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Neuroanatomy of Creativity

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Abstract: Creativity has long been a construct of interest to philosophers, psychologists and, more recently, neuroscientists. Recent efforts have focused on cognitive processes likely to be important to the manifestation of novelty and usefulness within a given social context. One such cognitive process – divergent thinking – is the process by which one extrapolates many possible answers to an initial stimulus or target data set. We sought to link well established measures of divergent thinking and creative achievement (Creative Achievement Questionnaire – CAQ) to cortical thickness in a cohort of young (23.7 ± 4.2 years), healthy subjects. Three independent judges ranked the creative products of each subject using the consensual assessment technique (Amabile, 1982) from which a "composite creativity index" (CCI) was derived. Structural magnetic resonance imaging was obtained at 1.5 Tesla Siemens scanner. Cortical reconstruction and volumetric segmentation were performed with the FreeSurfer image analysis suite. A region within the lingual gyrus was negatively correlated with CCI; the right posterior cingulate correlated positively with the CCI. For the CAQ, lower left lateral orbitofrontal volume correlated with higher creative achievement; higher cortical thickness was related to higher scores on the CAQ in the right angular gyrus. This is the first study to link cortical thickness measures to psychometric measures of creativity. The distribution of brain regions, associated with both divergent thinking and creative achievement, suggests that cognitive control of information flow among brain areas may be critical to understanding creative cognition. *Hum Brain Mapp 31:398–409, 2010.*

Key words: creativity; divergent thinking; creative achievement; intelligence; personality; frontotemporal dementia; cingulate; cortical thickness; brain imaging; MRI

INTRODUCTION

Researchers have long recognized creativity to be an important individual difference variable, critically linked with, but distinguishable from, intelligence in the manifestation of "genius" (Galton, 1869). Like intelligence, academic discussions over definitions of this construct extend over decades and involve considerations of the creative person, the cognitive process underlying creativity, the creative environment or influence, and the creative product (Batey and Furnham, 2006). However, some consensus has emerged around a definition that appears to link these disparate influences: creativity refers to the production of something both *novel* and *useful* within a *given social context* (Flaherty, 2005). Although complex, the neuroscientific inquiry of creativity is amenable to the tools of cognitive psychology and the cognitive neurosciences, linking creative behavior to activity within and between brain

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networks. A main challenge is to avoid the many facile simplifications that often arise when discussing such a complex cognitive construct (Dietrich, 2007). At the same time, a goal of modern neuroscience is to expand and synthesize toward the creation of a coherent theoretical framework, the few limited tools and techniques that have emerged to assess creative expression.

There likely exist myriad cognitive skills necessary to produce something both "novel and useful." These skills probably manifest differentially within various domains (e.g., visual art *vs.* scientific discovery), and common creativity might differ substantially from creative genius (Dietrich, 2004). Indeed, creative productivity has been studied across numerous activities, like musical improvisation (Bengtsson et al., 2007; Berkowitz and Ansari, 2008; Brown et al., 2006; Limb and Braun, 2008); visual art perception and esthetics (Bhattacharya and Petsche, 2002; Cela-Conde et al., 2004; Kirk et al., 2009); dance (Fink et al., 2009b); neural comparisons between groups of artists, musicians, and matched controls during creative performance (Bhattacharya and Petsche, 2005; Gibson et al., 2009); and evaluation of combination of these across modalities and subjects (Petsche et al., 1997). In laboratory settings, the assessment of subject engagement in creative tasks is made mostly by tests of divergent thinking (DT), the process by which one extrapolates many possible answers to an initial stimulus or target data set (Guilford, 1967). Other central constructs include *fluid intelligence* (Cattell, 1943), *insight*—the flash of recognition that a problem is solved (Jung-Beeman et al., 2004), and "*flow*" defined as "when the person is fully immersed in what he or she is doing by a feeling of energized focus, full involvement, and success in the process of the activity" (Csikszentmihalyi, 1996). In all likelihood, some combination of these and other cognitive processes underlies the creative process, which involves a focused attention to the exclusion of other competing stimuli (i.e., flow); divergence of ideas to numerous possible novel solutions to a given problem (i.e., divergent reasoning); if one is lucky a flash of insight, if not then convergence on the best solution (i.e. utility); and perseverance in the face of social acceptance or resistance (i.e., personality variables). Comprehensive neuroscience research is evolving to incorporate combination of these and other cognitive and personality measures to address the complex construct of creativity.

Neurological inquiries regarding creativity have tended to focus on whether the frontal lobes are engaged or whether more posterior brain regions (Heilman et al., 2003) or subcortical structures such as the basal ganglia are more predominant (Dietrich, 2004). Such efforts are based largely on data gleaned from neurological and psychiatric patients (Pollack et al., 2007). Indeed, *de novo* artistic expression has been associated with left frontotemporal (Finkelstein et al., 1991) and right temporal lobe epilepsy (Mendez, 2005), several case studies of frontotemporal dementia (FTD) (Miller et al., 1998, 2000; Thomas Anterion et al., 2002), a case of Parkinson's disease treated with dopaminergic agonists (Schrag and Trimble, 2001), and a single case of subarachnoid hemorrhage (Lythgoe et al., 2005). Subsequent systematic study of artistic ability associated with the various dementias found no general increase in creativity to be linked with FTD, 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).

