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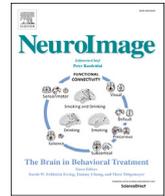
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Differences in brain activity patterns during creative idea generation between eminent and non-eminent thinkers

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ABSTRACT

An influential model of the neural mechanisms of creative thought suggests that creativity is manifested in the joint contributions of the Default Mode Network (DMN; a set of regions in the medial PFC, lateral and medial parietal cortex, and the medial temporal lobes) and the executive networks within the dorsolateral PFC. Several empirical reports have offered support for this model by showing that complex interactions between these brain systems account for individual differences in creative performance. The present study examined whether the engagement of these regions in idea generation is modulated by one's eminence in a creativity-related field. Twenty ($n = 20$) healthy eminent creators from diverse fields of expertise and a 'smart' comparison group of sixteen ($n = 16$) age- and education-matched non-eminent thinkers were administered a creative generation task (an adaptation of the Alternative Uses Task) and a control perceptual task, while undergoing functional magnetic resonance imaging (fMRI). The participants' verbal responses were recorded through a noise-canceling microphone and were later coded for fluency and accuracy. Behavioral and fMRI analyses revealed commonalities between groups, but also distinct patterns of activation in default mode and executive brain regions between the eminent and the non-eminent participants during creative thinking. We interpret these findings in the context of the well-documented contributions of these regions in the generation of creative ideas as modulated, in this study, by participants' creative eminence.

1. Introduction

The ability to produce ideas deemed both novel and useful (Simonton, 2012) has been a commonly accepted definition of creativity across a rapidly growing number of investigations on the cognitive and neural mechanisms supporting creative thinking (Beatty et al., 2015a, 2015b; 2018; Kounios and Beeman, 2014; Mayseless et al., 2015; Pinho et al., 2016). A seeming point of consensus across this research is the perspective that creativity involves ordinary cognitive processes such as memory (Abraham, 2014; Abraham and Bubic, 2015; Abraham et al., 2012; Chrysikou and Thompson-Schill, 2011; Kenett, 2014), attention (Benedek et al., 2014; Zabelina, 2018) and executive function

(Chrysikou, 2019; Chrysikou et al., 2014; Gonen-Yaacovi et al., 2013; Mayseless et al., 2014; Mayseless and Shamay-Tsoory, 2015; Zabelina and Ganis, 2018). Yet, only a handful of studies within the blossoming field of the cognitive neuroscience of creativity have examined the extent to which the same or different neural functional systems are involved in extraordinary (sometimes referred to as 'big C') relative to everyday (sometimes referred to as 'little C') creative achievement (Kaufman and Beghetto, 2009). Indeed, a question that has not received much attention in the field pertains to whether and how one's creative eminence in a given area of expertise—as established over the creator's lifetime—is reflected in the cognitive and neural systems shown to support creative thought.

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A seminal study on this topic—known as the *Iowa Study of Creative Genius* (Andreasen and Ramachandran, 2012)—used functional magnetic resonance imaging to examine potential differences in neural activation during a free word association task between two groups of participants with high creativity from different fields (4 artists and 3 scientists). The results showed a marked left hemisphere involvement in this task, but no significant differences between the two creator groups. Other studies with larger samples have examined this question in other fields of expertise, using domain-specific tasks. For example, Limb and Braun (2008) have demonstrated that expert jazz musicians' execution of improvised relative to well-practiced musical sequences is associated with transient hypofunction in prefrontal cortical regions, a pattern not observed in novices, and similar results have been reported in other domains of musical expertise (e.g., Liu et al., 2012).

Addressing the potentially restricted generalizability of these past findings, the Big-C project at the University of California Los Angeles is the largest and most comprehensive study of extraordinary creativity to date, involving examinations of exceptionally creative individuals within the visual arts and the sciences, using functional neuroimaging and well-established creativity measures. One of the notable highlights of the Big-C project is the use of a 'smart' comparison group of well-accomplished, but not especially creative, individuals—matched to the exceptionally creative subjects in age, gender, intelligence, and parental education background (Japardi et al., 2018). As in the earlier studies, findings from the Big-C project indicate little differences in divergent thinking performance among the groups, yet a dissociation at the neural level suggesting that Big-C thinkers recruit less frontal and occipital brain regions relative to the smart comparison group. These results have been interpreted to support the view that exceptional creativity is linked to reduced engagement of task-positive brain networks (Japardi et al., 2018), and might, overall, reflect increased neural efficiency (see Neubauer and Fink, 2009 for a similar hypothesis from intelligence research).

