

Cerebral blood flow associated with creative performance: A comparative study

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Creativity is important for social survival and individual wellbeing; science, art, philosophy and technology have been enriched and expanded by this trait. To our knowledge this is the first study probing differences in brain cerebral blood flow (CBF) between highly creative individuals (scientists and/or artists socially recognized for their contributions to their fields with creativity indexes corresponding to the 99% percentile) and average control subjects while performing a verbal task from the Torrance Tests of Creative Thinking. Additionally, we correlated CBF with creativity dimensions such as fluency, originality and flexibility. Subjects with a high creative performance showed greater CBF activity in right precentral gyrus, right culmen, left and right middle frontal gyrus, right frontal rectal gyrus, left frontal orbital gyrus, and left inferior gyrus (BA 6, 10, 11, 47, 20), and cerebellum; confirming bilateral cerebral contribution. These structures have been involved in cognition, emotion, working memory, and novelty response. The score on the three creativity dimensions – fluency, originality, and flexibility– correlated with CBF activation in right middle frontal gyrus and right rectal gyrus (Brodmann Area 6, 11). Moreover, fluency and flexibility strongly correlated with CBF in left inferior frontal gyrus and originality correlated with CBF in left superior temporal gyrus and cerebellar tonsil. These findings suggest an integration of perceptual, volitional, cognitive and emotional processes in creativity. The higher CBF found in particular brain regions of highly creative individuals during the performance of a creative task provides evidence of a specific neural network related to the creative process.

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Introduction

Creativity plays a crucial role in cultural life and also in individual development and well being. It involves pleasure, which enables individuals to persevere in their creations over time in spite of difficulties or rejection. Understanding how creativity occurs and which brain processes are involved with it is a challenging task, and such an understanding might transform our view of ourselves and our societies (Zeki, 2001). In the 19th century, creativity was first considered as a biological trait (Galton, 1892). Also at that time it was proposed that there was a high rate of synaesthesia (when a sense is experienced in the modality of another sense; for example, tasting shape, or hearing color) among highly creative individuals (Galton, 1880). Furthermore, it was suggested that geniality is related with an altered neurophysiology. However, it was not until the beginning of the 21st century that scientists realized that complete theories of creativity and aesthetics should be neurobiologically based and a new research field called *neuroesthetics* was established (Zeki, 2001).

Creativity means bringing into being; it involves generation of novelty and transformation of the existent. There have been proposed theoretical models describing stages or dimensions of the creative process. That is the case of the association integration–elaboration–communication phenomenological model (Chávez, 1999, Chávez, 2004). This model was developed from phenomenological observations of poets and deep phenomenological interview with scientists, writers, music composers, and plastic artists. The first stage of this model involves the association of previously unrelated elements of inner and outer experiences. Sensorial, cognitive, and affective integrations take place involving different degrees of consciousness. This phase includes (a) episodes of automatic creation (what has been called inspiration), (b) sudden insight (also known as illumination) achieved when we perform any other apparently unrelated activity, a process that has

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been named incubation (Wallas, 1926, Boden, 1994, Torrance and Safter, 1999), and (c) conscious combination of elements. The phase of elaboration involves the following conscious work invested in the ideas gained through the previous phase and involves volition. The phase of communication allows transmitting the associations, often unleashing new creative processes in other individuals, making creativity “contagious.” Margaret Boden (1994), an influential author in the field differentiated between two types of creativity: psychological creativity *P* and historic creativity *H*. *P* creativity occurs in one person’s mind and it does not matter if other people already had that idea; *H* creativity is new for the person but also for humanity. Several external factors (such as fashion, rivals, disease, economy, and war, among others) influence the survival overtime of this kind of creativity; for that reason, there cannot be a single and systematic explanation for *H* creativity, but all *H* creativity is *P* creativity by definition; therefore, an explanation of *P* creativity will include *H* creativity as well (Boden, 1994).

