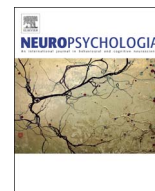




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Functional magnetic resonance imaging of divergent and convergent thinking in Big-C creativity

Kevin Japardi^{a,b,*}, Susan Bookheimer^{a,b,c}, Kendra Knudsen^b, Dara G. Ghahremani^{a,b},
Robert M. Bilder^{a,b,c}

^a Department of Psychiatry and Biobehavioral Sciences, David Geffen School of Medicine at UCLA, University of California, Los Angeles, CA 90095, USA

^b UCLA Semel Institute of Neuroscience and Human Behavior, David Geffen School of Medicine, 760 Westwood Plaza, Los Angeles, CA 90024, USA

^c Department of Psychology, UCLA College of Letters and Science, University of California, Los Angeles, CA 90095, USA

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ABSTRACT

The cognitive and physiological processes underlying creativity remain unclear, and very few studies to date have attempted to identify the behavioral and brain characteristics that distinguish exceptional (“Big-C”) from everyday (“little-c”) creativity. The Big-C Project examined functional brain responses during tasks demanding divergent and convergent thinking in 35 Big-C Visual Artists (VIS), 41 Big-C Scientists (SCI), and 31 individuals in a “smart comparison group” (SCG) matched to the Big-C groups on parental educational attainment and estimated IQ. Functional MRI (fMRI) scans included two activation paradigms widely used in prior creativity research, the Alternate Uses Task (AUT) and Remote Associates Task (RAT), to assess brain function during divergent and convergent thinking, respectively. Task performance did not differ between groups. Functional MRI activation in Big-C and SCG groups differed during the divergent thinking task. No differences in activation were seen during the convergent thinking task. Big-C groups had less activation than SCG in frontal pole, right frontal operculum, left middle frontal gyrus, and bilaterally in occipital cortex. SCI displayed lower frontal and parietal activation relative to the SCG when generating alternate uses in the AUT, while VIS displayed lower frontal activation than SCI and SCG when generating typical qualities (the control condition in the AUT). VIS showed more activation in right inferior frontal gyrus and left supramarginal gyrus relative to SCI. All groups displayed considerable overlapping activation during the RAT. The results confirm substantial overlap in functional activation across groups, but suggest that exceptionally creative individuals may depend less on task-positive networks during tasks that demand divergent thinking.

1. Introduction

Creativity has burgeoned as a topic of scientific inquiry since the middle of the 20th century, but there is limited understanding of the cognitive and physiological processes underlying creativity. While there have been multiple definitions of creativity, one prominent theory holds that creativity requires the generation of products that are novel, valuable, and surprising (Simonton, 2012). The field also recognizes distinctions among “Big-C” (exceptional creativity), “little-c” everyday creativity, and other intermediate levels including “mini-c” and “Pro-c” to reflect dynamic learning processes and professional-level expertise (Kaufman and Beghetto, 2009).

Joy Paul Guilford is widely credited with drawing a distinction between two basic cognitive processes important for creative thinking (Guilford, 1967): *divergent thinking* (the ability to disengage from

prevailing modes of thought and expression to generate novel ideas and solutions) (Benedek et al., 2014; Flaherty, 2005; Heilman, 2016), and *convergent thinking* (the recruitment and interaction of different cognitive processes to find a common solution to a given problem (Heilman, 2016; Mednick, 1962)). The most widely used tasks to investigate divergent and convergent thinking processes relevant to creativity, are the alternate uses task (AUT) and remote associates task (RAT), respectively (Abraham et al., 2014, 2012; Fink et al., 2009). Meta-analysis of the fMRI studies suggested that engaging in either of these tasks (relative to several different contrast conditions) is associated with lateral frontal activations, with some left-lateralization and engagement of language centers in both frontal and temporoparietal cortices consistent with the verbal nature of these tasks (Boccia et al., 2015). There are noteworthy exceptions: for example, one study found less prefrontal and greater left lateral occipitotemporal activations associated with

* Correspondence to: UCLA Department of Psychiatry and Biobehavioral Sciences, David Geffen School of Medicine, 760 Westwood Plaza, Ste B8-169, Los Angeles, CA 90024, USA.
E-mail addresses: kjapardi@mednet.ucla.edu (K. Japardi), sbook@g.ucla.edu (S. Bookheimer), KKnudsen@mednet.ucla.edu (K. Knudsen), darag@ucla.edu (D.G. Ghahremani), RBilder@mednet.ucla.edu (R.M. Bilder).

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“open ended” unusual use generation, a finding considered relevant to perceptual and conceptual search characteristics of the task (Chrysikou and Thompson-Schill, 2011). These studies primarily aimed to reveal brain mechanisms important for executing the tasks, and examined students not selected for their creative achievements, leaving open questions about how Big-C individuals might process the same tasks.

Andreasen and Ramchandran (2012) provided a scholarly review of the often-help impression that scientific and artistic creativity arise from fundamentally different “cultures,” and may be associated with distinctive brain mechanisms (for example, that artists might excel at divergent and scientists at convergent thinking), but so far there has been little empirical investigation of this critical question. The Iowa Study of Creative Genius (Andreasen and Ramchandran, 2012) examined functional brain activation in exceptionally creative individuals using a word association task during fMRI in seven Big-C individuals (4 artists and 3 scientists) and showed no differences between groups, with both artists and scientists showing predominantly left hemisphere activations. Conclusions from this fascinating project remain limited, however, by the sample sizes, and lack of a comparison group not selected for creative achievement. In a study of professional jazz musicians, improvisation was associated with deactivations of lateral frontal and increased activations of medial frontal regions (Limb and Braun, 2008). Medial frontal cortex is a core node of the “default mode network,” which has been linked to “mind wandering” and creativity, but it seems likely that creative cognition is mediated by complex interplay of default mode and other “task positive” networks (Beaty, 2015).