A recent study (Meyer et al., 2019) examining differences in distal simulation ability—arguably, an attribute of highly imaginative minds—has revealed similar findings: Creative experts were shown to experience behaviorally more vivid simulations relative to controls, and this ability was related to traditional measures of creativity and lifetime creative achievement. Importantly, although both groups recruited medial prefrontal cortex during simulation of common or proximal events, creative experts also recruited the dorsomedial system of the default mode network (DMN) for distal simulations and this network also showed increased functional connectivity across the brain only within the creative group. The DMN comprises a set of regions including the anterior medial prefrontal cortex and the posterior cingulate (*core system*, Andrews-Hanna et al., 2010); the dorsomedial prefrontal cortex, temporoparietal junction, and inferior temporal cortex (*dorsomedial sub-system*); and the posterior inferior parietal cortex, retrosplenial cortex, parahippocampal area, and the hippocampus (*medial temporal lobe sub-system*) and shows increased activity when participants are not actively engaged in any particular task (e.g., during rest; cf. Andrews-Hanna et al., 2010).

The DMN is at the heart of an influential model of how creative thinking processes are implemented in the brain (Jung et al., 2013). According to this model, creative idea generation is ascribed to the DMN, whereas idea evaluation is supported by a network of executive regions within the frontal cortex collectively discussed as the Executive Control network (ECN; Jung et al., 2013; see also Beaty et al., 2016; Chrysikou, 2018, 2019). A growing body of recent research has offered support for this model by highlighting that creative thinking may rely on a flexible and dynamic communication between the DMN and the ECN (Beaty et al., 2018; Chrysikou, 2018; Ellamil et al., 2012; Kenett et al., 2018; for reviews see Beaty et al., 2016; Zabelina and Andrews-Hanna, 2016). For example, increased functional connectivity at rest between the ECN and the DMN has been linked to higher performance on divergent thinking tasks (Beaty et al., 2014). Similarly, activity within the DMN and ECN systems, including the medial PFC and cingulate cortex, appears to

underlie the ability to produce original ideas while generating alternative uses for common objects (Shamay-Tsoory et al., 2011), whereas increased functional connectivity between areas within the DMN (i.e., cingulate cortex and the precuneus) and dorsolateral PFC has been associated with the generation of alternative uses for common objects, but not the generation of common characteristics for these objects (Beaty et al., 2015).

With the notable exception of the handful of investigations reviewed above (e.g., Japardi et al., 2018; Meyer et al., 2019; Limb and Braun, 2008) very little research in the cognitive neuroscience of creativity has examined potential differences in the contribution of these systems to creative thinking between eminent and non-eminent thinkers and none have done so in a diverse group of creators. Here, we used functional magnetic resonance imaging (fMRI) during a generative creativity task to examine the neural correlates of creativity in a heterogeneous group of eminent creators from diverse fields of expertise. Following past work (Japardi et al., 2018), we used a 'smart' comparison group of age- and education-matched non-eminent thinkers as control subjects. Guided by earlier studies (e.g., Japardi et al., 2018), we hypothesized that the neural mechanisms supporting exceptional creativity are domain-general; thus, we anticipated our findings from a diverse and heterogeneous group of eminent creators to mirror those of past studies in line with the neural efficiency hypothesis.

2. Material & methods

2.1. Participants

We recruited 20 eminent creators ($M_{age} = 51.80$, $SD = 12.48$; 11 males) with notably high creative achievement in one of several creative domains (psychology/neuroscience, education, writing, comedy, law, design, music, business, and politics). A group of 16 individuals matched to the eminent group in age and education, but who did not have any specific achievement in any particular creative domain were recruited to serve as a 'smart' comparison group ($M_{age} = 50.00$, $SD = 15.04$; 6 males). Verification of high or low creative achievement was based on the Creativity Achievement Questionnaire (CAQ; see *Materials*), with eminent creators determined as having a CAQ score of at least 2 standard deviations from the mean reported score on the scale (Carson et al., 2005). The recruitment of the eminent creators involved first the identification of prominent ('magnet') individuals within a given field and asking them to identify and nominate the most imaginative and creative people in their field; eminent creators were then invited and they were recruited provided they met the criteria for the study (e.g., contraindications for neuroimaging) and were willing and able to travel and stay overnight for the duration of the study. Beyond this selection process, eminence was further examined through objective measures (e.g., citation counts, performances, fellowships, publication records, etc.). To allow for a standardized measure of assessment across fields of eminence, we used the CAQ as an objective measure of creative achievement, acknowledging that it might reflect some domains of eminence (e.g., arts, science) better than others (e.g., education, law). All participants were from the continental United States, met all inclusion criteria for magnetic resonance imaging, and were not diagnosed with any neurological or psychiatric condition that might have affected brain structure or function. Participants provided informed consent and were paid for their participation. The study was approved by the Thomas Jefferson University Institutional Review Board.