Several electroencephalography (EEG) studies provide tantalizing support that imaging of the creative experience is both possible and informative to understanding the interactions of distributed neural networks. Early EEG studies demonstrated that highly creative individuals differed from normal controls in (1) greater activity within right parietotemporal areas, (2) higher alpha activity during analogs of "inspiration," and (3) greater tendency to present physiological over-response (Martindale and Greenough, 1973; Martindale and Hasenfus, 1978; Martindale and Hines, 1975). In the middle phase of EEG studies, researchers described greater "dimensional complexity" over central and parietal cortices in subjects engaged in DT (Molle et al., 1996). Similarly, one study that compared gifted, intelligent, creative, and average individuals found lower levels of mental activity in highly creative subjects when compared to average individuals when engaged in the solution of creative problems (Jausovec, 2000). This same group (Jausovec and Jausovec, 2000) found that EEG coherence (during "rest" with eyes open) was significantly related to creativity scores, particularly across the right hemisphere. Finally, one researcher studied healthy males and found that good creative DT performance ($N = 15$) related to increased centroparietal interhemispheric connectivity and greater right hemisphere interconnectivity (Razumnikova, 2000). This same researcher found different patterns of interhemispheric connectivity and amplitude in men and women, suggesting significant sex-mediated differences in creative cognition (Razumnikova, 2004). More recently, this researcher found increased power in the frontal cortex and increased desynchronization over the posterior cortex associated with performance during a verbal insight task (Razumnikova, 2007). Additional EEG work is reported for the rarely studied realm of scientific hypothesis generation. Twenty-five gifted and twenty-five age-matched controls were compared, with results suggesting increased information transfer within left posterior brain regions of the gifted children compared to controls (Jin et al., 2006).

One research group has contributed much to the newest phase of EEG studies of creativity, with initial studies showing lower levels of cortical arousal during creative problem solving, and stronger alpha synchronization in centroparietal cortices associated with more original responses (Fink and Neubauer, 2006). This same group found the creativity–alpha power relationship to be mediated by the personality characteristic of Introversion–

Extraversion (Fink and Neubauer, 2008). Finally, in a combined EEG/fMRI study, they were able to interpret EEG alpha band synchronization, particularly within the frontal lobe, with active cognitive processes rather than cortical idling (Fink et al., 2009a). Thus, there is considerable heterogeneity of findings across EEG studies of creative cognition, making it difficulty to draw robust conclusions regarding the impact or direction of alpha activity, synchronization and localization of these factors within frontal, posterior, or even lateralized hemispheric cortices. Moreover, when such relationships are found, they appear to be mediated by giftedness (Jausovec, 2000; Jin et al., 2006), personality variables (Fink and Neubauer, 2008), and sex (Razumnikova, 2004).

The neurobiology of creativity also has been investigated with brain imaging techniques including regional cerebral blood flow, single photon emission computerized tomography (SPECT), positron emission tomography (PET), and functional magnetic resonance imaging (fMRI). One early study (Carlsson et al., 2000) was undertaken in 12 healthy male subjects stratified by either high or low scores on the creative functioning test (Smith and Carlsson, 1990). Blood flow measures were compared during performance of verbal fluency and DT. The highly creative group was characterized by bilateral frontal activation during DT compared to predominantly left hemisphere activation in the low creative group. Interestingly, better performance on the DT task was *negatively* correlated with higher activity within superior frontal regions. Such inverse correlations are suggestive of neural or network efficiency and have also been reported in neuroimaging studies of intelligence (Haier et al., 1988, 1992; Neubauer et al., 2004), although these efficiencies are now hypothesized to exist mainly for the frontal lobes (Neubauer and Fink, 2009). In another study, SPECT was used with 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 in the right postcentral gyrus, bilateral rectus gyrus, right inferior parietal lobule, and right parahippocampal gyrus (Chavez et al., 2004). PET was used to study nine healthy subjects as they performed verbal insight tasks (Starchenko et al., 2003). These authors found that the creative process activated left Brodmann area (BA) 40 and the cingulate gyrus (BA 32). This same group used PET to study normal subjects as they performed verbal creativity tasks and observed brain activations in the left parietotemporal brain regions (BAs 39 and 40) (Bechtereva et al., 2004). One fMRI study attempted to localize creative story generation within the brains of a cohort of eight normal subjects (Howard-Jones et al., 2005). When creative story generation was contrasted with uncreative story generation, significant activations were observed within bilateral medial frontal gyri (BAs 9 and 10) and the left anterior cingulate (BA 32). A novel study had subjects generate responses to the Rorschach inkblots (Asari et al., 2008). These researchers found that when unique responses were compared to more frequently generated responses, greater activations were observed within the right temporal pole (BA 38). When a less stringent threshold was used, additional regions associated with unique blot generation were identified within the left orbitofrontal region (BA 11), left cingulate (BA 32), and the left parietal cortices (BA 39). Thus, across functional studies, there appears to be some convergence, as noted previously, suggesting importance of the parietal cortex (BAs 39 and 40) to the creative process, the cingulate (BA 32) involved with internal selection, and frontal regions being engaged relevant to task complexity (BAs 8, 9, and 47) (Starchenko et al., 2003).

