N=63$). This imaging technique has powerful potential and the discussion of neuro-metabolism and cognition provides much food for thought (Jung et al., 2009-this issue).

Functional imaging studies based on blood flow also are providing new information. Two fMRI papers focus on cognitive processes related to intelligence. These papers demonstrate both the potential for experimental cognitive psychology approaches for studies of neuro-intelligence and the complexities involved. From Scotland, Waiter and colleagues used fMRI to study the n-back test of working memory and the inspection time test of visual processing speed (Waiter et al., 2009-this issue). Subjects were over 60 years old ($n=47$ for inspection time; $n=37$ for n-back). Performance on both tests correlated to scores on the Raven's Matrices, but the imaging results indicated that the extent of brain activation during the tests does not mediate the correlations between test performance and the Raven's scores. Rympa and Prabharkaran report a series of three fMRI experiments ($n=12$ young adults in each) examining aspects of brain efficiency (Rypma & Prabhakaran, 2009-this issue). They argue that functional imaging experiments need to use tasks that separate the effects of processing speed from those of processing capacity. Their results, like those of Waiter et al., underscore the difficulties of comparing functional imaging experiments when different tasks are used, although they do find evidence of efficient processing related to better task performance in some, but not all brain areas for some, but not all, tasks depending on their complexity.

Neubauer and colleagues in Austria have published several papers addressing the concept of brain efficiency and how it relates to intelligence, mostly with EEG techniques. Here Neubauer & Fink report new evidence in 61 adults regarding efficiency and the functional connectivity of the brain during a figural–spatial task (Neubauer & Fink, 2009-this issue). They find short-distance connections show more efficiency in brighter subjects, especially in males. This is quite an intriguing finding for follow-up. Their work also underscores the importance of separate analyses in males and females.

The papers in this issue use a variety of neuro-imaging techniques and analyses to investigate anatomical, functional, cognitive, psychometric, and biochemical aspects of individual differences in intelligence. The first twenty-year phase of this research demonstrated that large samples are required and that sex and age are important independent variables. As we begin the next phase, we see these issues being addressed. The new data continue to push our theories and tax our imaginations. Questions about the neural basis of intelligence become more sophisticated as tentative answers are suggested and tested. Soon, we can try brain-based imaging assessment of intellectual abilities, but such neuro-metric efforts must at least demonstrate stringent cross validation in large samples.

As neuro-intelligence studies progress and engage 21st century neuroscience, issues about enhancement of intelligence are sure to be raised. Since one context of these issues undoubtedly will be education, we can easily predict new controversies will replace many of the old psychometric ones. As always, such controversies are best informed with data and debated publically. We are hopeful that funding for the next phase of intelligence studies will overcome old biases and become adequate for neuro-imaging budgets with large, diverse samples. There are some positive signs. With luck, the next phase will take only ten years instead of twenty and the next special issue on this subject will be even more exciting.

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