Considering the complexity of creativity, some researchers have focused on specific characteristics of creative products whereas others consider specific parts of the creative process in order to assess creativity. Regarding the latter, the Torrance Tests of Creative Thinking (TTCT) are standardized psychometric tests evaluating creative performance (Torrance, 1990); the TTCT provide standard stimuli from which the creative process is reproduced in controlled environments. The TTCT are based on the evaluation of divergent thinking (Guilford, 1968), the production of a variety of responses not determined by explicitly given information. A normal distribution of the creativity index in the general population has been reported using these tests, finding no significant differences between genders (Torrance, 1990, Torrance and Safter, 1999). Specific forms of cognition have been identified in highly creative individuals. These are: (1) *divergent thinking*, proposed by the cognitive psychologist J. P. Guilford (1968). Divergent thinking is a style of thinking that produces a number of different possible answers, opposed to *convergent thinking*, which leads to a single correct answer (what most intelligence tests evaluate). Even if divergent thinking is a necessary condition for creative achievement, convergent thinking is also required in order to facilitate appropriate responses and suppress inappropriate ones, particularly during the elaboration phase of the creative process (Guilford, 1968). (2) *The bisociation of no-related matrixes*, proposed by the writer Arthur Koestler. The bisociation of no-related matrixes is the ability to connect previously unrelated skills or matrixes of thought (Koestler, 1964). (3) The *janusian* and *homospacial* processes, identified by the psychiatrist Albert Rothenberg after evaluating dozens of individuals awarded with the Nobel Prize. The homospacial process involves superimposition of discrete entities, which may be visual or other kinds of mental representations. The janusian process consists of actively conceiving multiple opposites or antitheses simultaneously (Rothenberg, 2000). (4) The *tertiary* process, proposed by the psychoanalyst Silvano Arieti, is the integration of *primary* and *secondary* processes simultaneously (Arieti, 1976). Secondary process refers to logical thinking. Primary process is present in dreams and in psychotic thinking, but also in works of art; scientists such as Einstein, Loewi, Kekulé, and Mendeleev seem to have used it during some phases of their creative production (Root-Bernstein and Root-Bernstein, 1999, Mazzarello, 2000). Primary process cognition has been related to right cerebral hemisphere activation whereas secondary process has been related to left hemisphere

activation (Martindale et al., 1984). Highly creative individuals have a tendency to be physiologically overreactive to stimulation. For instance, when compared to less creative subjects the highly creative exhibit prolonged alpha electroencephalographic (EEG) blocking in response to tones; they habituate slower to stimuli; and they rate electric shocks as being more painful (Martindale, 1978, Martindale et al., 1984, Martindale et al., 1996). In addition, large and consistent EEG differences between high and low creative individuals have been observed only during creative task performance. Less creative subjects tend to show alpha blocking on all types of cognitive tasks, including creative tasks, while highly creative individuals tend to be differentially reactive. During non-creative tasks highly creative individuals also exhibit alpha blocking. However, they tend to operate at a relatively low level of arousal and to show alpha enhancement during creative tasks (Martindale, 1978). The right-hemisphere EEG activity in parieto-temporal areas tends to be significantly higher than left-hemisphere activity in highly creative individuals specifically during creative tasks performance (Martindale et al., 1984, Martindale, 1990). Nonetheless, it was found that more creative individuals exhibited higher alpha indices during an analog of creative inspiration (the association phase) than during an analog of creative elaboration. This pattern was not found in less creative subjects (Martindale and Hasenfus, 1978).

When comparing regional cerebral blood flow (rCBF) between low and highly creative individuals during the performance of creative tasks, highly creative subjects tend to show more bilateral prefrontal rCBF whereas low creative individuals display functions predominantly in the left cerebral hemisphere (Carlsson et al., 2000). Another study compared the results of EEG and CBF measures from two different populations. These individuals were administered the same verbal creative tasks. It was found that greater creative performance was related to higher values of spatial synchronization in anterior cortical areas and a general increase of the coherence in both frontal areas. Highly creative performance was also associated with higher CBF in both frontal lobes, particularly Brodmann Areas (BA) 8–11 and 44–47 (Bekhtereva et al., 2001). In contrast to Carlsson et al. (2000) research, in this study individuals were not selected using creativity index scores. In a later CBF PET study (Bekhtereva et al., 2004) the authors evaluated 25 healthy subjects recruited from the general population administering two different cognitive strategies of creativity: the first strategy consisted in composing a story using a list of words from different semantic areas; the second strategy involved filling gaps between words and making logical associations. Creative performance correlated with activation in the left parieto-temporal regions (BA 39 and 40).