Undoubtedly, localization of creativity to certain regions of the brain is hampered by the lack of a systematic framework by which to empirically approach such a complex construct. For example, a wealth of research exists from the psychometric literature linking creativity to intelligence and personality variables (Batey and Furnham, 2006), yet these measures are rarely included in modern neuroimaging studies to assess the discriminant validity of the creativity measure of interest (e.g., DT). Most studies conflate creativity with a discrete cognitive process as opposed to assuming that a given cognitive process (e.g., DT, insight, fluid intelligence) is but one of many components making up the creative act. What these studies highlight is that a construct as complex as creativity will never be "localized" in the brain—be it the right hemisphere, anterior cingulate cortex, or other locus. Rather, individual findings will be dependent upon the task used as a "proxy" measure (e.g., insight, DT, convergent thinking), the population under scrutiny (e.g., college undergraduates, experts), and even methodological issues related to structural versus functional brain characteristics.

Neuroscience inquiries of creativity show a muddled picture likely related to subject, modality, and metric issues: Lesion studies tend to localize creativity to the anterior frontal and temporal poles; EEG studies show both "higher" and "lower" activation and more diffuse or focal activity based on task and subject characteristics; functional imaging studies show a tendency toward frontal, parietal, and cingulate localization. All studies have relatively small samples limiting statistical power. The current report attempts to address some of these shortcomings by (1) administration of psychometrically valid measures of intelligence, personality, and creativity (i.e., DT, creative achievement) to a large cohort of healthy subjects, (2) undertaking the first structural magnetic resonance imaging study linking constructs central to creativity to cortical thickness, and (3) linking our results to previous studies across the neuroscientific, behavioral neurology, and psychometric literatures.

The hypotheses we are testing are informed by recent findings. We showed that measures of DT were related to biochemical measures of *N*-acetylaspartate (NAA) in gray matter regions within the anterior cingulate gyrus (Jung et al., 2009). The relationship was complex, with both positive and negative associations observed; however, consistent relationships were seen between NAA and DT within medial gray matter regions (i.e., cingulate gyrus) across all subjects. As NAA is a marker of neuronal density and/or mass (Barker, 2001), similar relationships would be hypothesized between neuronal thickness and DT in regions including the cingulate cortex. More broadly, only one report, in normally developing children, has attempted to link behavioral skill with brain structural and functional imaging in the same cohort (Lu et al., in press). These authors found that children performing better on a naming task had both increased fronto-parietal activation and thinner cortex within the same regions, interpreted to represent "mature" brain organization shown previously in normally developing children (Gogtay et al., 2004; Shaw et al., 2006). Based on these findings we hypothesized that (1) *a priori*, cortical thickness in the cingulate gyrus would be associated with increased creativity as measured by DT and (2) in *exploratory tests across the entire cortical mantle*, less thickness would be associated with increased creativity as measured by DT.

METHODS

Sample

Sixty-five subjects were recruited for the present study. Four subjects were not included in the analysis due to missing behavioral data, leaving a final sample of sixty-one. Fifty-six of these sixty-one subjects were reported on previously in research linking DT to NAA (Jung et al., 2009). Subjects were young adults (23.7 ± 4.2 years), well matched by sex (33 males, 28 females), and the two sexes did not differ significantly on Full-Scale Intelligence Quotient (FSIQ) from the Wechsler Abbreviated Scale of Intelligence (males = 118.12 ± 10.78; females = 117.14 ± 8.41). They were recruited by postings in various departments and classrooms around the University of New Mexico. All participants signed a consent form approved by the institutional review board of the University of New Mexico prior to participation in the experimental protocol. Prior to entry into the study, participants were screened by a clinical neuropsychologist (REJ) and met no criteria for neurological and psychological disorders that would impact experimental hypotheses (e.g., learning disorders, traumatic brain injury, major depressive disorder). Subjects were also screened for conditions that would prohibit undergoing an MRI scan (e.g., metal implant, orthodontic braces, severe claustrophobia).

Behavioral Measures

All subjects completed the Creative Achievement Questionnaire (CAQ), a reliable and valid measure of creative productivity across ten domains including visual arts, music, creative writing, dance, drama, architecture, humor, scientific discovery, invention, and culinary arts (Carson et al., 2005). The CAQ has a test–retest reliability of 0.81, a split-half reliability $\alpha = 0.92$, predictive ability on judged "Creative Evaluation" in "making a collage" of $r = 0.59$ ($P = 0.0001$), and convergent validity with the personality variable "Openness to Experience" of $r = 0.33$ ($P = 0.01$). For each domain area, the subject was asked to place a checkmark next to a concrete achievement in a given domain (e.g., "My musical talent has been critiqued in a local publication"). Each checkmark was then allotted the number of points (0–7) next to the particular achievement across each of the 10 domains. Some items were marked by an asterisk (e.g., "I have received a grant to pursue my work in science or medicine"); the subject was to indicate the number of times these achievements have occurred, and these were then multiplied by the item number. The checkmarks and multiplied numbers were summed for a total score on the CAQ.