2.2. Materials

fMRI Task: We used a version of the Alternative Uses Task (AUT) optimized for fMRI studies (adapted from Chrysikou and Thompson-Schill, 2011) that included seventy-two black-and-white photographs of everyday objects (see Fig. 1 for examples). During the AUT participants were instructed to generate a novel use for the object,

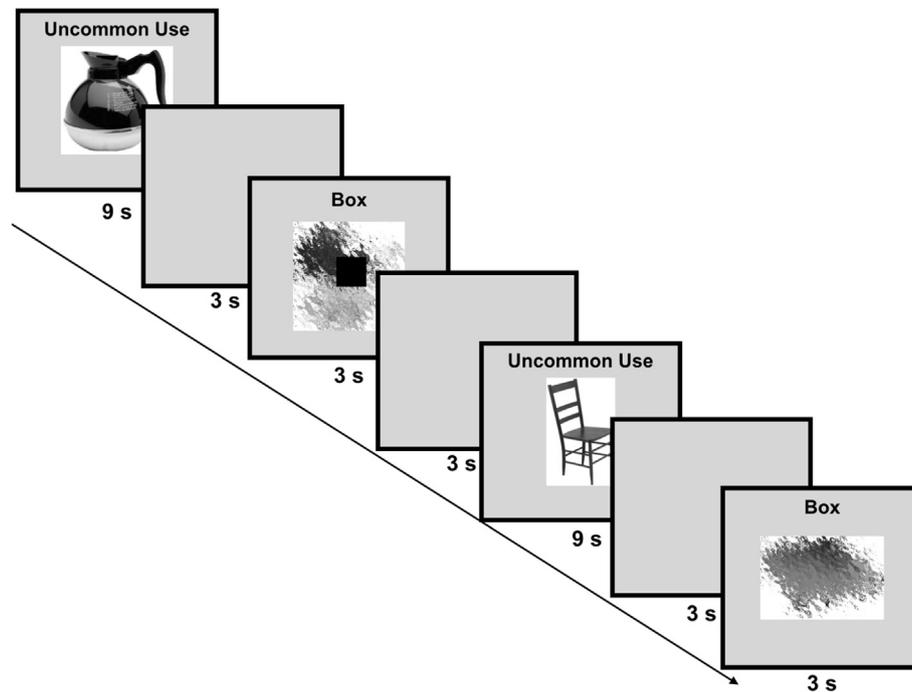


Fig. 1. Example trials and their duration. Participants either generated aloud an uncommon use for each object or performed a baseline task in which they verified aloud whether a square box was superimposed on top of abstract black and white images; s = seconds. The events were jittered with the inclusion of additional null trials, which extended the inter-stimulus interval from 3s to either 6, 9, or 12s.

one they had not seen or attempted before that would be plausible, yet, which would deviate significantly from the object's common use. Participants were informed that the tasks had no right or wrong answers and that they should feel free to produce any response they judged fit. They were instructed to respond as quickly as possible and to remain silent if unable to generate a response. We used a perceptual baseline task that included seventy-two scrambled images of the same AUT objects as baseline stimuli, half of which included a superimposed 1 in. \times 1 in. black box on their center. During the baseline task subjects were asked to say aloud "yes" if the black box was superimposed on the scrambled image and "no" if it was not. The selection of this perceptual baseline task relative to other possible control tasks (e.g., generating common uses or common characteristics for the objects) was guided by extensive pilot work that has shown participants inadvertently thinking about uncommon uses or characteristics after generating common ones in such control tasks. The perceptual baseline task employed here has been used successfully as a control task to the AUT (Chrysikou and Thompson-Schill, 2011) because it maintains the same level of visual information while also requiring overt verbal responses. The order of stimuli presentation was randomized and the items were divided in three \sim 10 min runs of 24 items each. Stimuli were presented using E-prime 2.0 software (Psychology Software Tools, Inc.) on a PC computer connected to an Epson 8100 3-LCD projector (Epson America, Long Beach, CA) housed in a custom RF shield box. Subjects' overt responses were obtained using LitemicTM 3140 fiber optical Dual-Channel Noise Canceling Microphone System for MRI Communication (Or-Yehuda, Israel, www.optoacoustics.com) and were transcribed using a MacBook Pro laptop computer (Apple Computer, Cupertino, CA).