A previous study conducted by our research team found positive significant correlation between the figural and verbal creativity indexes and the cerebral blood flow in the right anterior cerebellum and the right precentral gyrus (BA 6), the right postcentral gyrus (BA 3), the left middle frontal gyrus (BA 11), the right rectal gyrus (BA 11), the right inferior parietal lobule (BA 40), and the right parahippocampal gyrus (BA 35). These brain areas are involved in multimodal processing, in complex cognitive functions such as imagery, association processes, memory and novelty processing, among others (Chávez et al., 2004).

Jung-Beeman et al. (2004) conducted an fMRI study using a modified form of Mednick’s test of creative cognition where subjects encountered three problem words and attempted to produce a single solution word. They found that solving problems

with a subjective feeling of insight activated a complex cortical network; the right anterior superior temporal gyrus was a key component. Using EEG they found a sudden burst of high frequency (gamma band) neural activity in right anterior superior temporal area prior to insight solutions. The right anterior temporal gyrus has been associated with making connections across distantly related information (Jung-Beeman et al., 2004).

Vartanian and Goel (2005, 2007) conducted fMRI studies seeking to determine if the right and left prefrontal cortex (PFC) would engage differently when generating hypothesis, a key feature of creative cognition. For this purpose they used a modification of Guilford's classic match problems; a good performance involves the ability of making set shifts or movements from one state in a problem space to a horizontally displaced state, referred as lateral transformations by these researchers. The generation of hypothesis that required set shifts activated the right ventral lateral PFC (BA 47), left middle frontal gyrus (BA 9), and left frontal pole (BA 10). The activation in right dorsal lateral PFC (BA 46) and cerebellum covaried as a function of the number of solutions that were generated (Goel and Vartanian, 2005). A later study using anagram problems confirmed the involvement of right ventral lateral PFC (BA 47) with hypothesis generation (Vartanian and Goel, 2005, Vartanian and Goel, 2007).

Gómez-Beldarrain et al. evaluated 18 patients with PFC lesions finding an impairment of counterfactual thinking (mental simulations of what might have been if another behavior had been executed). Counterfactual thinking correlated positively with creativity measures (design fluency test). The researchers conclude that the PFC is crucial only for the spontaneous generation of counterfactual thinking (Gomez-Beldarrain et al., 2005).

Howard-Jones et al. (2005) performed an fMRI investigation (Howard-Jones et al., 2005) in 8 healthy undergraduate and graduate students and required them to produce creative and uncreative stories from related and unrelated word sets finding that when participants were being creative there was an increase in activity in the prefrontal areas, in particular right medial frontal gyrus (BA 9 and 10); additional activity in these areas was observed when using unrelated word sets. The authors suggest that these prefrontal areas are involved with the divergent semantic processing associated with creativity.

The aims of the present research were to compare the CBF between average and highly creative individuals during the performance of a creative task and to correlate the CBF with the scores on creativity dimensions (fluency, originality, and flexibility) using Single Photon Emission Computerized Tomography (SPECT) and statistical parametric mapping. Our a priori areas were the fronto-temporal regions because of their involvement in cognitive and emotional functions that are critical to the creative process.

Materials and methods

Participants

One hundred individuals, including forty national and international awarded artist and/or scientists in the peak of their production, were evaluated using the TTCT Figural form B. From that sample twelve right-handed participants were recruited using their creativity index (CI) obtained with the TTCT as selection criteria. Group I was integrated by individuals with CI > 139, which is considered very high or "gifted." This CI has been found in one