Three DT tasks were administered: Free Condition of the Design Fluency Test (DFT), Four Line Condition of the DFT, and Uses of Objects Test (UOT) (Lezak et al., 2004). In the Free Condition of the DFT, subjects were instructed to draw as many unique designs as they could in a period of 5 min. For the Four Line condition they were constrained in drawing designs composed of certain types of lines (e.g., straight, dots, curved) during 4 min. Good to excellent inter-rater reliabilities (0.66–0.99) using these two measures have been shown by other groups (Carter et al., 1998; Jones-Gotman, 1991). For the UOT, subjects were given 1 min to produce as many novel and creative uses as they could think of for common objects (e.g., paper clip). Inter-rater reliability of this measure ranged between 0.62 and 0.95; loadings of 0.51 and 0.52 have been reported on the factor of "spontaneous flexibility" (Domino and Domino, 2006).

Three independent judges ranked the creative products of each subject using the consensual assessment technique (Amabile, 1982) from which a "composite creativity index" (CCI) was derived. In our study, the independent judges were college aged raters who assessed the output of creativity measures as follows: (1) raters binned the output of each subject into one of five categories ranked on their own perception of creativity (1 = least, 2 = low, 3 = average, 4 = high, 5 = most); (2) raters were further instructed to bin their rankings to conform to a normal distribution (1 = 5%, 2 = 20%, 3 = 50%, 4 = 20%, 5 = 5%); (3) finally, raters were instructed to rank order each subject's output for creativity relative to others within each category. Inter-rater reliabilities between judges were high across the three measures of DT (0.81–0.94). Rankings for each subject were averaged across the three measures to form the CCI, z-transformed (mean of 0, standard deviation of 1), and then converted to a standard score (mean of 100, standard deviation of 15) to create a CCI.

Participants were also administered the Wechsler Abbreviated Scale of Intelligence (WASI) and NEO-Five Factor Inventory (NEO-FFI). The WASI consists of four subtests: Vocabulary, Similarities, Block Design, and Matrix Reasoning (Wechsler, 1999). Based on these four subtests one can derive measures of Verbal IQ, Performance IQ, and a composite Full Scale IQ. The NEO-FFI is a self-administered measure of normal personality functioning, which produces summary scores across five domains: neuroticism, extraversion, openness, agreeableness, and conscientiousness (Costa and McCrae, 1992).

Image Acquisition and Processing

Structural imaging was obtained at 1.5 Tesla Siemens using a T1 coronal gradient echo sequence [TE = 4.76 ms; TR = 12 ms; voxel size = $0.6 \times 0.6 \times 1.5$ mm^3; acquisition time = 7:15]. Subjects' heads were stabilized with tape across the forehead and padding around the sides. For all scans, each T1 was reviewed for image quality. Cortical reconstruction and volumetric segmentation were performed with the FreeSurfer image analysis suite, which is documented and freely available for download online (http://surfer.nmr.mgh.harvard.edu/). The methodology for FreeSurfer is described in full in several papers (Dale et al., 1999; Dale and Sereno, 1993; Desikan et al., 2006; Fischl and Dale, 2000; Fischl et al., 1999a,b, 2001, 2002, 2004a,b; Segonne et al., 2007). For this study, we focused on the cortical results. Procedures for the measurement of cortical thickness have been validated against histological analysis (Rosas et al., 2002) and manual measurements (Kuperberg et al., 2003; Salat et al., 2004). The results of the automatic segmentations were reviewed and any errors were corrected.

Statistical Analysis

To investigate the correlation between cortical thickness measurements and creativity scores, we performed a surface-based group analysis using tools within FreeSurfer. First, the subjects' surface was smoothed using a full-width/half-maximum Gaussian kernel of 10 mm. This smoothing was done so that all subjects in this study could be displayed on a common template, which is an average brain as described at http://surfer.nmr.mgh. harvard.edu/ to perform and visualize a group analysis. Freesurfer's mri_glmfit was used to fit a general linear model at each vertex in the cortex to perform between-group averaging and statistical inference on the cortical surface. The design matrix consisted of two discrete groups (male and female), with CCI or CAQ, FSIQ, and age as covariates and the slope used was different offset/intercept, different slope (DODS). The contrast matrix used [0, 0, 0.5, 0.5, 0, 0, 0, 0; F, M, FCCI(CAQ), MCCI(CAQ), F IQ, M IQ, F age, M age] investigated the average correlation affect of cortical thickness and either the CCI or CAQ measures, while regressing out the effect of group (gender), FSIQ and age, which was a two-tailed *t*-test. Age and sex were regressed to account for structural differences, and IQ was regressed to account for significant correlations between creativity measures and IQ (Sternberg, 2005). We used similar statistical methods that were used in prior thickness studies (Juranek et al., 2008; Nesvåg et al., 2008; Wright et al., 2007) to ascertain surface-based group differences using the general linear model tools within FreeSurfer. To correct for multiple comparisons, a Monte-Carlo simulation (mc-z; synthesized, smoothed z-field) within FreeSurfer was utilized, and the results were smoothed by the residual and repeated for 10,000 iterations, using a threshold of $P < 0.01$ (two-tailed), which is the probability of forming a maximum cluster of that size or larger during the simulation under the null hypothesis. This procedure replaces FDR and FWE procedures commonly used in structural or functional paradigms to correct for multiple corrections and presents the likelihood that the cluster of vertices would have arisen by chance. Only significant clusters >100 mm^2 in size are presented in the tables, except for one a priori region with a surface area of 90 mm^2.

