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11 Creativity and Intelligence: Brain Networks That Link and Differentiate the Expression of Genius

Rex E. Jung and Richard J. Haier

If you're so smart, why aren't you a genius? The simple answer is that intelligence and creativity are not the same thing and genius apparently requires both (Jensen, 1998). Psychology has a long history of discussing this issue, and numerous distinctions have been hypothesized to augment general definitions of intelligence, creativity, and genius. Empirical testing of competing ideas, however, depends on measurement. Tests of intelligence and tests of creativity evolved during the twentieth century and both kinds of tests now have good psychometric qualities. Early research using electroencephalographic (EEG) techniques and positron emission tomography (PET) suggested that (1) intelligence and creativity test scores were related to neural activity (i.e., excitation) in the frontal lobes and other areas (with hemispheric differences), and that (2) less activity (i.e., neuronal disinhibition) was related to higher scores for both concepts (see Runco, 2004, for a review of creativity studies, and see Jung & Haier, 2007, for a review of intelligence studies). Prior to the advent of neuroimaging techniques, Eysenck (1995) formulated a theory of creativity and the brain that proposed the importance of disinhibition (i.e., less neuronal activation), especially in the frontal lobes. Thus, while the interplay of both neuronal excitatory and disinhibitory processes characterize studies of creativity, the focus on neuronal disinhibition, particularly within the frontal lobes, predates the advent of modern neuroimaging studies.

The widespread availability of sophisticated neuroimaging technologies and analysis techniques allows new kinds of studies using psychometric tools to investigate brain characteristics of both concepts. Now we can address more complex questions. The ultimate aim is to determine the specific neural networks that underlie intelligence and creativity, in their various forms and especially as they relate to genius. Two key questions are (1) whether, and to what extent, such networks overlap and (2) what unique aspects of the network must be present which make the simultaneous

expression of intelligence and creativity (i.e., genius) relatively rare? These questions and the implications of tentative answers are the focus of this chapter. We will present a brain model for intelligence and a model for creativity and discuss how genius may emerge from the overlapping and unique aspects of these models.

Before we get to the brain models and the studies on which they are based, we need to note two points. First is the emerging distinction, within the cognitive neurosciences, between the association of regions of interest with general cognitive functioning and the identification of brain networks subserving specific cognitive tasks. This is a rather subtle distinction, but it is an important one for appreciating the potential interplay of intelligence and creativity. Thousands of studies implicate various brain regions as "central" to numerous cognitive tasks including working memory, visual attention, episodic memory, and problem solving, to name a few. A review paper of 275 brain imaging paradigms identified similar brain regions activated during performance of such cognitive tasks (Cabeza & Nyberg, 2000). Several interesting generalizations emerged from this article: (1) vastly different cognitive tasks (e.g., space perception, working memory) engaged similar brain regions; (2) the anterior cingulate is engaged during a wide range of "demanding" cognitive tasks involving "intention to act" (or inhibition of action); and (3) contrary to popular belief, specific "brain regions are not committed to specific functions." We point to these statements to illustrate the empirical basis for the shift away from the phrenology-like idea of one brain area for one cognitive function to a perspective that focuses on the many brain areas that work together in a network. While we will be discussing particular regions of interest identified within individual studies, our overarching goal will be to forge a network of prospective regions subserving intelligence, creativity, and genius.

Second, predating neuroimaging, there is a long history within the neurosciences of evaluating brain function through careful examination of case studies and/or lesion analysis. This is due to the fact that, while multiple brain areas might serve a given cognitive function, removal of discrete brain region through disease or injury will reveal brain regions critical to performance of such functions. Three iconic examples include (1) Phineas Gage, who survived the passage of an iron rod through his frontal lobes resulting in profoundly changed personality (Harlow, 1848); (2) "Tan," the description of whom led to the localization of expressive speech areas of the brain (Broca, 1861); and (3) "H.M.," whose bilateral temporal surgical lesions led to heightened understanding of memory

encoding (Scoville & Milner, 1957). Less frequently studied, although equally important, were the brains of examples of extreme cognitive ability, such as savant abilities of extraordinary memory or mathematical calculation and synesthesia (blending of senses such as seeing numbers as colors). These studies suggest (1) that savant ability comes at the expense of "executive or integrative (brain) mechanisms" (Snyder & Mitchell, 1999) and (2) that artistic and musical ability may appear suddenly after left temporal degeneration (Miller, Boone, Cummings, Read, & Mishkin, 2000) and synesthesia may appear after brain damage (Ro, et al., 2007).

In this chapter, we will review these case studies in more detail and then review the brain imaging literature relevant to intelligence and creativity. Our goal is to develop comparative brain models. With a few exceptions, these reports address either creativity or intelligence. However, we start with the one major example in the neurological annals who provides important clues regarding the trifecta of intelligence, creativity, and genius: Albert Einstein.