individual among a hundred in open population samples. Group II was composed of individuals with CI=103–111, which is considered as "average" (Torrance, 1990). The groups were paired by sex and age. Pregnancy was excluded among the females studied. The subjects did not suffer from psychiatric, neurological, or other medical disorders, nor did they have history of drug abuse. This was confirmed through clinical evaluations (medical and psychiatric). In addition, only individuals presenting Symptom Check List 90-R (SCL-90-R) scores <1 for all subscales were recruited (Derogatis, 1994), which allowed us to exclude individuals suffering any state of psychological distress. For our study we used the Spanish version of the SLR-90-R (Bonicatto et al., 1997), a self-report scale providing the severity and profile of psychopathology, differentiation between behavioral symptoms of somatization, obsessive-compulsiveness, interpersonal sensibility, depression, anxiety, hostility, phobic anxiety, paranoid ideation, and psychotic behavior. Participants were not under any kind of medication (details of the sample are described in Table 1).

Procedure

Cerebral blood flow imaging was performed using SPECT. Two TTCT verbal-A tasks: "Just Suppose" and "Unusual Uses" (as described later in this paper) were administered during brain image acquisition. The TTCT was the ideal instrument for this purpose because it does not require writing or drawing like many other creativity tests, it can be assessed verbally in a dark room, and it provides a creativity index and scores for other creativity dimensions such as fluency, originality, and flexibility. In all cases the participants were evaluated in a dark room and they had their eyes covered. All the procedures were performed in compliance with the relevant laws and institutional guidelines and were approved by the National Institute of Psychiatry "Ramón de la Fuente" (INPRF) Ethics and Scientific Committees. Informed consent was obtained and signed by all the subjects.

Creativity assessment

The Torrance Tests of Creative Thinking (TTCT) figural and verbal forms were used to assess creativity (Torrance, 1990). These psychometric tests are used to evaluate divergent thinking (Plucker and Renzulli, 1999). The TTCT provide a creativity index (CI) and scores the following dimensions of the creative process: (a)

Table 1
Characteristics of the subjects participating in the study

Variables	High creative subjects		Average creative subjects		<i>p</i> value
	<i>M</i>	<i>sd</i>	<i>M</i>	<i>sd</i>	
Age	33.7	9.5	40.6	7.3	0.183
SCL-90 scores	0.30	0.11	0.48	0.29	0.181
CI—TTCT figural*	148.17	7.36	107.3	3.8	0.0001
CI—TTCT verbal*	132.7	14.4	83.7	7.7	0.0001
Fluency*	63.3	15.8	24.8	10.7	0.001
Originality*	52.7	11.9	12	5.4	0.0001
Flexibility*	31	9.8	11	4.9	0.001

Variables marked with * showed significant differences between groups. Fluency, originality, and flexibility values were obtained in the "Unusual Uses" creative task and correspond with the brain images acquisition.

flexibility, the ability to move from one conceptual field to another; (b) fluency, the number of relevant responses, which is related to the ability to produce and consider many alternatives; (c) originality, the amount of unusual responses, which involves “getting away from the obvious and common place or breaking away from habit bound thinking” (Torrance and Safter, 1999), original ideas are statistically infrequent; (d) elaboration, the number of details on each response; (e) resistance to premature closure, the ability to remain open to uncertainty; (f) abstractness of titles, the degree of abstraction versus concreteness. Additional points are added to the final score for the presence of other recognized creative strengths such as emotional expressiveness, story telling articulateness, movement or action, expressiveness of titles, synthesis of incomplete figures, unusual visualization, internal visualization, extending or breaking boundaries, humor, richness of imagery, colorfulness of imagery, and fantasy. The TTCT have shown high reliability ($r > 0.90$) and high predictive validity ($r > 0.57$) for future career image and for academic and style-living creative achievements in 22- and 30-year follow-up studies (Torrance, 1988, 1990, 1993). The TTCT have been used in more than 2000 research projects and translated into 30 languages (Cramond, 1999). We used the Spanish version of the tests (Chávez-Eakle et al., 2006). Training for the administration and scoring of the TTCT were obtained at the Torrance Center for Creative Studies at the University of Georgia, USA, where inter-rater reliability was confirmed ($r > 0.90$).