Screening and Individual Differences Measures: Participants were administered a battery of screening and behavioral measures including: the Structured Interview of Cognition and Personality and the MINI International Neuropsychiatric Interview to verify study eligibility and neuropsychiatric health and the CAQ (Carson et al., 2005) as a measure of eminence and creative achievement. These measures were administered individually following standard neuropsychological procedures.

2.3. Study procedures

Study Design. Following informed consent procedures, all participants underwent a semi-structured interview which was conducted by a trained study coordinator using the screening measures specified above. These interviews lasted last approximately 2 h. Within 3–5 days all participants completed brain imaging at the Marcus Center for Integrated Health at Thomas Jefferson University.

fMRI Task Procedures. Following an event-related design, each 10-min run comprised 92 trials: 24 experimental trials [lasting 9000 ms, followed by a 3000-ms intertrial interval (ITI)], 28 baseline trials (lasting 3000 ms, followed by a 3000-ms ITI), and 40 null events (lasting 3000 ms; see Fig. 1 for trial timing and composition). The onset times of the events were jittered by pseudorandomizing the trial types within each run using Optseq2 (<http://surfer.nmr.mgh.harvard.edu/optseq>); the first and last six trials within each block were null events. The task instructions were presented at the beginning of each block; a prompt also appeared above each trial item (i.e., "Uncommon Use" or "Box"). Before the experiment, all subjects completed a 5-min training session to familiarize themselves with the experimental procedures and received feedback from the experimenter regarding task compliance. All participant responses during the fMRI portion of the study were recorded and later transcribed and coded for fluency and accuracy.

2.4. MRI data acquisition

Structural and functional brain imaging was conducted on a 3 T S Magnetom Biograph mMR scanner using a 12-channel head coil. Structural images were obtained with a T1 sagittal MPRAGE sequence (TE = 2.46 ms; TR = 1600 ms; voxel size = $1.0 \times 1.0 \times 1.0$ mm³; FOV = 252 mm; slices = 176; acquisition time = 7:26 min). Each echo-planar fMRI run was performed in 48 contiguous 3-mm axial slices (TR = 3000 ms; TE = 25 ms; voxel size = 3 mm \times 3 mm \times 3 mm; FoV = 236 mm; acquisition time = 9:45 min). For all scans, each image was manually inspected for image quality.

2.5. MRI data processing and analysis

fMRI data preprocessing and analysis were carried out using FEAT (fMRI Expert Analysis Tool) Version 6.00, part of FSL (FMRIB's Software Library, www.fmrib.ox.ac.uk/fsl). Individual FLAIR and T1-weighted structural brain images were extracted using brain extraction tool (BET). Structural images were registered non-linearly to the Montreal Neurological Institute (MNI) MNI-152, 2 mm template brain using FNIRT within the FSL package. The functional data were preprocessed and analyzed using the fMRI expert analysis tool (FEAT). The first 4 vol of each functional run were discarded to allow for the magnetic field to reach a steady state. Individual subject data analysis per run included motion correction using MCFLIRT; slice-timing correction using Hanning-windowed sinc interpolation; spatial smoothing using a Gaussian kernel of full width at half minimum (FWHM) 5 mm, and highpass temporal filtering (Gaussian-weighted least-squares straight line fitting, with $\sigma = 100$ s). Functional images were registered to the high-resolution anatomical image using a boundary-based registration implemented within FSL's FLIRT.

A general linear model was used to derive per-run activity estimates for each voxel. First level analyses modeled four hemodynamic response explanatory variables (EVs) for the experimental AUT trials, the perceptual baseline trials, the null events, and the incorrect responses, defined as non-task compliant answers in the AUT (e.g., generating common uses). Individual participant data were entered into a higher-level fixed-effect analysis to measure and average neural response to the four EV's across all three fMRI runs. For the comparisons between groups, a mixed-effects analysis was performed (FLAME, <https://fsl.fmrib.ox.ac.uk/fsl/fslwiki>). Z (Gaussianised T/F) statistic images were thresholded non-parametrically using clusters determined by $Z > 3.1$ and a (corrected) cluster significance threshold of $P = 0.01$ (Worsley, 2001).