Intelligence

A Case Report of Genius

Albert Einstein is perhaps the most revered intellectual icon of the twentieth century, and one of the few figures of human progress for whom we have retained the brain for scientific study. In his "golden year" he produced four stunning papers, covering Brownian motion (Einstein, 1905b), the special theory of relativity (Einstein, 1905d), statistical mechanics (Einstein, 1905a), and the photoelectric effect (Einstein, 1905c), out of which his most famous postulate emerged ($E = mc^2$), arguably the most recognizable formula representing applied genius in human history. He was sympathetic to the notion of scientific research on his brain, and underwent EEG recordings during his life. Einstein died on April 18, 1955, at the age of 76 from a ruptured aortic aneurysm, mentally adept to the end. His brain was removed on the morning of his death by Thomas S. Harvey, a pathologist at Princeton Hospital, with the consent of the family (Brian, 1996) and the estate executor (Highfield & Carter, 1993). The brain was photographed, measured with calipers, weighed, fixed in formalin for several months, and subsequently sectioned into about 240 blocks, each consisting of 10 cm^3 of tissue, and embedded in celloidin (Witelson, Kigar, & Harvey, 1999). The brain was described as unremarkable in appearance, and the weight (1,230 grams), length (17.2 cm left/16.4 cm right), and width (7.5 cm left/7.5 cm right) of the cerebral hemispheres were all within

the average range for men his age (Anderson & Harvey, 1996). The travels and travails of Einstein's brain following removal are described elsewhere (Abraham, 2002; Paterniti, 2000), and following several inquiries to Dr. Harvey regarding the results of the analysis of Einstein's brain ("Brain of Einstein continues peregrinations," 1981; "Brain that rocked physics rests in cider box," 1978), other research reports eventually followed.

More detailed morphological characteristics of Einstein's brain were systematically compared to the brains of thirty-five male controls (mean age = 57+/–11; mean full scale intelligence quotient (FSIQ) = 116) possessing normal neurological and psychiatric status (Witelson et al., 1999). While Einstein's brain weight was significantly lower than that of a younger control cohort (1,230 cm versus 1,400 cm), no differences were observed on measures of corpus callosum area, frontal lobe, and temporal lobe morphology. However, the parietal operculum was not present in Einstein, resulting in a larger expanse of the inferior parietal lobule, extending some 15 percent wider than similar regions of the controls. This unique morphology, found in none of the control subjects, resulted in a supramarginal gyrus undivided by a major sulcus (figure 11.1). The inferior parietal lobule is associated with visuospatial cognition, mathematical reasoning, and imagery of movement (Crammond, 1997), and its expansion was also noted in other cases of prominent physicists and mathematicians (Spitzka, 1907). The authors of this comparative study of Einstein's brain note that "variation in specific cognitive functions may be associated with the structure of the brain regions mediating those functions" and conclude that the parietal lobule may be implicated in visuospatial intelligence (Witelson et al., 1999, 2152).

Two other studies of Einstein's brain investigated whether differences at the cellular level (e.g., neuron/glia) could explain his genius (Anderson & Harvey, 1996; Diamond, Scheibel, Murphy, & Harvey, 1985). The first study used the blocks of tissue obtained from frontal and parietal regions, bilaterally, comprising superior prefrontal and inferior parietal association cortices. These regions of Einstein's brain were compared to eleven controls ranging in age from 47 to 80 years, obtained from a Veteran's Administration (VA) hospital and fixed in a manner similar to those obtained from Einstein. Cell counts were made of neurons, astrocytes, and oligodendrocytes, from which a neuronal-to-glial ratio was computed. Glial cells provide metabolic support (i.e., nutrition) to neurons. Results indicated that, compared to controls, Einstein had significantly fewer neurons per glial cells in the left inferior parietal cortex, which the authors interpreted to suggest "a response by glial cells to greater neuronal metabolic need"