Two activities from the TTCT verbal were selected as creative tasks to be administered to the subjects just before the brain scanning. The first activity, “Just Suppose,” was chosen as warming-up activity. In this task the subjects are required to imagine a specific improbable situation and describe all the things they think would happen if that given situation came true. The second activity “Unusual Uses” was administered immediately after the injection of the radiotracer. In this activity the subjects are required to relay all the uses they can list for cardboard boxes. In both activities the same standardized instructions are given to all the participants and all were encouraged to “think of the most fun, unusual, interesting and intelligent” responses (Torrance, 1990). The responses produced in both tasks were recorded and later scored.

Cerebral SPECT and image analysis

Cerebral blood flow imaging was performed using SPECT, with 99m-Tc-dimer of ethyl-cysteinate (99 m-Tc-ECD) as a radiotracer, prepared according to the specifications suggested by the manufacturer. Cerebral SPECTs were carried out in the Nuclear Medicine Department at the INPRF. A catheter was placed in a vein of the left forearm of each subject 30 min before radiotracer injection. Each individual was placed in a dark room attenuated of visual and auditory stimuli; their eyes were also covered. Once the subjects were in place, the two creativity tasks were administered. As we explained earlier, the first task (“Just Suppose”) was a warm-up activity, whereas the second task (“Unusual Uses, cardboard boxes”) was administered immediately after intravenous injection of the radiotracer Tc99m-ECD. All individuals remained in the dark room for 10 min upon completing the second creativity task.

The 99 m-Tc-ECD dosage was 740–925 MBq (20–25 mCi). Thirty minutes posterior to the injection, the subjects were placed in the SPECT, with their heads positioned in the orbitomeatal axis

to initiate data acquisition. The equipment is comprised of a three head Gamma camera (Multi-SPECT, Siemens) with ultra high-resolution fanbeam collimators. Data were acquired in a 128×128 -pixel matrix with a $1.23 \times$ zoom lens. Each head camera scanned a 120° angle, thus, the three heads completed a total 360° rotation around the head of the subject, obtaining 120 angular projections, 3° each (40 by detector), with a minimum of 8 million counts per study. The acquisition time for the images was 25 to 30 min. Image reconstruction was made with a 0.9 back projection filter Shepp-logan-hanning with a 9.0 mm spatial resolution. An attenuation correction of 0.12 cm^{-1} was applied to each transversal slice using the method of Chang et al. (1995).

Images processing and statistical analyses

The image processing and analysis performed used statistical parametric mapping SPM2 (SPM2, Wellcome Department of Cognitive Neurology, London; <http://www.fil.ion.ucl.ac.uk/spm>) (Friston et al., 1995) and MRIcro software version 1.36 (Rorden and Brett, 2000) (www.mricro.com). The SPECT images were visually inspected for image quality. All the images were transformed to analyze format for their further automatic realignment by application of an algorithm that reorients images along the intercommisural plane. Then, the images were spatially (stereotactically) normalized using sinc-interpolation into the SPECT image template from the Montreal Neurological Institute (MNI). For the determination of parameters an average image, derived from a total of all images, was used. The voxel size was fixed in $2 \times 2 \times 2$ mm. The normalized images were smoothed with an isotropic Gaussian filter with a $6 \times 6 \times 6$ mm value (Friston et al., 1995). The design matrix chosen for analysis was a two-sample t statistic provided by SPM2 and was used for comparisons between average and highly creativity subjects. Furthermore, a simple regression (correlation) was performed where the normalized voxel blood flow rates for every scan were the dependent variables and the independent variables were the score of each creativity dimension. Mean voxel value was chosen for global calculation and proportional scaling to 50 mg/100 mL/min for global normalization. This arbitrary value was derived from mean cerebral blood flow, but was used conventionally in this analysis. The significant threshold for a priori regions (fronto-temporal) was a t -value of at least 3 (p -corrected value < 0.05 at cluster level) and clusters formed by more than 10 voxels. However, all the areas that survive these statistical and extension thresholds were reported. The multiple comparison correction was performed using the false discovery rate (FDR) approach (Genovese et al., 2002). Results were graphically presented in the Talairach–Tournoux coordinate system (Talairach and Tournoux, 1988) and overlaid on the MNI template of average T1 MRI.