We selected *a priori* a set of Regions of Interest (ROIs) across key-to-creativity areas within the DMN and ECN (see Table 3). ROIs were defined anatomically using the Harvard-Oxford Structural Cortical Atlases as implemented in FSL. FSL's featquery tool was used to interrogate the results of the main analysis and extract ROI measurements. All voxels within each ROI for the contrast between the AUT and the perceptual baseline were included in analyses, and the magnitude of the contrast was estimated with a measure of percent signal change (i.e., beta values). Independent sample *t*-tests were used to examine differences in the local maxima (Z-statistics) for each ROI between the eminent and non-eminent participant groups. Secondary exploratory correlational analyses (Pearson's *r*) were used to examine relationships among the ROIs, with a false discovery rate (FDR) correction for multiple correlation analyses (Benjamini and Hochberg, 1995), with FDR of 5% and critical *p* value of .01.

3. Results

3.1. Behavioral results

Participants' demographic and behavioral characteristics are presented in Table 1. Confirming our recruitment criteria, the high-

Table 1
Descriptive statistics across participants' demographic measures and AUT performance.

Measure	High-Eminence Group Mean (SD)	Low-Eminence Group Mean (SD)
Age	51.80 (12.48)	50.00 (15.04)
Gender	55% male	38% male
Education (in years)	18.80 (2.51)	18.69 (2.44)
CAQ	38.85 (36.12)	14.58 (17.95)
AUT percent correct responses	76% (12.74)	78% (16.76)

Note: SD = standard deviation.

eminence group had significantly higher scores on the CAQ than the low-eminence group ($t [34] = 2.10, p = .045$, two-tailed). There were no significant differences in age ($t [34] = 0.39, p = 0.70$, two-tailed), gender ($\chi^2 [1] = 1.09, p = 0.30$, two-tailed), or education ($t [34] = 0.14, p = 0.89$, two-tailed) between the high- and low-eminence groups. Participant responses from the AUT and baseline tasks were first transcribed from the fMRI session recordings and reviewed and coded for accuracy and fluency (i.e., number of correct responses). Participants did not differ in their performance (fluency) on the AUT ($t [34] = 0.31, p = 0.76$, two-tailed). Thus, in line with our predictions, beyond their significant differences in CAQ score that determined group membership, eminent and non-eminent thinkers did not differ on any demographic measures or their performance on the AUT.

3.2. fMRI results

Whole Brain Analysis. A whole-brain analysis identified 2 clusters reflecting a significant task (AUT vs. Baseline) \times group (eminent vs. non-eminent) interaction, with eminent thinkers having significantly higher activity than non-eminent thinkers in the right supramarginal gyrus and the right transverse temporal gyrus (Table 2). The opposite contrast elicited 11 clusters reflecting a significant task (AUT vs. Baseline) \times group (eminent vs. non-eminent) interaction, with non-eminent thinkers having significantly higher activity than eminent thinkers in the in the left lingual gyrus, left frontal pole, anterior cingulate gyrus, left parietal cortex (precuneus), right temporal pole, left fusiform gyrus, left middle frontal gyrus, left hippocampal gyrus, right angular gyrus, posterior cingulate cortex, and right fusiform gyrus (Table 2).

Overall, these results suggest a more extensive network of regions for the non-eminent thinkers relative to the eminent thinkers across mainly the DMN and the left dorsolateral prefrontal cortex (left middle frontal gyrus)—a key area of the ECN—during the AUT task relative to the perceptual baseline task. In contrast, eminent thinkers engaged a substantially more focused set of regions mainly in the right temporoparietal cortex during the creative generation task (Fig. 2).

Exploratory ROI Analysis. To examine potential differences between the two groups regarding the co-activation of regions within the DMN and ECN shown in past research to contribute to creative thinking (e.g.,

Table 2

Clusters and local maxima associated with a significant task \times group interaction determined at $Z > 3.1$ and a (corrected) cluster significance threshold of $P = 0.01$.

Eminent > Non-Eminent						
Cluster size (voxels)	Z_{max}	p_{max}	x_{max}	y_{max}	z_{max}	Region
321	6.87	<.001	68	-38	28	R inferior parietal cortex; supramarginal gyrus
300	5.55	.001	50	-20	10	R temporal cortex; transverse temporal gyrus
Non-eminent > Eminent						
Cluster size (voxels)	Z_{max}	p_{max}	x_{max}	y_{max}	z_{max}	Region
5008	6.92	<.001	-4	-88	4	L Occipital Cortex; Lingual Gyrus
1562	6.4	<.001	-4	60	2	L Frontal Pole
1285	7.28	<.001	-4	-8	30	Anterior Cingulate Cortex
1030	7.38	<.001	-36	-74	48	L Posterior Parietal Cortex; Precuneus
421	6.83	<.001	28	6	-44	R Temporal Pole
361	6.05	<.001	-46	-60	-24	L Fusiform Gyrus
348	5.44	<.001	-38	18	48	L Middle Frontal Gyrus
290	6.23	.001	-24	-4	-38	L Parahippocampal Gyrus
259	5.54	.003	38	-60	40	R Angular Gyrus
248	6.56	.003	0	-32	36	Posterior Cingulate Cortex
210	5.32	.008	32	-68	-12	R Fusiform Gyrus

Note: L = Left, R = Right.