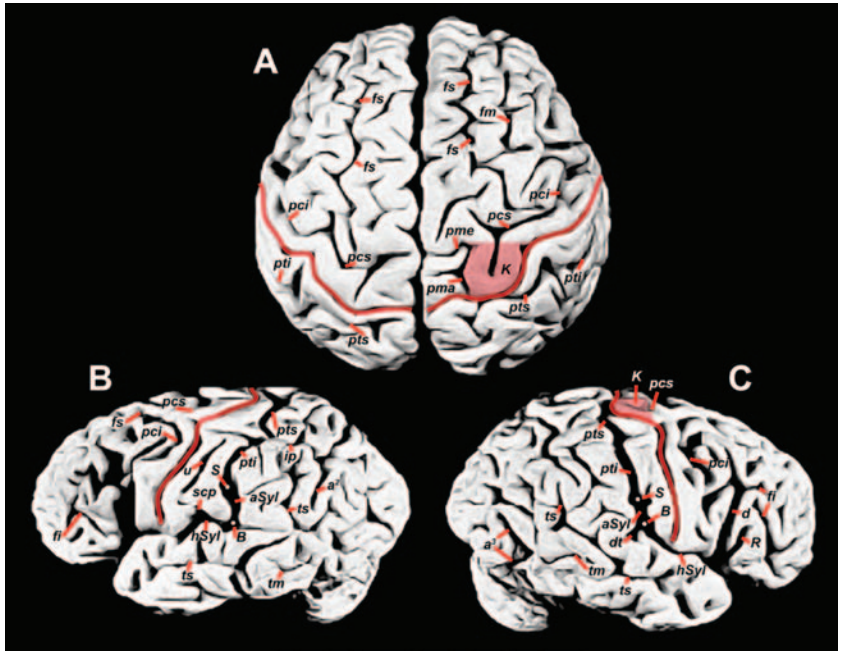

Figure 11.1

Photographs of Einstein's brain (adapted from Falk, 2009). (A) Dorsal view, (B) left lateral view, (C) right lateral view. Sulci: angular (a2), anterior occipital (a3), ascending limb of the posterior Sylvian fissure (aSyl), central fissure (red lines), diagonal (d), descending terminal portion of aSyl (dt), inferior frontal (fi), middle frontal (fm), superior frontal (fs), horizontal limb of the posterior Sylvian fissure (hSyl), intraparietal (ip), precentral inferior and superior (pci, pcs), marginal precentral (pma), medial precentral (pme), postcentral inferior and superior (pti, pts), ascending ramus of Sylvian fissure (R), subcentral posterior sulcus (scp), middle temporal (tm), superior temporal sulcus (ts), unnamed sulcus in postcentral gyrus (u). Other features: branching point between hSyl and aSyl (white dots, B), hand motor cortex knob (K, shaded in A, C), termination of aSyl (white dots, S). With kind permission of Falk, D. (2009). New information about Albert Einstein's brain. *Frontiers in Evolutionary Neuroscience*, *1*(3): doi: 10.3389/neuro.18.003.2009.

(Diamond et al., 1985). In other words, Einstein had more glial cells per neuron in this area, suggesting that these neurons might work harder or more efficiently. The second study focused on determining the density of a block of tissue from the right prefrontal association cortex, compared to comparable regions from male controls aged 63 to 79 years. Results indicated increased neuronal packing (i.e., the same number of neurons in a smaller space), which the authors interpret as potentially "decreasing interneuronal conduction time" and thus potentially facilitating cortical connectivity (Anderson & Harvey, 1996). This would be consistent with greater efficiency of brain processing in this region. Thus, these studies suggest that Einstein's brain differed from others in a frontal-parietal network. Information processing in the left inferior parietal lobe (especially the supramarginal gyrus) may have been more powerful and its integration in the right prefrontal cortex may have been more efficient.

Numerous researchers have critiqued the studies of Einstein's brain for various methodological flaws (Galaburda, 1999; Hines, 1998) and, to be sure, the comparison of one exceptional individual to various controls does not lead definitively to localization of genius within the brain. Moreover, not all areas of Einstein's brain have been studied, and a network approach calls for understanding how a key area in the parietal lobe is connected to other areas. We also don't know if the specific brain findings are related to Einstein's intelligence, his creativity, or to his genius.

Brain Networks of Intelligence from Imaging Studies: The P-FIT Theory

People differ in intellectual ability, and these differences are related to features of the brain as determined by neuroimaging studies of the last twenty-five years. We reviewed these studies in 2007; at that time there were thirty-seven studies that used different imaging techniques and different measures of intelligence in samples of different sizes and compositions (Jung & Haier, 2007). Some brain areas were implicated more often than others across these studies. These areas were distributed across the brain but were found mostly in parietal and frontal areas. We proposed the parieto-frontal integration theory (P-FIT) of intelligence, which hypothesized that efficient information flow among these areas, or subgroups of these areas, was a basis for individual differences in intelligence. The P-FIT model is shown in figure 11.2. This hypothesis recognizes that humans gather and process information predominantly through auditory and/or visual means (usually in combination)—thus the network involves a sequence of seven broad information-processing events (shown below in this paragraph in italics). At the start is processing of sensory information