The Big-C Project at UCLA aimed to examine the neural substrates underlying divergent and convergent thinking in highly creative individuals relative to a healthy comparison group, using the two tasks most widely used to study creativity, the AUT (Guilford, 1967) and the Remote Associates Task (RAT) (Mednick, 1968). We expected all our groups to show task-relevant activations similar to those shown in prior investigations, but remained agnostic as to whether Big-C individuals might show greater or lesser activation within these networks, and did not make any prior hypotheses about differences between our Big-C artists and scientists. We chose our Big-C domains based on prior factor analyses of the Creative Achievement Questionnaire (CAQ) (Carson et al., 2005), suggesting that visual arts and scientific/invention loaded on coherent factors (Bilder and Knudsen, 2014; Carson et al., 2005). Big-C Visual Artists and Scientists were recruited through a peer-nomination network and Internet searches, with eligibility based on domain-specific achievements, and endorsement of the novelty of their contributions by peers within their respective domains. A major challenge for research on brain and behavior in Big-C creativity is the fact that individuals with high levels of achievement in creative domains also possess higher levels of academic achievement and/or higher levels of intellectual ability, which may be considered a confounding factor. We therefore decided to recruit a “smart” comparison group that was matched to our Big-C groups, not only on age and sex, but also on intelligence and parental educational background. We aimed to answer two main questions: (1) Do Big-C individuals show distinctive patterns of brain activation, relative to a comparison group not selected for creative achievement, while performing tests of divergent and convergent thinking? (2) Among Big-C creatives, are there significant differences in brain activation between Big-C Visual Artists and Scientists?

2. Methods & materials

2.1. Study recruitment

We created an advisory group of internationally acclaimed creative achievers in diverse disciplines spanning the visual arts (e.g. painting, drawing, sculpture, photography, graphic design, animation) and the sciences (e.g. biology, neuroscience, chemistry, mathematics) to nominate potential Big-C participants between ages 21 and 60. We additionally received input from colleagues at the National Endowment

for the Arts. The actual levels of achievement for the nominees were verified using Internet searches and other objective measures of productivity (e.g., for scientists, we computed bibliometric statistics using the ISI Web of Science, patents received, and grants received; for artists, we reviewed the number of level of exhibitions; and for both groups we reviewed awards received). Big-C visual artists (VIS) were required to have multiple international exhibitions, while Big-C scientists (SCI) were required to have multiple internationally acclaimed publications (supported by high h-index scores and citations relative to age peers), inventions, or both. These criteria were based on empirical observations of CAQ scores from a prior study of 300 healthy community participants, not selected for creative achievement (the UCLA-300 Project), where individuals with this level of achievement were outliers (above the 98th percentile).

Our comparison group was recruited from the UCLA-300 Project (for those participants who had agreed to be re-contacted for participation in future studies) and additional postings in the community. Comparison group participants were healthy by self-report. All participants satisfied basic MRI safety screening criteria. This study was reviewed and approved by the institutional review board at UCLA (IRB #12–001335), and informed consent was obtained from all participants before any study procedures commenced.

2.2. Characterization and behavioral assessment

The groups were recruited to be comparable in age, sex, race/ethnicity, parental education, and estimated intelligence quotient (IQ), based on the Wechsler Adult Intelligence Scale, 4th Edition (WAIS-IV) age-corrected scaled scores on Vocabulary and Matrix Reasoning subtests, following the estimation formula of (Denney et al., 2015). To maximize satisfaction of these criteria, our recruitment of participants for the comparison group focused on individuals with higher educational achievement. Because the Big-C groups had high levels of educational attainment and Estimated IQ, and we selected comparison group participants who possessed similar levels of parental educational attainment, we refer to this group as the Smart Comparison Group (SCG). Handedness was assessed using a modified Edinburgh Inventory (Oldfield, 1971), and Laterality Quotient (LQ) computed as $(R-L)/(R+L)$, where R indicates the number of items (out of 10) performed with the right hand, L indicates the number of items performed with the left hand, and the scores thus range from + 1.0 (all right) to – 1.0 (all left). Participants also completed additional procedures including: (1) a semi-structured interview; (2) a battery of self-report questionnaires examining personality, schizotypal features and social responsiveness; (3) and a battery of cognitive tests examining working memory, fluency, response inhibition, and divergent/convergent thinking. Data from these additional procedures are the subject of separate publications, but we include here results from the Torrance Tests of Creative Thinking (TTCT; including the Unusual Uses (UU) test, Picture Completion (PC) Test, and Lines Test, along with the Creative Strengths (CS) measures, all as scored by TTCT staff) and the RAT (Mednick 1968), in order to examine the convergent validity of these conventionally-administered tests with the findings from in-scanner performance of similar tests (see below). We also report the measures of general intellectual ability (as noted above) and the Ravens Advanced Progressive Matrices, Short Form (which is a 12-item subset of the RAPM that correlated 0.90 with the RAPM 36-item long form; Arthur and Day, 1994). Participant Estimated IQ was calculated from WAIS-IV Vocabulary and Matrix Reasoning age-corrected scaled scores using the following equation: Estimated IQ = (WAIS-IV Vocabulary age-corrected scaled score + WAIS-IV Matrix Reasoning age-corrected scaled score) * 2.43 + 45.03. Further explanation of this equation is detailed in Denney et al., 2015.

2.3. fMRI tasks

Participants practiced each fMRI task prior to their MRI session on a

separate set of practice items that did not appear in the experiment. Each task consisted of two runs that included unique stimuli, counter-balanced for stimulus presentation order. Visual stimuli were presented using a set of MRI-compatible stereoscopic goggles (Resonance Technology, Northridge, California). Functional tasks were presented using MATLAB R2010a and Psychtoolbox Version 3.0.8 on an Apple iMac computer (Apple, Inc., Cupertino, CA). Responses were collected via a four-button response box (Current Designs, Philadelphia, PA). Participants used their right hand for responding. Button presses were used to collect responses rather than verbal responses, in order to limit motion during scanning. Accuracy of responding was validated using a post-scanning verbal recall procedure (see below).

2.3.1. AUT fMRI design

We used an AUT with items (words representing objects) selected from a published list (Abraham et al., 2012), translated from German to English. Words with very low frequencies in the English language, deemed too abstract, containing multiple separate words, or redundant with other listed objects were eliminated. Given the established differences between conditions (i.e., fewer words tend to be produced for alternate uses (AU) compared to typical qualities (TQ)), we used results from pilot testing to help better match the total number of responses generated across conditions, by eliminating those items for which there were highest discrepancies between the AU and TQ conditions.