RESULTS

The CCI measure was weakly, but significantly, correlated with FSIQ across the entire sample ($r = 0.28$, $P = 0.03$). This relationship was stronger for FSIQ at or below 120 ($r = 0.44$, $P = 0.008$) and null above 120 ($r = 0.06$, $P = 0.78$), suggesting concordant psychometric properties between our creativity measure and measures described previously in the research literature (Sternberg, 2005). Current measures of creativity, as captured with the CCI ($r = 0.47$, $P < 0.001$) and CAQ ($r = 0.36$, $P = 0.006$), were correlated with Openness to Experience from the NEO FFI, as previously reported in the creativity literature (Furnham, 1999; Wolfradt and Pretz, 2001). Finally, the CCI and CAQ were weakly correlated ($r = 0.26$, $P = 0.05$).

We found several discrete clusters at $P < 0.01$ that had a negative correlation with CCI and cortical thickness, which indicated decreased cortical thickness in relation to higher CCI scores (Fig. 1a–c and Table I). In the left hemisphere, the lingual gyrus ($P = 0.0192$) was negatively correlated with CCI. Several regions in the right hemisphere were also negatively correlated with CCI, including the following: the fusiform ($P = 0.0008$), the cuneus ($P = 0.0006$), angular gyrus ($P = 0.0011$), and a cluster with the largest surface area that was composed of vertices from three regions, the inferior parietal, lateral occipital, and superior parietal ($P = 0.0001$), with the centroid in the inferior parietal region. One region, the right posterior cingulate, correlated positively with the CCI ($P = 0.0012$), indicating increased cortical thickness related to higher CCI scores.

For the CAQ, there was one area for which lower cortical thickness was related to higher scores on the CAQ: the left lateral orbitofrontal region ($P = 0.0065$). Similarly, there was one area where higher cortical thickness was related to higher scores on the CAQ in the right angular gyrus ($P = 0.0007$) (Fig. 2a–b and Table II).

Controlling for CAQ or CCI did not appreciably change the results other than altering region size and significance levels of individual regions relative to one another.

DISCUSSION

This is the first study to link cortical thickness measures to psychometric measures of creativity. We found a

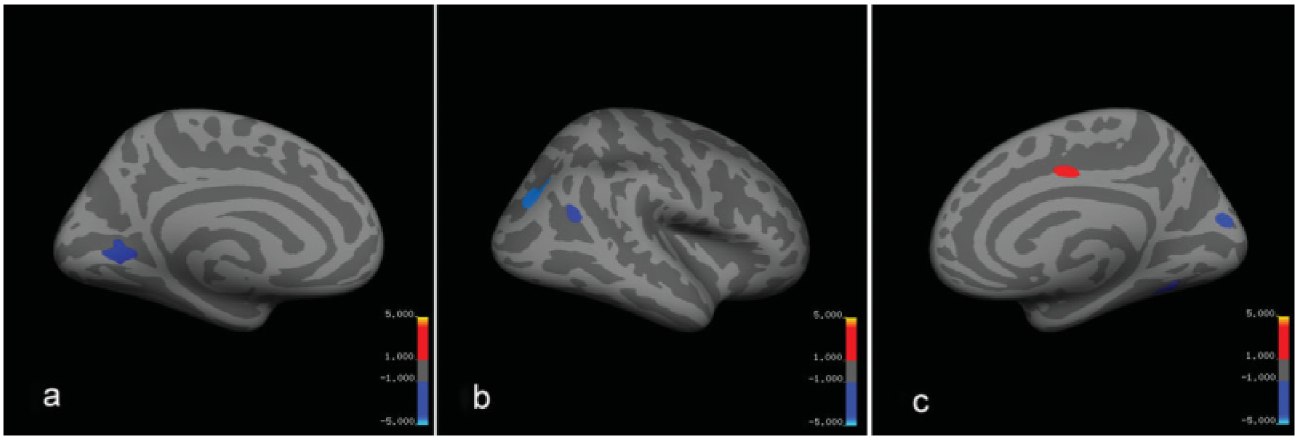

Figure 1.