Table 3
Correlational analyses (Pearson’s *r*) across local maxima ROIs and creative achievement by group.

Eminent		CAQ	Precuneus	SPL	MPFC	Anterior MTG	Angular Gyrus	SFG	MFG	IFG (PT)	IFG (PO)
CAQ			-.35	-.28	-.04	-.45	-.58	-.19	.03	-.25	-.30
Non Eminent		CAQ	Precuneus	SPL	MPFC	Anterior MTG	Angular Gyrus	SFG	MFG	IFG (PT)	IFG (PO)
CAQ			.28	.28	.23	.36	-.01	.24	.15	.41	.82**

Note: **p* < .01; ***p* < .001, FDR-corrected for multiple comparisons at FDR = 0.05 with a critical *p* value of .01 (Benjamini-Hochberg, 1995). CAQ = Creativity Achievement Questionnaire; SPL = Superior Parietal Lobule; MPFC = Medial Prefrontal Cortex; MTG = Middle Temporal Gyrus; SFG = Superior Frontal Gyrus; MFG = Middle Frontal Gyrus; IFG = Inferior Frontal Gyrus; PT = pars triangularis; PO = pars opercularis.

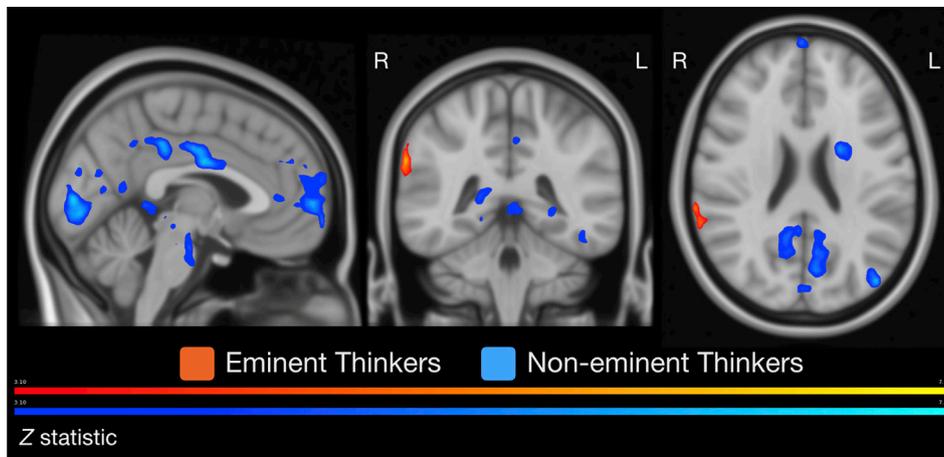


Fig. 2. Statistical map of the task (AUT vs. Baseline) × group (eminent vs. non-eminent) interaction. Clusters determined at *Z* > 3.1 and a (corrected) cluster significance threshold of *P* = 0.01. *L* = Left; *R* = Right.

Beauty et al., 2014, 2016; Kenett et al., 2018) we selected *a priori* five regions within the DMN (precuneus, superior parietal lobule, angular gyrus, medial prefrontal cortex, and anterior middle temporal gyrus) and four regions within the ECN (superior frontal gyrus, middle frontal gyrus, and inferior frontal gyrus [pars triangularis and pars orbitalis]). Due to the focus of this investigation on creative thinking specifically, we chose to examine these subsets of the two networks relative to the DMN and

ECN in their entirety, because they have been consistently involved in creative thinking in past work. We first used independent sample *t*-tests on the local maxima activity across all ROIs, which, however, did not elicit any significant differences between the two groups (all *ps* > .05).

We then examined with a series of secondary exploratory correlational analyses the relationships between (a) the local maxima of activity in these regions and creative achievement as measured by the CAQ; and

Table 4
Correlational analyses (Pearson’s *r*) among local maxima ROIs by group.