The AUT lasted approximately 10 min, consisting of 8 alternating blocks of AU and TQ trials. Each AU and TQ block consisted of 4 items displayed for 20 s each. Control blocks in which participants made button presses were presented after every two items for 20 s. The task also included an inter-stimulus interval between 2 and 5 s.

Participants were instructed to think of as many distinct AU or TQ for the presented word and to respond with a button press for each distinct thought that came to mind (Fig. 1). An alternate use was defined as any use that was not a conventional use of the object shown (Item = Brick, Alternate Uses = shoe, plate). A typical quality was defined as a conventional, descriptive adjective of the object shown (Item = Umbrella, Typical Qualities = waterproof, colorful). Participants were also instructed that there was no limit to what was considered “too unusual” (i.e. they should not feel restricted to thinking of only tangible, real-world possibilities).

AUT responses were scored for fluency and originality by 6 raters (each rater scoring all cases). Raters tallied the total number of acceptable responses following the rules defined in the AUT Scoring Manual (Wilson et al., 1954). We used the average score of all 6 raters for fluency (Intraclass Correlation Coefficient (ICC) = 0.99), the total number of acceptable responses. Challenges to the reliable scoring of originality in Alternate Uses Tests is well known (Benedek et al., 2013), and because originality scores tend to be strongly correlated with fluency scores, we assessed the reliability of two approaches. First, we examined the residual of the originality score (to control for the effect of fluency using linear regression). As others have found, these scores were not as reliable as we would like (ICC = 0.63). Second, we examined the maximum originality score (as suggested by Benedek et al., 2013). We first identified the maximum originality score (scaled from 1 for least original response to 5 for most original response) for each trial, considering the scores for all responses to the stimulus word within that

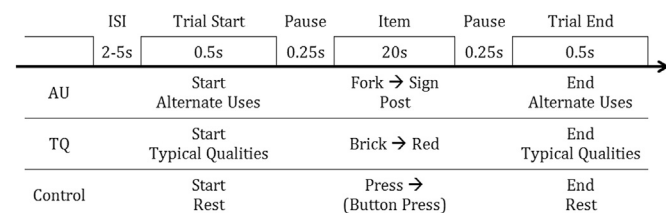


Fig. 1. AUT fMRI Task: AU = Alternate Uses condition. TQ = Typical Qualities condition.

trial, to yield a “trial maximum originality score”. We then summed the trial maximum originality scores across all trials to yield a total, maximum originality score.” This method revealed the most reliability using all of our six raters (ICC = 0.94); thus we used the average of these two raters’ residual scores for subsequent analyses.

2.3.2. RAT fMRI design

The RAT had a maximum duration of 14 min, consisting of 12 alternating blocks of Synonyms (SYN) and Associations (ASSOC), separated by blocks of Characters (CHAR) (11 blocks). Each SYN and ASSOC block consisted of 6 trials, with CHAR blocks having 3 trials. In each trial, participants were presented with three items centrally on the screen on a single line and had 14 s to formulate their solution. Once a solution was found, they indicated so by pressing a button and continuing to the response collection period after a jittered inter-stimulus interval (taken from an exponential distribution with a mean of 2 s and a range between 0.5 s and 3 s). During the 1.5-second fixed response window, participants selected one of four possible answers from a multiple-choice array, containing four word-stem choices (e.g. the first two letters of a single word, such as “Ho-” for Horse). Word stems were used to prevent participants from relying on recognition of the correct answer from the response options, increasing the likelihood that they would select the stem of the solution they already had in mind. The response period was followed by an inter-stimulus interval before presentation of the next trial (taken from an exponential distribution ranging from 0.5 s to 7 s with a mean of 2 s).

Examples of the sets of words or characters and the rules of each condition are illustrated in Fig. 2. During CHAR, participants identified the initial character across three sets of characters that had semi-randomized sequence (e.g., BX8T3, B?U34, B1Q&T), and then had to indicate their answer choice by pressing a button corresponding to that character's position in a multiple choice array (e.g., if the array had the characters *, B, X, and? the correct choice should be the 2nd button, “B”). During SYN, participants were asked to identify the two synonyms or closely-related words from a list of three words (e.g., for stimuli HOP, WALK, JUMP, correct responses would be “Ho” or “Ju”). During ASSOC, participants were instructed to think of a fourth word that can be associated with all three words presented, similar to the original RAT developed by Mednick (1962). For example, if the words shown were “Sea”, “Rocking”, and “Shoe”, the participant might ideally think of the word “Horse”.

2.3.3. Post-fMRI task recall session

Recall sessions for both functional tasks were conducted immediately after the MRI session to determine or verify solutions produced while in the scanner. Both recall sessions were conducted in a testing room adjacent to the scanner to reduce the time between fMRI completion and response recall. The recall session followed the same order as the MRI session (AUT first, RAT second). For the AUT, participants were shown the same items they had seen in the scanner and instructed to recall as many AU and TQ as they could recall from their performance while in the scanner. For the RAT, participants were given the same list of Association trials, and were asked to quickly fill in the associative word they had selected during the scan.

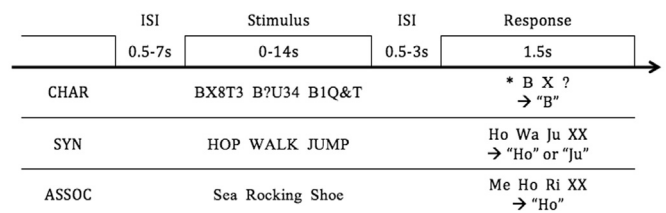


Fig. 2. RAT fMRI Task. CHAR = Characters condition. SYN = Synonyms condition. ASSOC = Associations condition.

Table 1
Age, sex, CAQ scores, level of education, and Estimated IQ scores across all MRI participants.