Statistical maps ($P < 0.01$) of significant clusters from Monte-Carlo simulations of the CCI–cortical thickness correlation overlaid on the FreeSurfer average subject. Color bar indicates $-\log(10)P$, where P corresponds to the CWP values in Table I. Blue color indicates a negative correlation (decreased cortical thickness correlates with the CCI) and red indicates a positive correlation (increased cortical thickness correlates with the CCI). (a) Medial left hemisphere; (b) lateral right hemisphere; (c) medial right hemisphere.

network where *increased* and *decreased* cortical thickness related to creativity as measured with DT and creative achievement. The network was not limited to one lobe of the brain, nor to one hemisphere, nor to the "more is better" notion that tends to characterize research within the cognitive neurosciences (Jung et al., 2005). Rather, we found an interplay of *increased* gray matter thickness related to both CCI and CAQ performance within the right posterior cingulate gyrus and right angular gyrus, as well as *decreased* thickness related to these same measures in regions including the left frontal lobe, lingual, cuneus, angular, inferior parietal, and fusiform gyri. In terms of BAs, these regions include BAs 11, 18, 19, 24, and 39. These regions all survived Monte-Carlo simulations to assess whether they could have arisen by chance; therefore, subsequent discussions can be undertaken with some

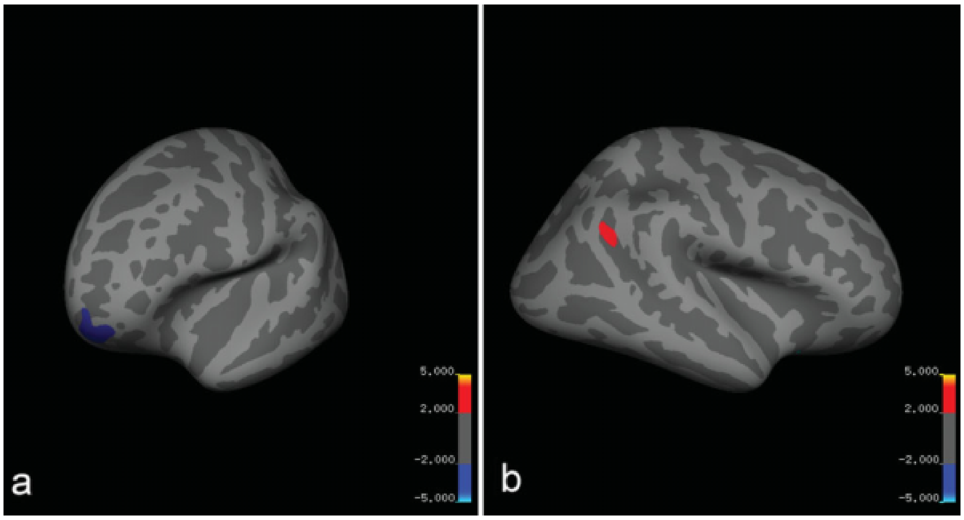

Figure 2.

Statistical maps ($P < 0.01$) of significant clusters from Monte-Carlo simulations of the CAQ–cortical thickness correlation overlaid on the FreeSurfer average subject. Color bar indicates $-\log(10)P$, where P corresponds to the CWP values in Table II. (a) Lateral left hemisphere; blue indicates a negative correlation (decreased cortical thickness correlates with the CAQ) and (b) right lateral hemisphere; red indicates a positive correlation (increased cortical thickness correlates with the CAQ).

TABLE I. Creative composite index (divergent thinking tasks): Regions surviving Monte Carlo simulation ($P < 0.01$)

Max	Size (mm^2)	Tal$X$	Tal$Y$	TalZ	CWP	Vtxs	Gyrus
Left hemisphere							
−4.31[a]	376.78	−12	−66	5.4	0.02	706	Lingual (BA 18)
Right hemisphere							
−3.425[a]	165.95	5.5	−74.7	22	0.0006	216	Cuneus (BA 18)
−2.726[a]	242.43	33.4	−71.9	21	0.0001	470	Inferior parietal (BA 19)
−3.069[a]	138.14	30	−58.5	−6.2	0.0008	245	Fusiform (BA 19)
−2.789[a]	109.54	43.9	−56.5	21.3	0.0011	213	Angular (BA 39)
3.311[b]	90.04	7	−4.2	37.9	0.0012	224	Cingulate (BA 24)

Max: positive value = positive correlation between cortical thickness and CCI; negative value = negative correlation between cortical thickness and CCI.

Size (mm^2) = surface area of the cluster in square millimeters; Tal$X$ = Talairach region X plane; Tal$Y$ = Talairach region Y plane; TalZ = Talairach region Z plane; CWP = clusterwise probability, which is the P value; Vtxs = number of contiguous vertices.

[a] Regions surviving both Monte Carlo simulation and size constraints.

[b] Region surviving both Monte Carlo simulation and a priori constraints.

level of certainty, given that this is the first study to link cortical thickness measures to psychometric measures of creativity in a normal healthy cohort.