Results

Comparison between high and average creative performance

Significant CBF differences between groups were found. Highly creative subjects (those who obtained a CI > 139 on the TTCT) had increased CBF in: (a) right precentral gyrus (p -corrected = 0.007), BA 6; (b) right cerebellum, culmen (p -corrected = 0.013), (c) left middle frontal gyrus (p -corrected = 0.016; p -corrected = 0.034), BA 6 and 10, (d) right frontal rectal gyrus (p -corrected = 0.023) BA 11, (e) left frontal orbital gyrus (p -corrected = 0.027) BA 47, and (f) left

Table 2
Brain regions with higher CBF in highly creative individuals

High > Average CI	Coordinates			Hemisphere	Region	BA	Cluster size	Values		
	X	Y	Z					Z	<i>p</i> -corr	<i>p</i> -uncorr
	58	-6	48	Right	Precentral gyrus	6	104	3.79	0.007	0.000
	24	-32	-28	Right	Cerebellum (culmen)		140	3.55	0.013	0.000
	-38	8	42	Left	Middle frontal gyrus	6	40	3.47	0.016	0.000
	10	10	-22	Right	Frontal rectal gyrus	11	51	3.33	0.023	0.000
	-18	22	-26	Left	Frontal orbital gyrus	47	52	3.25	0.027	0.001
	-32	38	16	Left	Middle frontal gyrus	10	41	3.15	0.034	0.001
	-66	-16	-26	Left	Inferior temporal gyrus	20	101	2.98	0.050	0.001

Coordinates and anatomic localization of voxels clusters are shown for the regions with higher metabolism in the highly creative group. Z values, *p*-corrected (*p*-corr), and *p*-uncorrected (*p*-uncorr) correspond to the maximum significance value of each cluster. CI, creativity index. BA, Brodmann Area. Cluster size corresponds to the number of voxels in the cluster. Coordinates correspond to the Montreal Neurological Institute (MNI) system. Regions were obtained converting coordinates to the Talairach–Tornoux system.

inferior temporal gyrus (*p*-corrected=0.05), BA 20. The results are summarized in Table 2 and in Fig. 1.

Correlation of CBF and creativity dimensions: fluency, originality, and flexibility

Fluency scores strongly correlated with CBF in the left inferior frontal gyrus, BA 47 (*p*-corrected=0.012); right inferior parietal lobule, BA 40 (*p*-corrected=0.038); right rectal gyrus, BA 11 (*p*-corrected=0.035); right middle frontal gyrus, BA 6 (*p*-corrected=0.041); left supramarginal gyrus, BA 40 (*p*-corrected=0.046); and right postcentral gyrus, BA 1 (*p*-corrected=0.05). Originality scores correlated with higher CBF in the right rectal gyrus, BA 11 (*p*-corrected=0.015); right cerebellar tonsil (*p*-corrected=0.040); right

and left middle frontal gyrus, BA 6 and 10 (*p*-corrected=0.043; *p*-corrected=0.047); and left superior temporal gyrus, BA 38 (*p*-corrected=0.046). Flexibility scores correlated with CBF in the left inferior frontal gyrus, BA 47 (*p*-corrected=0.012); right middle frontal gyrus, BA 6 (*p*-corrected=0.020); and right rectal gyrus, BA 11 (*p*-corrected=0.036). The results are summarized in Table 3 and in Fig. 2.

Discussion

Our results showed that a brain bilateral distributed system is involved in highly creative performance. During the performance of a verbal creative task highly creative individuals showed greater CBF in regions that have been associated with functions that are