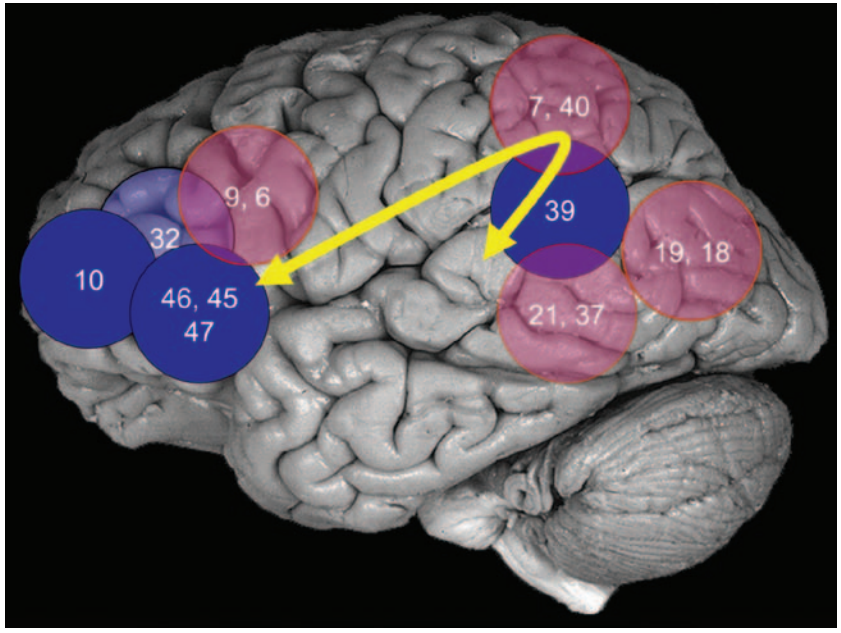

Figure 11.2
P-FIT theory of intelligence. Numbers indicate Brodmann areas. Blue = left lateralized; purple = bilateral; yellow arrow = arcuate fasciculus.

via the extrastriate cortex and fusiform gyrus, involving recognition and subsequent *imagery* of visual input and analysis of auditory *syntax* input in Wernicke's area and surrounding regions. This basic sensory processing is then fed forward to the angular, supramarginal, and inferior parietal cortices, wherein structural *symbolism* and/or *abstraction* are generated and manipulated. The parietal cortex then interacts with frontal regions that serve to *hypothesis test* various solutions to a given problem. The anterior cingulate is involved in *response selection* as well as *inhibition* of competing responses. This process is critically dependent on the fidelity of underlying white matter needed to facilitate rapid and error-free transmission of data between frontal and parietal lobes. The P-FIT is a "network" perspective, conforming to Cabeza and Nyberg's (2000) nascent conceptualization that several brain regions within more integrative "association zones" (i.e., not strictly dedicated to sensory or motor functions) of the frontal and parietal lobes function as cognitive "hubs" subserving multiple cognitive tasks.

Since our 2007 review, more than fifty additional imaging studies of intelligence have been published, most supporting the P-FIT model (Deary,

Penke, & Johnson, 2010). Importantly, these newer studies have become more sophisticated. They have better image-analysis methods (Li, et al., 2009; van den Heuvel, Stam, Kahn, & Pol, 2009), use multivariate combinations of test batteries to extract intelligence factors (Colom et al., 2009), and now commonly have large samples of 100 or more subjects (Tamnes et al., 2010). Developmental studies address P-FIT areas in children and adolescents (Karama et al., 2009; Luders et al., 2011; Schmithorst, 2009), and also are increasingly investigating sex differences (Luders et al., 2008; Tang et al., 2010). Genetic studies have determined that intelligence and brain structures (i.e., gray and white matter) share common genes (Bishop, Fossella, Croucher, & Duncan, 2008; Chiang et al., 2009; Liu et al., 2010). The pace of research publications regarding intelligence and the brain is increasing dramatically (Haier, 2009). These imaging studies of intelligence and the P-FIT, along with the case study reports, offer a framework for studies of creativity that may generate a comparable brain network model.

Creativity

Case Reports Regarding Creativity: Frontotemporal Dementia and Other Lesions

Neurological inquiries regarding creativity converge on the frontal lobes and their inhibitory interactions with temporal, occipital, and parietal lobes (TOP) (Flaherty, 2011; Heilman, Nadeau, & Beversdorf, 2003). This convergence has arisen, at least in part, from several case reports of patients having developed frontotemporal dementia (FTD) and *subsequently* experiencing dramatically increased creative capacity (Miller et al., 1998). Initially, Miller and colleagues reported a few single case reports of creativity in FTD. They subsequently reported that some 17 percent of their entire cohort of sixty-nine patients diagnosed with FTD (twelve patients) exhibited increased visual or musical creativity, and that damage to the left temporal lobe and sparing of the frontal lobes was "a unifying feature of the patients with ability" (Miller et al., 2000, 461). However, left temporal lobe lesions are not exclusively associated with *de novo* artistic expression, which has also been reported in right temporal lobe epilepsy (Mendez, 2005), a case of Parkinson's disease treated with dopaminergic agonists (Schrag & Trimble, 2001), a case of subarachnoid hemorrhage (Lythgoe, Pollak, Kalmus, de Haan, & Chong, 2005), and in a case of insular ischemia (Thomas-Anterion et al., 2010). Subsequent systematic study of artistic ability associated with the various dementias found no general increase in creativity to be linked with FTD (or semantic or dementia of the Alzheim-

er's type), with the authors noting that "despite the existence of these isolated patients with increased artistic production, however, apathy leading to diminished creativity is more clinically typical of patients with FTD, suggesting that these case studies may be the exception rather than the rule" (Rankin et al., 2007, 49). Thus, these cases suggest that damage to the temporal lobe may be associated with increased artistic creativity in only a very small number of people, but this may be an important clue. Frontal lobe inhibition of the temporal lobe may play a key role, or it may be an alternative pathway to increased creativity.