	Group			Test Statistic	DF	P	Post-Hoc
	VIS	SCI	SCG				
Age	42.9 ± 7.23	45.1 ± 8.24	42.2 ± 9.44	F = 1.05	2, 89	0.36	–
Sex	16 M, 14 F	17 M, 15 F	15 M, 15 F	F = 0.04	2, 89	0.96	–
Race (% W)	67	75	87	$\chi^2 = 3.33$	2	0.19	–
Ethnicity (% NH-L)	97	94	93	$\chi^2 = 0.39$	2	0.82	–
CAQ	655 ± 988	220 ± 227	82.0 ± 243	$\chi^2 = 34.9$	2	p < .001	VIS + SCI > SCG
Education	18.7 ± 0.96	21.0 ± 0.00	18.9 ± 1.33	$\chi^2 = 55.7$	2	p < .001	SCI > VIS + SCG
Maternal Education	15.4 ± 0.65	15.2 ± 0.61	15.3 ± 0.63	F = 0.03	2, 87	0.97	–
Paternal Education	15.48 ± 3.91	16.75 ± 3.08	15.87 ± 2.65	F = 1.22	2, 86	0.3	–
Estimated IQ	111 ± 11.1	116 ± 10.3	113 ± 10.3	F = 1.12	2, 83	0.33	–
Hand Preference (L, M, R)	0, 5, 24	2, 3, 25	2, 0, 25	$\chi^2 = 6.74$	4	0.15	–
LQ	0.88 ± 0.16	0.77 ± 0.53	0.82 ± 0.53	F = 0.40	2, 83	0.67	–

Level of education codes used: 15 = some college, no degree, 16 = Associate degree (occupational, technical, or vocational program), 17 = Associate degree (academic program), 18 = Bachelor's degree (e.g. BA, BS), 19 = Master's degree (e.g. MA, MS, MBA), 20 = Professional school degree (e.g. MD, DDS, JD), 21 = Doctoral degree (e.g. Ph.D.). DF = degrees of freedom, LQ = Laterality Quotient; Handedness: (L = left, M = mixed, R = right), Post-Hoc = Post-Hoc between-group comparisons corrected using Bonferroni correction.

2.4. Functional MRI acquisition

Participants were scanned on a Siemens Magnetom Trio head-only 3 T scanner with a 12-channel head coil. For each participant, a high-resolution T₁-weighted sagittal magnetization-prepared rapid acquisition gradient-echo (MPRAGE) structural image was obtained (repetition time (TR) = 2530 ms, echo time (TE) = 3.31 ms, matrix size = 256 × 256, field-of-view = 256 mm, flip angle = 7°, 176 slices with 1 mm isometric voxels). Functional blood oxygenation level dependent (BOLD) images were acquired using an echo-planar imaging (EPI) sequence (TR = 2000 ms, TE = 30 ms, matrix size = 64 × 64, field-of-view = 192 mm, 34 slices with 3 mm isometric voxels). An additional high-resolution T₂-weighted segmented spin-echo structural image (TR = 5000 ms, TE = 34 ms, matrix size = 128 × 128, field-of-view = 192 mm, 36 slices, 1.5 mm in-plane resolution, 3 mm thick) in the same anatomical planes as the BOLD images was acquired to improve alignment to a standard coordinate system.

2.5. Behavioral data analyses

Behavioral data were analyzed using IBM SPSS Statistics Version 24. Analyses of nominal (categorical) variables used the SPSS Crosstabs function and exact chi-square computed using asymptotic or Monte-Carlo methods. Distributions of ordinal and interval level scores were first examined for normality and homogeneity of variance across groups before analyses of group differences, which used the SPSS General Linear Models (GLM) procedure. For tests that yield a single score (e.g., RAT Total Correct) we used univariate analyses to examine the effect of group (VIS, SCI, SCG). For tests yielding multiple measures, we used GLM Multivariate analysis, and when the same dependent measure was obtained under several conditions we used the Repeated Measures approach enabling assessment of group by condition interaction effects. We followed up significant GLM effects involving group. All comparisons were corrected for multiple comparisons using Bonferroni correction.

2.6. Task fMRI group analyses

Our fMRI analyses were conducted using the FMRIB Software Library (FSL). Standard fMRI preprocessing was run on the functional data (e.g., motion correction, brain extraction, spatial smoothing at 5 mm full width at half maximum (FWHM), and temporal filtering). All participant data were registered to a standard space using a three-stage registration procedure: preprocessed images were first registered to the high-resolution T₂-weighted structural scan via a rigid body linear registration using 6 degrees of freedom (3 rotational, 3 translational),

then to the MPRAGE using FSL's Boundary-Based Registration, and finally normalized to standard space (Montreal Neurological Institute (MNI)) using a linear affine transform with 12 degrees of freedom.

A three-level general linear model analysis (using FSL's FEAT) was conducted for both functional tasks: (1) the first level model examined activation within individual task runs, (2) the second level model tested for mean activation across both runs per participant, and (3) the third level tested for between-group differences.

At the first level, both the AUT and RAT were modeled using a block design, modeling each condition convolved with a double-gamma hemodynamic response function (HRF), including additional covariates for motion (3 translational, 3 rotational) and individual volumes flagged for outlying framewise displacement above a 2 mm threshold (average number of volumes flagged overall = 1.47 ± 3.92). Global signal was also included as an additional covariate for participants with apparent non-motion related artifacts (e.g., radiofrequency (RF) noise), similar to scrubbing techniques used in resting state fMRI analyses (Power et al., 2014).

Mean activation across runs were analyzed at the second-level using fixed effects models. Between-group analyses were conducted using FSL's Mixed-Effects FLAME 1 modeling, treating participant as random effect, using cluster-corrected statistics with a voxel threshold of $z > 2.3$ and a cluster threshold of $p < 0.05$, to investigate statistically significant regions of activation between Big-C and SCG groups. To reduce the number of voxel-wise comparisons, we created an activation mask consisting of voxels that exceeded threshold across all groups combined.

In addition to within-condition activation, we were interested in two direct contrasts: (1) divergent thinking during the AUT (AU > TQ), and (2) convergent thinking during the RAT (ASSOC > SYN + CHAR). To investigate functional activation correlated with response fluency and originality, we conducted additional analyses on the AUT data using these variables as covariates.