Eminent		SPL	MPFC	Anterior MTG	Angular Gyrus	SFG	MFG	IFG (PT)	IFG (PO)
Precuneus		.02	-.03	.28	.60*	.11	.46	.29	.41*
SPL			-.04	.15	.18	.56*	.28	.39	.32
MPFC				.11	.05	-.12	-.11	.53	.07
Anterior MTG					.30	.12	.09	.28	.11
Angular Gyrus						-.02	.22	.34	.19
SFG							.62*	.32	.61*
MFG								.37	.65*
IFG (PT)									.56*
Non Eminent		SPL	MPFC	Anterior MTG	Angular Gyrus	SFG	MFG	IFG (PT)	IFG (PO)
Precuneus		.52	.69*	.72*	.42	.84**	.46	.53	.69*
SPL			.55	.40	.68*	.50	.80**	.38	.21
MPFC				.79**	.61	.70*	.58	.66*	.44
Anterior MTG					.36	.71*	.53	.79**	.59
Angular Gyrus						.36	.59	.24	-.04
SFG							.65*	.57	.61*
MFG								.52	.13
IFG (PT)									.58*

Note: **p* < .01; ***p* < .001, FDR-corrected for multiple comparisons at FDR = 0.05 with a critical *p* value of .01 (Benjamini-Hochberg, 1995). SPL = Superior Parietal Lobule; MPFC = Medial Prefrontal Cortex; MTG = Middle Temporal Gyrus; SFG = Superior Frontal Gyrus; MFG = Middle Frontal Gyrus; IFG = Inferior Frontal Gyrus; PT = pars triangularis; PO = pars opercularis.

(b) the local maxima of activity in these regions among each other, for each participant group. The results of these analyses are reported in [Tables 3 and 4](#), respectively. Overall, scores on the CAQ were not significantly correlated with activity in any ROI for eminent thinkers but were positively correlated with activity in the inferior frontal gyrus (pars opercularis) in the non-eminent thinkers ([Table 3](#)). In line with the whole-brain fMRI analysis results, regions across the DMN were extensively correlated to regions of the ECN and to each other for the non-eminent thinkers, whereas similar relationships—but to a lesser degree—were observed for the eminent thinkers ([Table 4](#)).

Using Fisher's r to z transformation procedure, we then examined whether the correlations between the CAQ and the ROIs, as well as the pairs of ROIs significantly differed between eminent and non-eminent creators. The results of these analyses are presented in [Table 5](#). We note that due to this difference in overall activity between the two groups, it is possible that the these results are an artifact of the increased variance in activity in the non-eminent group, thus should be interpreted with caution. Nevertheless, although this secondary ROI analysis is exploratory and primarily descriptive due to the small sample size per group in this study, it reflects a pattern of results consistent with the primary analysis wherein eminent thinkers engage, overall, a more restricted network of regions during creative generation. Future studies with larger samples would allow for a more comprehensive statistical examination of these findings.

4. Discussion

A long-standing question across creativity neuroscience pertains to whether the same cognitive and neural mechanisms underlie creative thinking in exceptionally creative individuals—those seemingly disproportionately responsible for a considerable number of groundbreaking creative achievements. Despite the rapid growth of research in the neuroscience of creativity, a surprisingly small number of studies has been devoted to the topic of extraordinary creativity. Among them, investigations have focused on homogenous groups of artists or scientists and have generally elicited results that suggest increased neural efficiency (as marked by lower recruitment of brain regions) among individuals with high creative achievement (e.g., [Japardi et al., 2018](#); [Limb and Braun, 2008](#)). Here, we examined whether the engagement of these regions in idea generation would show a similar neural signature in a heterogenous group of eminent creators from diverse fields of expertise, who were compared to a 'smart' comparison group of age- and education-matched non-eminent thinkers. We classified participants based on their scores on the CAQ ([Carson et al., 2005](#)) and collected neural responses during the AUT, a well-established measure of creative thinking ([Chrysikou and Thompson-Schill, 2011](#); [Japardi et al., 2018](#)).

Behaviorally, eminent and non-eminent creators did not differ in their performance on the AUT, generating similar numbers of correct responses for the task. With regards to the neuroimaging findings, our analyses revealed a significant task by group interaction, with eminent thinkers having significantly higher activity than non-eminent thinkers in the right supramarginal gyrus and the right transverse temporal gyrus and non-eminent thinkers having significantly higher activity than eminent thinkers in several regions across the DMN and ECN, including the left lingual gyrus, the left frontal pole, the anterior cingulate gyrus, the left parietal cortex, and the posterior cingulate cortex. Secondary exploratory ROI analyses suggested possible differences in the contributions of default and executive networks to creative achievement between the eminent and non-eminent groups, although we cannot exclude the possibility that these results might be attributed the increased variance in the non-eminent group due to the difference in overall neural activity between the two groups. Future studies with larger samples are necessary to investigate this pattern of results with more advanced analytic methods.