Neurologist Alice Flaherty has taken a further step in the conceptualization of creative expression with a model of creative drive involving frontotemporal and dopaminergic control of idea generation (Flaherty, 2005). She takes a neurological perspective, focused on the behaviors central to creativity, and weaves together a compelling tapestry from careful study of individual patients. The key features of this model include (1) incorporation of the limbic system as the "driver" of creative pursuits, (2) the notion that creativity is domain independent (i.e., a common component spans creative expressions as varied as artists, scientists, musicians, and so on), and (3) a prediction of similar neurological underpinnings across normal controls, psychiatric patients, and lesion patients. For example, patients with temporal lobe epilepsy were often noted to have a strong drive to write (called "hypergraphia"), also noted in some manic patients, as well as in frontotemporal lobe dementia (FTLD). What these patients had in common was dysfunction of the temporal lobe, which normally inhibits frontal lobe functioning (Menzel et al., 1998). Thus, overt lesions or mild dysfunction to the temporal lobes served to "disinhibit" frontal interactions with other nodes (i.e., language/visuospatial) underlying behavioral output, with right-hemisphere lesions producing higher incidence of hypergraphia, and left lesions producing increased visual and musical output. She also hypothesizes a role for dopamine in novelty-seeking and goal-directed behavior (Mink, 1996). Finally, the frontal lobes are hypothesized to block creative drive when lesioned or dysfunctional (e.g., in depression, anxiety, Wernicke's aphasia). What Flaherty's model introduces to the picture is the notion of mutually inhibitory nodes (i.e., frontal, temporal, subcortical) within a network of brain regions subserving creativity. This model can be tested with neuroimaging.

Neuroimaging of Creativity and the "Frontal Disinhibition Model" (F-DIM)

Brain studies of creativity have not advanced as rapidly as those of intelligence, but results so far are informative and summarized in three recent

reviews (Arden, Chavez, Grazioplene, & Jung, 2010; Dietrich & Kanso, 2010; Sawyer, 2011). Arden et al.'s review of forty-five brain-imaging studies of creative cognition did not reveal much consistency among studies. Given the wide range of measures used to assess creativity and the measurement error inherent across the various neuroimaging measures, they conclude that "it is impossible to know whether any results should be attributed to the measures, to the imaging modality or to unreliability in one or both" (152). Dietrich and Kanso reviewed neuroimaging experiments of divergent thinking, artistic creativity, and insight from sixty-three research articles, including the forty-five papers reviewed by Arden et al. (Dietrich & Kanso, 2010). They, too, found that "creative thinking does not appear to depend on any single mental process or brain region, and it is not especially associated with the right hemisphere, defocused attention, low arousal, or alpha synchronization, as sometimes hypothesized" (845). However, they did offer some general conclusions, albeit of a highly qualified nature: "Tasks purportedly involving creative cognition induce changes in prefrontal activity" (ibid.). These changes include both increases and decreases, span all (or most?) of frontal lobe regions, and are not exclusive to the frontal lobes; thus, creativity may not be either "localized" or even "localizable." Sawyer's review of the cognitive neuroscience of creativity similarly notes that (1) "the entire brain is active when people are engaged in creative tasks," (2) "left and right hemispheres are equally activated in most creative tasks," (3) and "the same brain areas are active that are active in many everyday tasks" (149). All three reviews suggest that the construct of "creativity" would benefit greatly from further parsing into subcomponents from which more fine-grained cognitive neurosciences results might emerge. However, all three reviews rely almost exclusively on functional (i.e., EEG, functional magnetic resonance imaging [fMRI]) studies. All functional imaging studies are influenced by task demands during image acquisition. Thus, the inability to localize a network of underlying creativity may have as much to do with methodological vagaries related to task and acquisition techniques as with construct problems. Structural and lesion studies avoid task demand problems.

Luckily for the construct of creativity, divergent thinking has long been parsed into subcomponents comprised of fluency (i.e., the raw number of items produced), flexibility (i.e., different conceptual categories produced), and originality (i.e., novel responses produced). The notion of "originality" permeates the creativity literature (Runco & Charles, 1993), and one recent study provides important insights (Shamay-Tsoory, Adler, Aharon-Peretz, Perry, & Mayseless, 2011). Forty patients with localized brain damage (i.e.,

lesions) to various regions, and seventeen matched controls, completed the Torrance Test of Creative Thinking and the Alternate Uses Test, both reliable and valid measures of one aspect of divergent thinking. In those subjects with medial frontal lesions, and particularly right medial frontal lesions, originality scores (the "novel" part of "novel and useful") across measures were significantly reduced. Similarly, in those subjects with left parietal lobe lesions, originality scores were significantly higher, even significantly higher than normal control subjects. The authors interpret their findings to support a right lateralized frontoparietal network of brain regions supporting originality, with "lesions in the right hemisphere (being) associated with impaired creativity, whereas damage to the left hemisphere (being) associated with somewhat increased creativity." Taken together with the studies showing left temporal lobe degeneration associated with increased artistic and musical creativity in patients with FTD, this study suggests that *lower* brain integrity within left hemisphere brain structures—particularly left anterior temporal and inferior parietal lobes—serves to "disinhibit" other brain regions associated with increased novelty generation as measured by both artistic endeavors, and psychometric tests of divergent thinking.