3. Results

3.1. Big-C MRI participants

A total of 107 participants were enrolled, including 35 VIS, 41 SCI, and 31 SCG participants. A subset of these participated in MRI scanning ($n = 92$), comprising 30 VIS, 32 SCI, and 30 SCG (Table 1). Reasons for exclusion from MRI were: claustrophobia, limited availability, and participant refusal for other reasons (Fig. S1). No significant between-group differences were found for age, sex, and Estimated IQ. SCI showed significantly higher education than VSI and SCG. Our VIS and SCI were found to have significantly greater CAQ scores than SCG. The

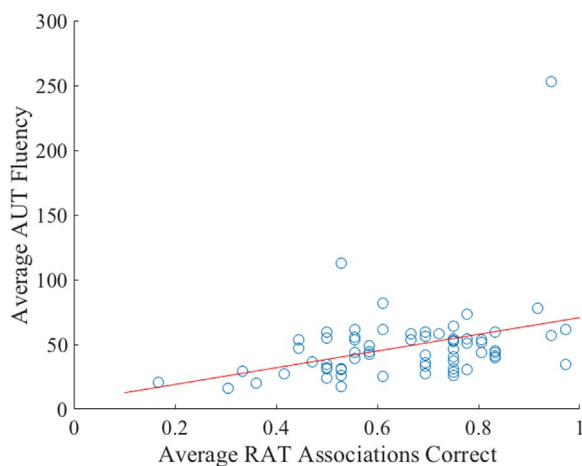


Fig. 3. Correlation between AUT Fluency scores and Average RAT Performance. A positive correlation was found between participant AUT fluency scores and their RAT performance ($r = 0.36$, $p = 0.003$). The positive correlation survived removal of the fluency score outlier ($r = 0.33$, $p = 0.008$).

significant difference in CAQ scores remained before and after exclusion of one outlier in the SCG group (one individual reported a CAQ score $> 20,000$), which we believe most likely reflected the participant's misunderstanding of the scale. We were not able to confirm this with the individual.

Seventy-three participants were included in the final AUT analysis, consisting of 26 VIS (14 males, 42.7 ± 8.2 yrs old), 22 SCI (12 males, 42 ± 6.9 yrs old), and 25 SCG (11 males, 42.2 ± 9.5 yrs old). Reasons for exclusion from this analysis included MRI data with excessive motion, scanner-related artifacts (e.g., RF noise), or participants failing to follow task instructions.

Eighty-five participants were included in our final RAT analyses, consisting of 26 VIS (14 males, 42.7 ± 7.6 yrs old), 30 SCI (15 males, 45.4 ± 7.9 yrs old), and 29 SCG (15 males, 42.7 ± 9.2 yrs old). Reasons for exclusion from this analysis were the same as for the AUT dataset, including some who did not complete both task runs.

No significant differences were found for age, sex, CAQ, education, and Estimated IQ for this subset of participants in comparison to our total MRI participant group.

3.2. Behavioral results

Mean numbers of responses (button-presses during scanning) in the AUT were analyzed using General Linear Models with group (VIS, SCI, SCG) as a between-subjects factor and condition (AU, TQ) as a within-subjects factor. Descriptive statistics are shown in Table S1. The main effect of condition was significant (Pillai's Trace = 0.51, $F = 88.8$, $DF = 1$, 84 , $p < 0.001$), showing the expected greater number of responses during the TQ compared to the AU condition. The main effect of group was not significant ($F = 1.29$, $DF = 1$, 84 , $p = 0.28$), and the group by condition interaction was not significant ($F = 0.83$, $DF = 2$, 84 , $p = 0.44$). The same analysis using the median, minimum, or maximum number of responses instead of the mean number of responses revealed almost identical results. The same analysis including sex as a between subjects factor and age as a covariate revealed the same findings; no significant effects of sex or age were found. We also analyzed the post-fMRI recall responses during the AUT with respect to the in-scanner button presses. The correlation between the number of button-presses per trial during scanning (mean 5.99, $SD 2.77$) and the number of responses during the recall session (mean 5.17, $SD 2.56$) was $r = 0.95$, $df = 71$, $p < 0.00001$. We further confirmed that there was not a significant interaction of response type (button press versus recall) with group (GLM with response type as within-subject factor: $F(2, 70) = 0.52$, $p > 0.59$).

The accuracy of RAT responses was also analyzed using General Linear Models with group as a between-subjects factor and condition (CHAR, SYN, ASSOC) as a within-subjects factor. The main effect of condition was significant (Pillai's Trace = 0.81, $F = 178.2$, $DF = 2$, 81 , $p < 0.001$). Post-hoc comparisons revealed that accuracy was significantly lower in the association condition relative to the other two conditions ($p < 0.001$). The main effect of group was not significant ($F = 2.35$, $DF = 2$, 82 , $p = 0.10$) nor was the group by condition interaction (Pillai's Trace = 0.023, $F = 0.48$, $DF = 4$, 164 , $p = 0.75$). Descriptive statistics are shown in Table S2. In post-hoc comparisons, VIS differed from SCI at a nominal p value of 0.037, but did not survive multiple comparisons correction.

The fluency and maximum originality of AUT responses were analyzed separately using General Linear Models with group as a between-subjects factor and our covariate (fluency or originality) as a within-subjects factor. We did not see any significant main effects of either covariate (Fluency: $F = 0.34$, $DF = 2$, 88 , $p = 0.71$; Maximum Originality: $F = 0.73$, $DF = 2$, 88 , $p = 0.49$) (Fig. S2).