Our findings are consistent with the recruitment of the dorsomedial system of DMN for distal simulations in eminent creators reported by

Table 5

Significant Correlation Differences Between Eminent and Non-eminent Creators Following Fisher's r to z Transformation.

Correlation Pairs	Fisher's z	p
CAQ, angular gyrus	1.77	.04
CAQ, IFG (PO)	-2.30	.01
Precuneus, MPFC	-2.22	.01
Precuneus, anterior MTG	-1.68	.046
Precuneus, SFG	-3.02	.001
MPFC, anterior MTG	-2.61	.005
MPFC, SFG	-2.03	.02
MPFC, angular gyrus	-1.79	.04
SPL, angular gyrus	-1.76	.04
SFG, anterior MTG	-2.03	.02
MFG, SPL	-2.20	.01
IFG (PT), anterior MTG	-2.13	.02
IFG (PO), MFG	1.75	.04

Note: Negative z values indicate a significantly stronger correlation in non-eminent than eminent creators. *SPL* = Superior Parietal Lobule; *MPFC* = Medial Prefrontal Cortex; *MTG* = Middle Temporal Gyrus; *SFG* = Superior Frontal Gyrus; *MFG* = Middle Frontal Gyrus; *IFG* = Inferior Frontal Gyrus; *PT* = pars triangularis; *PO* = pars opercularis.

[Meyer et al. \(2019\)](#), including activation in the temporoparietal junction and inferior temporal cortex we observed in the current study for the eminent group. Our results further mirror similar differences in neural recruitment during a variation of the AUT recently reported by [Japardi et al. \(2018\)](#) in homogenous groups of visual artists and scientists, relative to a matched comparison group of non-eminent thinkers. In that study, control participants showed significantly higher functional activation in visual cortex and right frontal pole relative to both groups of eminent creators, a result that parallels the extensive regions across medial, posterior, and frontal regions significantly recruited in the control group in the present study. The similarities in the results of the two investigations are noteworthy considering some methodological differences between them, including pictorial stimuli and overt responses in the current experiment, single relative to multiple responses in the AUT, different baseline tasks, higher variability in CAQ scores, and participant heterogeneity that was, by design, substantial in the current study. Although employing different and domain-specific tasks, decreases in the engagement of task-positive ECN networks in creative experts have been reported in previous work ([Limb and Braun, 2008](#); [Liu et al., 2012](#)), a finding consistent with the results of the current study. Taken together, our findings offer support for the neural efficiency hypothesis in exceptional creativity, by revealing a more restricted set of neural regions supporting creative thinking in eminent relative to non-eminent creators.

The results of this study contribute to the literature suggesting that extraordinary creative ability is not the outcome of a unique set of neurocognitive processes; rather, it is associated with the same neural mechanisms that support ordinary creativity, but to a different degree ([Japardi et al., 2018](#); cf. [Neubauer and Fink, 2009](#)). Indeed, our findings would support the argument that similar creative outcomes (here, as measured behaviorally by the AUT) come about with a less extensive recruitment of brain networks shown to contribute to creative thought ([Beatty et al., 2016](#); [Jung et al., 2013](#)), which we speculate may allow eminent creators to pursue concurrently, for example, multiple lines of creative thought. Yet, the precise consequences of this observed neural efficiency in the eminent groups for creative outcomes require much additional empirical work.

We note that it is possible that the observed pattern of results is tightly linked to the particular experimental task we employed here. First, although our perceptual baseline task was selected based on past research with the AUT ([Chrysikou and Thompson-Schill, 2011](#)), it is possible that a more generative baseline task would have elicited different results. Moreover, although the use of model tasks such as the AUT is critical methodologically in neuroscience studies and for comparisons across creativity investigations, it may, nevertheless, fail to

capture creative ideation reflective of extraordinary creative processes in the real world. Notwithstanding these possible task-related limitations, the generation of creative ideas within the known space and constraints of the AUT may offer a useful first step toward studies of extraordinary creativity, while allowing direct comparisons with non-eminent thinker control participants. Future investigations might consider incorporating additional and, perhaps, more ecologically valid creativity assessments for exceptionally creative subjects.

5. Conclusions

This study among the few to examine the neural bases of extraordinary creativity in a heterogeneous group of eminent creators from various fields of expertise. Our results contribute to the growing literature of neuroscience studies on exceptional creativity that suggest differences in the extent of recruitment of DMN and ECN regions in eminent creators, who achieve successful performance in creative ideation tasks with optimal neural efficiency.

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