We recently completed three "structural" imaging studies of creative cognition that have several advantages compared to the lesion studies reviewed above: (1) they are applied to large (i.e., >50) samples of healthy, young individuals; (2) they use reliable and valid measures of intelligence (Wechsler Scales), creativity (i.e., Alternate Uses Test; Creative Achievement Test), and personality (i.e., NEO-FFI) (Costa & McCrae, 1992); (3) they use neuroimaging measures that are not dependent upon task-related functional changes; and (4) they also assess "originality" as distinct from "fluency" or "flexibility" factors of divergent thinking. In our first study, we probed the relationship between creative cognition and concentration of N-acetyl-aspartate, a marker of neuronal integrity, in a sample of fifty-six healthy people using proton magnetic resonance spectroscopy (MRS) (Jung, Gasparovic, Chavez, Flores et al., 2009). Three divergent thinking tasks (i.e., Alternate Uses Test) were ranked by three judges to create a creativity index using the consensual assessment technique (Amabile, 1982). N-acetyl-aspartate concentration was inversely correlated with creative cognition in the right anterior cingulate for high IQ subjects (>116 FSIQ), but positively correlated with creative cognition in the left anterior cingulate for average IQ subjects (<116 FSIQ). This finding is consistent with the notion of a threshold effect for creativity—high intelligence is necessary but not sufficient for creativity.

In our second study, we assessed cortical thickness in a cohort of sixty-one young adults, including the fifty-six from the spectroscopy study, using both measures of divergent thinking and creative achievement (Jung, Segall et al., 2010). We found cortical thickness in a region in the lingual gyrus was negatively associated with a psychometric measure of creative cognition, but was positively correlated with a different region in the right posterior cingulate. On measures of creative achievement, *less* gray matter volume in the left lateral orbitofrontal region was associated with higher creative achievement, but higher volume in the right angular gyrus correlated with creative achievement.

In our third study, we examined white matter integrity with a technique called diffusion tensor imaging (DTI), which measures the movement of water through myelinated axons. In a sample of seventy-two healthy young adults (including all of the previous subjects), we found an inverse relationship between white matter "integrity" (measured as "fractional anisotropy") and creative cognition in numerous regions within the left hemisphere, including the inferior frontal white matter and the superior longitudinal fasciculus (Jung, Grazioplene, Caprihan, Chavez, & Haier, 2010). The same relationship appeared in a small region within the right inferior frontal white matter and the anterior thalamic radiation. These three structural studies point to a decidedly left lateralized, frontosubcortical, and disinhibitory network of brain regions underlying creative cognition and achievement. These areas are summarized in figure 11.3 as part of the proposed F-DIM model of creativity. We describe this as a "model" as opposed to the P-FIT "theory" because it is based on a relatively few structural and lesion studies and is not readily testable until more experimental studies yield theoretical congruence.

These studies suggest to us that "less is more" with regard to creative cognition as measured by divergent thinking measures, particularly within frontosubcortical networks hypothesized to be central to creativity by several independent threads of thought (Dietrich, 2004; Flaherty, 2005; Heilman et al., 2003). The brain networks involved are likely *disinhibitory* in nature (Eysenck, 1995), with lesions and/or network degradation (i.e., cortical thinning, lower white matter coherence) located within a specific *network*, producing *increased* behavioral output. Central aspects of the network appear to include the frontal and temporal lobes, with cortical "tone" being modulated via interactions between the frontal lobes, basal ganglia and thalamus (part of the dopamine system) through white-matter pathways.