The inverse relationships between cortical thickness and the creativity measures in the present study speak to the possible importance of efficient information flow among brain areas. These results can be seen as consistent with our previous study showing inverse relationships between the neurometabolite NAA and creativity in a subset of the same cohort as presented here (Jung et al., 2009), and with a previous study showing decreased cortical thickness associated with functional activation in a cohort of older children (Lu et al., in press). Similarly, developmental studies of intelligence have shown accelerated cortical thinning in children (age 7–19) with the highest levels of intelligence in regions including the dorsal and rostral frontal lobes (Shaw et al., 2006). In studies spanning normal development, the parietal lobes have been found to thin most during adolescence (Sowell et al., 1999a), with the frontal lobes thinning most during late adolescence and early adulthood (Sowell et al., 1999b). The mechanism for such thinning has been postulated to involve more focused functional activation during skill acquisition as plasticity decreases and efficiency increases (Durston and Casey, 2006; Durston et al., 2006). These results, along with the current findings, would suggest that development of cognitive capacity (including creative capacity) can be associated with lower levels of cortical thickness in discrete regions of the brain, especially within younger age cohorts of which the present sample (lower age range = 18) at least partially overlaps. In applying this viewpoint to our cortical thickness results, a possible interpretation of our findings is that the generation of novel, original ideas is associated with less cortical thickness within frontal and (certain) posterior cortical regions, requiring higher functional activation to initiate cognitive control.

The distribution of significant areas throughout the brain, found in the current study, suggests that information flow among brain areas may be a key to creativity. We proposed a similar concept for an intelligence network based on a wide range of structural and functional neuroimaging studies (Jung and Haier, 2007), and some overlap in regions bears discussion. For example, cortical thickness within regions of the right angular gyrus (BA 39) was found to predict performance on both the CCI (*negative*) and CAQ (*positive*). In studies of intelligence, a wide range of research found correlations with right BA 39 across structural imaging modalities (Shaw et al., 2006), PET

TABLE II. Creative achievement questionnaire: Regions surviving Monte Carlo simulation ($P < 0.01$)

Max	Size (mm^2)	Tal$X$	Tal$Y$	TalZ	CWP	Vtxs	Gyrus
Left hemisphere							
−3.209[a]	488.27	−16	47.4	−14.9	0.0065	592	Orbitofrontal (BA 11)
Right hemisphere							
3.31[a]	118.98	44.2	−51.1	27.8	0.0007	281	Angular (BA 39)

Max: positive value = positive relationship between cortical thickness and CAQ; negative value = negative relationship between cortical thickness and CAQ.

Size (mm^2) = size of region in square millimeters; Tal$X$ = Talairach region X plane; Tal$Y$ = Talairach region Y plane; TalZ = Talairach region Z plane; CWP = clusterwise probability; Vtxs = number of contiguous vertices.

[a] Regions surviving both Monte Carlo simulation and size constraints.

(Esposito et al., 1999), and fMRI (Atherton et al., 2003; Lee et al., 2006). Indeed, other researchers (Jung-Beeman, 2005) have hypothesized the angular gyrus to be important to semantic activation, a process by which "first-order" associations are made. Interestingly, the right semantic field is specifically hypothesized to maintain weak semantic links, "including distant and unusual semantic features, features that seem irrelevant to the context, and secondary word meanings . . . rife with ambiguity" (p. 514). Along with other studies showing posterior parietal EEG activation associated with original ideational generation (Fink et al., 2009a; Fink and Neubauer, 2006; Grabner et al., 2007) and insight (Jung-Beeman et al., 2004), this parietal focus points to bottom–up activation of attentional and analogical knowledge stores (semantic/visuospatial) necessary for creative problem solving.

There were two regions where we saw *increased* cortical thickness related to creative capacity: the first in the right cingulate cortex (BA 24), related to performance on DT measures; the second within the right angular gyrus (BA 39), related to creative achievement (CAQ). Previous creativity studies report relationships between various creativity measures and activations within the cingulate gyrus and parietal cortex (Chavez et al., 2004; Howard-Jones et al., 2005; Molle et al., 1996; Razumnikova, 2000). Specialized cognitive activities ascribed to the cingulate cortex include monitoring unfavorable performance outcomes, response errors, and response conflicts (Ridderinkhof et al., 2004). Most salient to the current discussion, one study found greater activation in the left inferior parietal and angular gyri when subjects performed verbal alternate uses tasks (Fink et al., 2009a). The authors interpret this finding as consistent with the inferior parietal cortex being associated with verbal working memory processing, in particular the phonological store (Baddeley, 2003). As our results were found for creative achievement (CAQ), they were not task related per se, although perhaps reflecting homologous working memory processes associated with the visuospatial sketchpad.