The AUT Fluency score from the scanning session correlated with multiple indicators from the TTCT tests, including UU Fluency and Originality, PC Elaboration, Lines Fluency, Lines Originality, Lines Elaboration, and RAT total score ($r = 0.23$ – 0.34 , $DF = 77$ – 82 , $p = 0.04$ – 0.002 , two-tailed). The AUT Maximum Originality correlated with UU Originality, PC Elaboration, PC Titles, Lines Originality, Lines Elaboration, CS Story, CS UUVIS, CS RICH, CS Color, and RAT total score ($r = 0.23$ – 0.47 , $DF = 77$ – 82 , $p = 0.05$ to $p < 0.001$, two-tailed). We also found a significant positive correlation between AUT fluency during fMRI and performance on RAT ASSOC trials during fMRI ($r = 0.36$, $p = 0.003$) (Fig. 3). Despite completing an AUT (TTCT) and RAT during an out-of-scanner behavioral session, we did not find any significant differences in fMRI performance for the RAT, with a subtle trending effect in performance for those who had prior exposure to the AUT outside the scanner compared to those who had the task for the first time in the scanner ($t(1, 36) = 2.43$, $p < 0.02$). The order of behavioral and fMRI task completion also did not affect our fMRI results.

3.3. AUT fMRI activation

Within-group analysis revealed similar patterns of activation across all three groups during AU and TQ. Post-hoc conjunction analysis (Nichols et al., 2005) confirmed prominent left frontal and bilateral occipital cortex (OC) activation (Fig. S3).

Between-group analysis showed that SCG displayed greater activation than Big-C groups during periods of divergent thinking (AU $>$ TQ) within the right frontal pole (FP), right frontal operculum (FO), left middle frontal gyrus (MFG), and bilaterally across the OC (Fig. 4). SCG primarily displayed greater right FP and OC activation than VIS, while displaying higher bilateral MFG, left IFG, and slight left FP activation than SCI. VIS displayed significantly greater activation than SCI within the right inferior frontal gyrus (IFG) and left supramarginal gyrus (SMG) (Fig. S4).

3.4. RAT fMRI activation

Within-group analysis and post-hoc conjunction analysis revealed similar overlapping left-hemisphere dominant patterns of activation across all three conditions (Fig. 5). When participants performed the condition that required more complex associative processing (ASSOC $>$ CHAR + SYN), a shift was observed from posterior left hemisphere activation (i.e. during CHAR) towards more left frontal activation (i.e., during ASSOC) within each group. Left frontal within-group activation was also seen for ASSOC $>$ CHAR + SYN.

Between group analysis showed SCI displaying higher right frontal lobe activation than VIS during ASSOC than during CHAR (ASSOC $>$ CHAR) (Fig. S5).

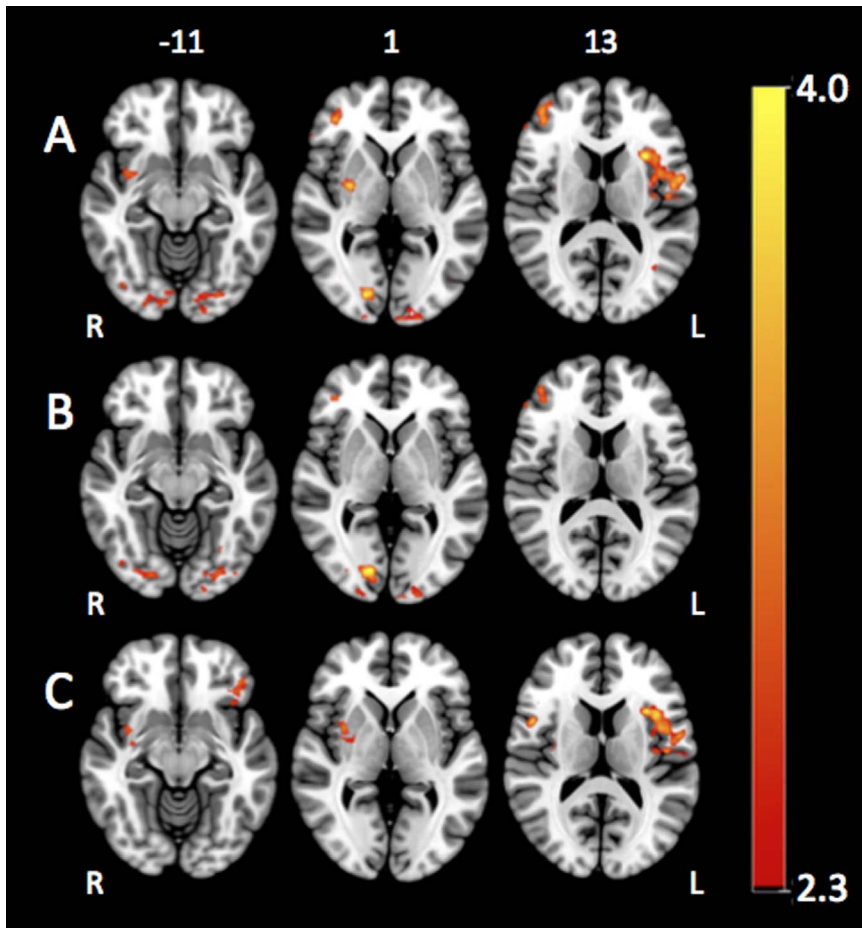


Fig. 4. Activation during AUT divergent thinking contrast (UU > TQ). (A) SCG shows significantly higher functional activation than both Big-C groups (SCG > VIS + SCI). (B) SCG show significantly greater visual cortex and right frontal pole activation than VIS (SCG > VIS). (C) SCG show significantly greater frontal activation than SCI (SCG > SCI). Results are thresholded using a voxel threshold of $z > 2.3$ and a cluster threshold of $p < 0.05$. Axial MNI z-slice values (mm) listed above each column.

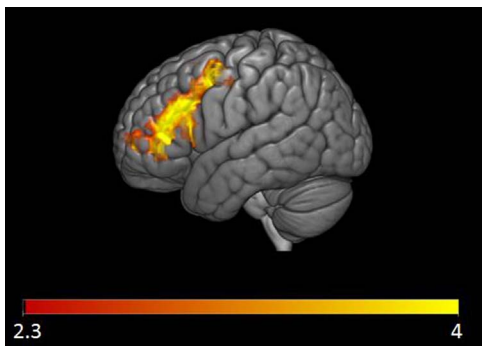


Fig. 5. Conjunction map showing significant left frontal activation across Big-C (VIS and SCI) and SCG groups during RAT complex associations (ASSOC > CHAR + SYN), within the left hemisphere. Results are thresholded using a voxel threshold of $z > 2.3$ and a cluster threshold of $p < 0.05$.