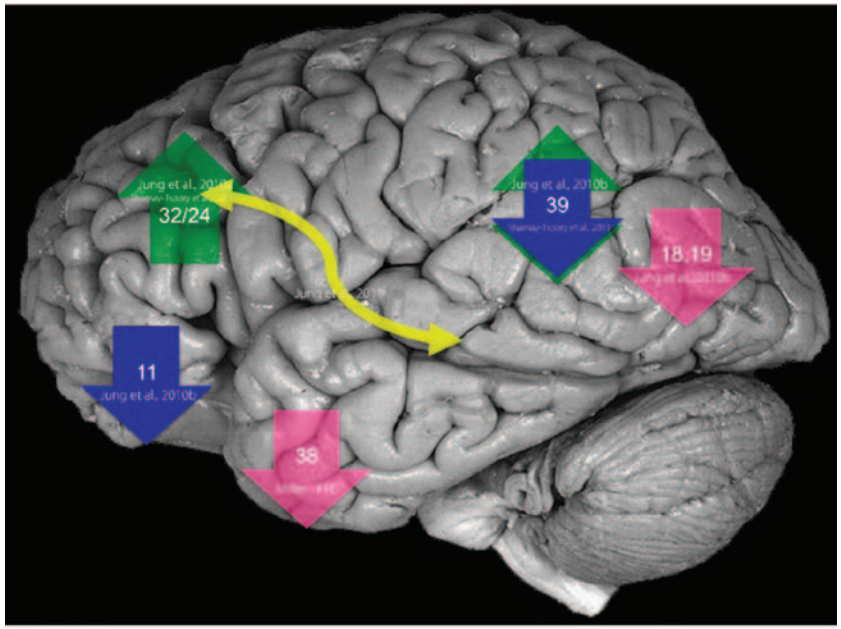

Figure 11.3
F-DIM model of creativity. Numbers indicate Brodmann areas. Blue = left lateralized; green = medial; purple = bilateral; yellow arrow = anterior thalamic radiation.

The story with intelligence may be similar—greater gray matter and better white-matter integrity go with higher scores but so does decreased function, which may reflect greater efficiency. That is to say that for both intelligence and creativity, we must look not only to *increased* neural tissue or activity in key brain regions (e.g., frontal lobes), but perhaps also to some mismatch between mutually excitatory and inhibitory brain regions (e.g., temporal lobes) that form a network subserving such complex human behaviors as creativity (e.g., planning, insight, inspiration). This notion of a delicate interplay of both *increases* and *decreases* in neural mass, white-matter organization, biochemical composition, and even functional activations within and between brain lobes and hemispheres is an important concept. Indeed, it is the rare brain that has highly developed networks of brain regions subserving intelligence (figure 11.2), and (concurrently) the somewhat underdeveloped network of brain regions associated with disinhibitory brain processes associated with creative cognition (figure 11.3). Such a finely tuned seesaw of complex higher and lower brain fidelity,

balanced in dynamic opposition, would almost guarantee the rare occurrence of genius.

Why are we able to create a model for a network of creativity in the brain whereas three reviews (including our own) failed to do so? There are several reasons why the structural imaging and lesion studies might provide a more coherent model. First, the "lesion" method of cognitive neuroscience has long been considered the "gold standard" of methodology, showing the critical node necessary to a given cognitive task (Broca, 1861). Second, the "structural" techniques have all been demonstrated to have extremely high levels of reliability as measured with interclass correlations, with proton magnetic resonance spectroscopy being 0.98 (Gasparovic et al., in press), diffusion tensor imaging being 0.80 (Danielian, Iwata, Thomasson, & Floeter, 2010), and structural magnetic resonance imaging (sMRI) being 0.96 (Wonderlick et al., 2009); a major review of functional techniques (which predominated in the creativity reviews) revealed only modest reliability of 0.50 (Bennett & Miller, 2010). Similarly, our model focuses exclusively on measures of divergent thinking and achievement, such as the multiple uses test and creative achievement questionnaire, both of which have high reliability and validity (Domino & Domino, 2006). In contrast, many of the measures used in the creativity reviews were "home grown," extraordinarily diverse, and consisted of measures with unknown (and unknowable) reliability and/or validity, such as (1) composing a piece of music mentally (Petsche, 1996), (2) imagining a new design for a pen (Kowatari, et al., 2009), or (3) developing hypotheses about variations in quail eggs (Jin, Kwon, Jeong, Kwon, & Shin, 2006), to name a few. The use of standardized measures of divergent thinking (i.e., multiple uses test, Torrance Test of Creative Thinking), combined with lesion analysis and/or reliable imaging methodology (e.g., MRS, DTI, sMRI, and even fMRI), will help advance the field.

Brain Networks of Genius

Is There Brain Overlap for Intelligence and Creativity?

Given its rare and often idiosyncratic nature, it is not surprising that there is no systematic study of genius in the brain imaging literature. Our brain models of intelligence and creativity serve as a first approximation for identifying networks possibly related to genius. Particular regions within the network are customarily described in terms of Brodmann areas (BAs) in reference to Korbinian Brodmann, who first created a detailed cartography of the human brain in 1905 (Brodmann, 1905). Looking at figures

11.2 and 11.3, a qualitative analysis would suggest overlap between the P-FIT and F-DIM areas in four regions, including BAs 18/19 in the occipital lobe, BA 39 (the angular gyrus) in the parietal lobe, and BA 32 (the anterior cingulate gyrus) in the frontal lobe. Note that although there is overlap in these relatively large areas, only the anterior cingulate appears to show a consistent picture of higher fidelity associated with higher ability for both intelligence and creativity.