NAA is often considered to be a proxy measure for neuronal mass (Barker, 2001). Thus, the finding of *increased* cortical thickness correlates to DT in the right cingulate (BA 24) might appear to contradict our previous research showing *inverse* NAA-DT relationships in a largely overlapping cohort (Jung et al., 2009). However, NAA, while found predominantly in neurons, serves numerous roles both within neurons and surrounding oligodendrocytes including the following: cellular osmolyte, storage vehicle for aspartate and glutamate, metabolic precursor of the excitatory dipeptide *N*-acetylaspartyl-glutamate, involvement in neuronal–glial signaling, participation in myelin formation, and molecular water pump (Baslow, 2003). Moreover, cortical thickness measures represent a broad range of tissue types—not strictly neuronal. Indeed, it is plausible that increased glial cell content would result in higher cortical thickness and lower levels of NAA within the same tissue. It is of note that Albert Einstein, a creative icon of the 20th century, had parietal lobes, which were 15% wider than control subjects (Witelson et al., 1999), while left BA 39 within the parietal cortex was found to have significantly higher glial:neuronal ratio on histology (Diamond et al., 1985). Future research focused on myoinositol, a glial marker within the proton spectrum, would potentially help disentangle this complex relationship between brain biochemistry, cortical thickness, and creativity.

Several *inverse* relationships were observed between cortical thickness measures and creativity as measured with the CCI. For the left hemisphere on the CCI, this was limited to the lingual gyrus (BA 18). Interestingly, a recent study reports that the lingual gyrus was preferentially activated to process novel events that were outside the focus of spatial attention (Stoppel et al., in press). These authors interpret this finding to support the lingual gyrus acting as a "novelty detector at early perceptual level" (p. 10). As two of the three DT measures that comprised the CCI were timed novel drawing tasks, it is plausible that structural differences within the lingual gyrus accounted for some of the behavioral differences on the CCI. Other regions in which inverse relationships were found for the CCI, in the right hemisphere, included the cuneus (BA 18), fusiform (BA 19), inferior parietal (BA 19), and angular gyrus (BA 39). Taken together, it is difficult to link the occipital and parietal regions to previous research in creativity, as no studies have focused on activation patterns clustered so posterior in the brain, although several EEG studies have found a preponderance of centroparietal involvement in high creative performance (Fink and Neubauer, 2006; Molle et al., 1996; Razumnikova, 2000). Similarly, the relationship between CCI and BA 39 is consistent with previous research showing relationships between cortical activation and performance on the Torrance Test of Creative Thinking (Chavez et al., 2004). However, no previous research has specifically assessed creative achievement in young adults, and the results should be interpreted with caution until replicated.

Finally, BA 11, within the left orbitofrontal cortex, was *inversely* related to the CAQ. This finding is of note given previous research showing creative increases in some patients suffering from FTD—a disease preferentially affecting the orbitofrontal cortex and temporal poles (Miller et al., 1998, 2000; Miller and Hou, 2004), although this relationship does not hold across a case-controlled cohort of patients with FTD (Rankin et al., 2007). The left orbitofrontal cortex is also of interest as it was one of the unconstrained regions found to predict unique responses when subjects responded to Rorschach inkblots in an fMRI paradigm (Asari et al., 2008). Indeed, both visual and auditory inputs project to the orbitofrontal cortex via the superior temporal sulcus and temporal pole. In turn, the orbitofrontal cortex projects back to regions distributed broadly throughout the cerebral cortex, including the amygdala (Barbas, 2007), anterior cingulate cortex (Carmichael and Price, 1996; Price, 2006), basal ganglia, and other cortical regions (including the parietal cortex)

(Rolls, 2008; Rolls and Deco, 2002). This network provides routes by which behavior (Rolls, 2005) and memory (Rolls and Xiang, 2005) are influenced. In both human and nonhuman primates, functioning of the orbitofrontal cortex appears to be critically involved in distinguishing rewarding from unrewarding stimuli as well as in altering behavior when reinforcement contingencies change (Rolls and Grabenhorst, 2008). This role of the orbitofrontal cortex is seen to play a critical evolutionary role by allowing maximal flexibility in possible actions. Indeed, by leveraging instrumental reinforcers in specifying goals for actions (and subsequent emotions), the orbitofrontal cortex guides the efficient matching of behavior to environmental contingencies (Rolls, 2005). Interestingly, a region of the primate orbitofrontal cortex responds to novel but not familiar visual stimuli (Rolls et al., 2005), a finding relevant to discussions of creativity.

The current research addresses aspects of creativity touching upon both novelty (DT) and usefulness (CAQ) within the same research paradigm. Moreover, by using psychometrically validated measures of creative process and product, this study incorporates two elements that psychometric theorists have considered to be central to creativity among the major domains of scientific inquiry including person, process, environment or influence, and product (Guilford, 1967; Torrance, 1974). The benefits of such a psychometric approach is the brevity of the measures, their reliability and validity, the normality of their distribution, the suitability of their use in a laboratory setting, and their appropriate use for subsequent correlation to brain measures including cortical thickness. However, the psychometric strength of such measures cannot hide the fact that subjects are not being creative in the laboratory, only simulating cognitive proxies for creativity and self-reporting their creative success out in the world [see Sternberg (1999; p. 7) for discussion]. We have used measures of DT and creative achievement to assess creative cognition in a cohort of normal college aged students. This should not be interpreted to mean that we equate DT or self-reported achievement with creativity writ large. Our measures would likely be inappropriate or inadequate to tap the spontaneous-emotional creativity that may be more characteristic of visual artists or improvisational musicians. That being said, our results indicate that creativity, in at least some forms, is amenable to neuroscience inquiry.

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