3.5. Post-fMRI session AUT fluency and originality covariate analyses

Fluency scores derived from the post-scanning recall session were positively correlated with activation in subcortical regions (e.g., mid-brain) and negatively correlated with activation in occipital cortex for both AU and TQ contrasts. Maximum originality scores were positively correlated with subcortical regions within AU and TQ and negatively correlated with left lateralized FP, orbitofrontal cortex (OFC), and IFG pars triangularis for the contrast of divergent thinking (AU > TQ) (Fig. S6).

3.6. Estimated IQ covariate analyses

Frontal cortical activation was positively correlated with Estimated IQ during periods of divergent thinking (AU > TQ) in the AUT (Fig. S7). Left frontal activation was also correlated with Estimated IQ during complex convergent thinking (ASSOC > CHAR + SYN) in the RAT.

4. Discussion

The Big-C Project aimed to examine brain and behavioral processes related to exceptional creative achievement, and in this paper, we describe functional brain activation associated with performance of two cognitive tasks in domains linked to creativity: divergent and convergent thinking. Our Big-C groups were truly exceptional, comprising visual artists and scientists who are outliers in achievement within their respective creative domains. Our study was further unique in ascertaining a “smart comparison group,” who were not selected for high creative achievement, but were well matched to our Big-C groups not only on age, sex, and racial/ethnic background, but further matched on estimated intellectual ability and parental education. These features of our study distinguish it from prior work using fMRI to investigate divergent and convergent thinking, which have included smaller groups of participants not selected for creative achievement. To our knowledge this project further comprises the largest investigation so far of brain and behavior in “Big-C” creativity, and perhaps the only controlled study of brain function in Big-C individuals relative to a comparison group.

The Big-C groups were distinguished primarily by showing less functional activation during the conditions most associated with creative, divergent thinking (i.e., generation of alternate uses relative to typical qualities in the AUT). The activation differences were found

primarily in lateral frontal regions, visual cortex, and the basal ganglia. Given that the within-group analyses revealed left frontal and bilateral occipital activations in all three of our groups, similar to those seen in several other studies of the AUT (Abraham et al., 2012; Fink et al., 2009), it is reasonable to conclude that the Big-C groups were using networks similar to those deployed by our smart controls and by other healthy people performing similar tasks. The difference observed in Big-C individuals thus appears more to reflect less activation in the same networks rather than use of different neural mechanisms to solve the task. This kind of effect, observed as less activation within the same neural network, is often considered to reflect increased “efficiency.” Alternatively, the contrast can be interpreted to indicate that the SCG required greater activation of this network to achieve the same results as our Big-C groups. It is important in this respect to note that we did not observe differences between groups in the levels of behavioral performance achieved on these tasks. This is helpful in interpreting the brain activation results, given that there is not a confound between group and performance, which complicates many other studies of brain-behavior relations in unique groups. On the other hand, it may be that our experimental tasks fail to capture the unique conceptual potentials of our Big-C artists and scientists, many of whom remarked that our tests generally did not tap the same cognitive processes they experience when doing creative work in their respective domains.

The more specific regions that distinguished the Big-C from SCG included the right frontal pole (FP), right frontal operculum (FO), left middle frontal gyrus (MFG), and bilateral occipital cortex (OC). The FP regions have enjoyed considerable attention in creativity research, particularly following demonstrations that transcranial direct current stimulation (tDCS) to this region may alter performance on creativity tasks (Green et al., 2017). This builds on prior conceptualizations that emphasize the role of FP in the representation of “counterfactuals” and the uniquely human capacity to consider alternative future-directed behavioral programs (Mansouri et al., 2017). The possible role of the right FO working in concert with FP to mediate task switching behaviors (a combination of considering alternative responses and inhibiting prepotent responses) has also been considered a mechanism underlying conceptual elaboration of the kinds involved in generating novel metaphors (Green, 2017). In contrast to these FP and FO components more specifically linked to divergent thinking, the left MFG and bilateral OC activations may be more linked to the generative language and visualization aspects of the task, which involved object representations.

There were also subtle differences between our Big-C groups, with visual artists displaying greater activation than scientists within the right IFG and left SMG when generating alternate uses and typical qualities during the AUT. If the “efficiency” interpretation noted above is valid, these findings suggest that scientists show somewhat more neural efficiency than visual artists on this task. We can also speculate, using reverse inference based on the putative functions subserved by these regions, that our artists may have deployed more response inhibition processes (often associated with right IFG activation) and elaborative semantic processing (linked to left SMG). Whether or not these specific regional inferences are valid, the findings are consistent with the interpretation that our scientists required less activation generally to produce similar levels of performance on the AUT. It is conceivable that this group is also accustomed to solving novel cognitive tasks that the demands were simply not as great as those for our other groups.

In addition to the group differences we observed, the observations of brain activation associated with both the divergent and convergent thinking tasks across participant groups are consistent with prior research in participants not selected for creativity, as noted above (Abraham et al., 2012; Fink et al., 2009). These findings serve as a positive validity check on our fMRI results. Further, despite a high degree of similarity across groups, the results on the RAT suggest subtle differences between groups. Big-C Scientists only displayed higher right frontal lobe activation in one contrast (ASSOC > CHAR), compared to

Big-C Visual Artists. This may reflect the scientists’ tendency to use a more “cognitive” strategy in their search for associates, differences in character processing (the condition with which the association condition is contrasted), or other unknown factors. While the left frontal activation seen across groups is similar to results shown in the Iowa Study of Creative Genius (Andreasen and Ramchandran, 2012), our results suggest that these left-lateralized findings may not be unique to Big-C but are similar to those found in individuals not selected for creative achievement.

Although one may speculate that the Big-C groups differ in divergent but not convergent thinking, we would caution against this interpretation of functional specificity, given that our study was not designed to detect an interaction of group with task type because we examined the two constructs separately across different task paradigms. An experimental approach that directly manipulates the kind of processing (divergent, convergent) within a single paradigm would be valuable to investigate that hypothesis.