The anterior cingulate gyrus is a region of the brain ubiquitous in its involvement in numerous cognitive neuroscientific studies (Cabeza & Nyberg, 2000). However, the role of the anterior cingulate in intelligence, creativity, and genius might be more specific (Colom, Jung, & Haier, 2006; Frangou, Chitins, & Williams, 2004; Gong et al., 2005; Jung, Gasparovic, Chavez, Caprihan et al., 2009; Jung, Segall et al., 2010; Pfleiderer et al., 2004). The anterior cingulate cortex has been demonstrated to contain a unique type of spindle cell, found only in large hominoids, with double the frequency in humans than in great apes, suggesting strong selection pressures in this particular brain structure (Nimchinsky et al., 1999). The anterior cingulate gyrus appears to have some level of specificity with respect to the ability of our species to (1) down-regulate and/or activate broad networks of brain regions in service of divergent thinking, and subsequently (2) up-regulate and/or focus resources within frontal lobe networks in service of convergent thinking and/or persistence in pushing a new idea out into the world. Future studies will help further parse structure-function relationships within the anterior cingulate cortex if undertaken in subjects selected for high intelligence, or high creativity, or genius.

Where Are the Unique Areas of Nonoverlap between Figures 11.2 and 11.3?

Mostly, the areas shown in figures 11.2 and 11.3 do not overlap. Figure 11.2 represents a network of regions largely lateral (on the outer surface) and superior (toward the top half of the brain) in their distribution, whereas figure 11.3 represents a network of largely inferior (toward the lower half) and more medial (on the inner surfaces of the brain). For example, while intelligence was found to be associated with posterior brain regions including the extrastriate and fusiform gyri near the lateral occipital lobes, many creativity studies (including our structural studies) find associations with the cuneus and precuneus on the medial wall between the two hemispheres of the brain. Intelligence is associated with integrity of the dorsolateral prefrontal cortex: creative achievement with lower volumes of the orbitofrontal cortex, and increased creative drive in FTLD with damage to

the left anterior temporal lobe. Intelligence is associated with integrity of white-matter tracts including the arcuate fasciculus and corpus callosum; divergent thinking and openness to experience were associated with lower measures of integrity within white-matter tracts linking the thalamus with frontal projection zones.

Intelligence and creativity appear to involve largely different brain networks. Tentatively, we interpret the former, focused on network integrity, to facilitate knowledge acquisition and retention, and the latter, focused on disinhibition of networks, to facilitate the generation of novel associations between knowledge stores. Whether there is a specific network for genius is not yet apparent.

The Mystery of the Einstein Area

One interesting anomaly when comparing figures 11.2 and 11.3 regards the inferior parietal lobule (BA 39). In studies of intelligence, this region has been implicated in better performance across studies, with greater volume, higher levels of the neuronal marker N-acetylaspartate, and greater functional activation all showing positive associations with measures of intelligence. In the "lesion" study of creativity reviewed above, however, subjects with damage to the left inferior parietal lobule performed better on measures of originality—some even performing better than normal control subjects. How can this be? Wasn't Einstein's brain unique by virtue of his inferior parietal lobule? But there is the rub: Einstein did not have a normal inferior parietal lobule, and the "abnormalities" were related to glial cells as opposed to neurons. Recall that Einstein had a 15 percent wider parietal lobe than controls and no parietal operculum (Witelson et al., 1999). However, subsequent studies showed that this greater parietal bulk was not comprised of neurons, but rather a higher number of glial cells—the support matrix of the brain (Diamond et al., 1985). Glial cells have customarily been viewed as the "glue" (literally what "glia" translates to) that holds the brain together. However, glial cells comprise 85 percent of the total brain volume, and we are entering into an era where the neuron doctrine of brain function is being slowly adapted to include the "glial doctrine," with recent studies demonstrating long-range communication between glial populations and glial modulation of neuronal tone (Fields & Stevens-Graham, 2002). Thus, Einstein's brain is not entirely inconsistent with a "lesion" model of genius comprising a network of brain regions, some with greater neuronal fidelity, some with lowered (i.e., disinhibitory) characteristics.

Conclusion

Complex phenomena like intelligence, creativity, and genius can be studied scientifically with modern neuroscience methods even as their definitions evolve with better empirical observations. Indeed, very clever individuals, such as Hans Eysenck, formulated hypotheses regarding genius without the benefit of sophisticated neuroimaging techniques that we now take for granted. These hypotheses were not too far off the mark given the benefit of careful interrogation with the tools and techniques of the modern neuroscientist. This has always been the case in science, whether investigating the nature of an atom or a gene or a memory. Such investigations typically raise more questions than they resolve; however, asking the right questions is key. Will an understanding of the neural basis of intelligence or creativity, or even genius, change how we approach education? There are already moves in this direction based on very tentative data (Ramsden et al., 2011) but much more research is necessary. As always, caution is required, but the future of creativity research looks bright indeed.

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