The difference between Big-C and SCG in functional activation during the AUT, as noted above, was seen despite similar fluency and originality behavioral scores across groups. Additional covariance analyses using fluency revealed significant positive correlations with subcortical regions throughout the AUT and negative correlations with visual cortex during periods of alternate uses. Significant negative correlations between originality and frontal pole, orbitofrontal cortex, and IFG pars triangularis were seen during a contrast of divergent thinking (AU > TQ), suggesting that decreased activation in these regions may be associated with higher levels of divergent thinking. These patterns are consistent with studies suggesting that decreased engagement of task positive networks, increased engagement of default mode network, or increasing reliance on subcortical networks during conditions involving creativity or mind-wandering (Christoff et al., 2016; Smallwood and Schooler, 2015). The negative correlations of frontal pole and ventral frontal activations maybe interpreted as decreases in task-positive cognitive control in association with divergent thinking processes. These results differ in part, however, from a recent study showing a positive correlation between AUT originality and ventral anterior cingulate cortex activation during a similar contrast of divergent thinking with 30 healthy volunteers (Maysseless et al., 2015).

The analyses including estimated IQ as a covariate suggested an association of higher intelligence with increased left frontal activation during both functional tasks. This finding reinforces the widely-held assumption that exceptional creativity is not simply a product of higher intellectual ability, given that this activation effect is opposite what would have been expected if our findings were impacted by a confound of intelligence with Big-C group membership (in fact, the Big-C groups activated frontal cortex *less than* SCG during divergent thinking). It is possible that those with higher intellectual ability, at least as measured by conventional IQ tests, rely more on frontal task positive networks to solve divergent thinking tasks, and that we were able to observe this effect because we intentionally selected a “smart” comparison group that successfully overcame potential confounds of Big-C status with intelligence. It should be recognized, however, that all of our groups were above average (by approximately one standard deviation), so it remains unclear to what extent our findings may generalize to samples more representative of the general population. Finally, our results may be considered from the perspective of the “threshold” hypothesis, originally articulated by Guilford (1967), that above a threshold (of approximately IQ = 120), further increases in intelligence would not confer additional creative advantage. This hypothesis has been interrogated repeatedly with conflicting results; recent work suggests that there likely is a relation but that it is complex, and highly dependent on the measures of creative potential or creative achievement selected (Jauk et al., 2013). Our findings indicate that there is indeed a neural correlate of IQ, that is shared across exceptionally creative and other individuals of above-average intellect, at least while they are performing tasks associated with creative cognition.

4.1. Limitations

There are myriad challenges in the scientific investigation of creativity and studying Big-C creativity poses additional challenges. It has been argued that studying the creative process means gathering information about the person and their responses while they are fully immersed in the given task within a “flow” state (Csikszentmihalyi, 1996). We are limited in our ability to measure creativity under traditional fMRI experimental conditions, which may not only fail to fully represent an individual's true creative processes, but further, actually conflict with them. Indeed, both the assumption that divergent and convergent thinking are critical to creative achievement, and the assumption that our AUT and RAT procedures provide robust measures of these constructs, may be wrong or only partially correct. Further concerns surround the method of data collection which affects the way in which the task is structured and amount of data collected (For example, during an fMRI session, the method of stimulus presentation and response collection are both highly constrained, there exist unknown effects of confinement (i.e., the requirement of lying still)) and sub-threshold levels of claustrophobia, there is a high level of noise from the scanner, and there are time constraints on acquisitions. We limited responding to button presses and conducted recall sessions outside of the scanner to help reduce artifacts that adversely impact studies requiring active verbalization during a scan (Huang et al., 2000). Our methods also enabled us to collect more trials during each task, in comparison to some prior studies (Fink et al., 2009), which may have improved single-to-noise ratios in specification of functional activation effects. But these methodological advantages come with concerns about the accuracy of our estimates of in-scanner performance. We found that participant responses outside the scanner were moderately correlated with in-scanner fMRI task responses (AUT $r = 0.52$, $p < 0.001$; RAT $r = 0.52$, $p < 0.001$), helping to attenuate but not entirely remove those concerns.

Our decision to study Big-C visual artists and scientists has both pros and cons. Supporting this decision was the putative increase in “homogeneity” within these groups, based on factor analyses of creative achievement questionnaire data. Further, we speculated that artists and scientists may differ in their approach to creative problem solving and use different brain mechanisms to perform tasks. On the other hand, this narrowing of domains of creativity necessarily decreases the extent to which our findings may generalize to other creative domains. We note anecdotally that the impression of “homogeneity” was difficult to support after witnessing the extent of diversity of styles of cognitive, attitudinal, and emotional styles that were expressed by our participants in all three groups. Finally, the ascertainment of Big-C participants necessarily involves an element of subjectivity. Given definitions of creativity that center on the combination of “value” and “novelty/surprise,” it is easier to provide objective measures of “value” with quantification of certain creative achievements, such as number of international exhibitions or an author's h-index. We used peer assessments in an attempt to validate the “novelty” of each Big-C candidate's contributions to their domain, but this remains a subjective process, subject to the same challenges faced by all evaluations of “how creative” a given current work may be, and how this work will be evaluated in the future.

5. Conclusions

Big-C individuals primarily displayed less functional activation within lateral frontal regions, visual cortex, and basal ganglia during conditions of divergent thinking, with subtle differences shown between Big-C groups, and no clear differences between groups in functional activation associated with convergent thinking. The findings support the hypothesis that Big-C creativity is associated with decreased reliance on task-positive networks, consistent with more “efficient” neuronal processing during divergent thinking. These differences

in activation during divergent thinking were not due to differences in behavioral performance.

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Author contributions

All authors contributed to writing the paper. RB and SB designed the study. DG coded and tested the RAT fMRI task. KJ coded and tested the AUT fMRI task as well as analyzed the MRI data and behavioral fMRI data. SB and DG provided expertise on image analyses and interpretation. RB provided expertise and helped analyze behavioral data. KJ and KK collected the MRI data and behavioral fMRI measures. KK coordinated the study, oversaw the behavioral data scoring, and conducted IQ testing.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at <http://dx.doi.org/10.1016/j.neuropsychologia.2018.02.017>.

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