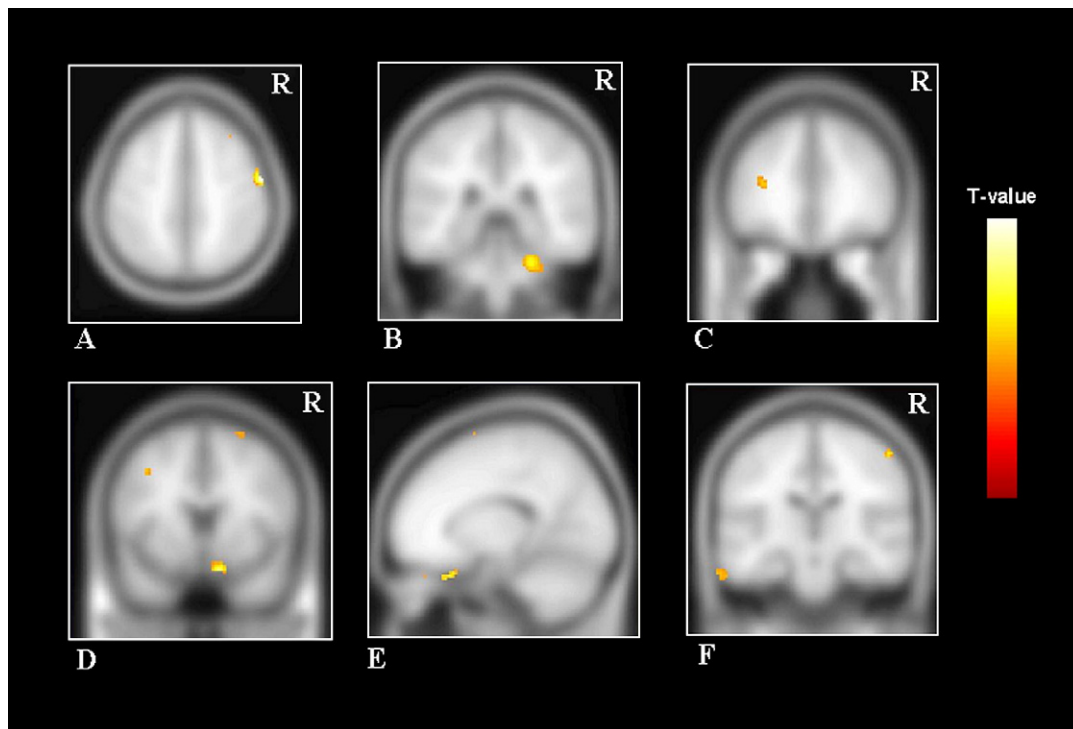


Fig. 1. Regions with higher CBF in highly creative individuals. Projections are coronal for panels B, C, D and F, axial for panel A and sagittal for panel E. (A) Right precentral gyrus Brodmann Area (BA) 6. (B) Right cerebellum, culmen. (C) Left middle frontal gyrus, BA 10. (D) Right frontal rectal gyrus, BA 11. (E) Left frontal orbital gyrus BA 47. (F) Left inferior temporal gyrus, BA 20. R, right hemisphere. For details of localization, cluster size, and significance, see Table 2.

Table 3
Statistical parametric mapping results showing clusters of voxels having significant regions of correlation

Creativity dimensions	Coordinates			Hemisphere	Region	BA	Cluster size	Values			
	X	Y	Z					Z	r	p-corr	p-uncorr
Fluency	-40	34	-22	Left	Inferior frontal gyrus	47	52	3.58	0.859	0.012	0.000
	64	-28	38	Right	Inferior parietal lobule	40	63	3.20	0.810	0.038	0.001
	10	10	-22	Right	Rectal gyrus	11	80	3.16	0.805	0.035	0.001
	40	6	38	Right	Middle frontal gyrus	6	26	3.08	0.794	0.041	0.001
	-62	-46	34	Left	Supramarginal gyrus	40	79	3.03	0.786	0.046	0.001
	52	-20	56	Right	Postcentral gyrus	1	52	2.99	0.779	0.050	0.001
Originality	10	10	-22	Right	Rectal gyrus	11	63	3.48	0.847	0.015	0.000
	24	-32	-26	Right	Cerebellar tonsil		96	3.07	0.792	0.040	0.011
	-32	38	14	Left	Middle frontal gyrus	10	33	3.04	0.787	0.043	0.001
	38	4	38	Right	Middle frontal gyrus	6	19	3.00	0.782	0.047	0.001
	-52	10	-10	Left	Superior temporal gyrus	38	10	3.02	0.691	0.046	0.001
Flexibility	-40	34	-22	Left	Inferior frontal gyrus	47	41	3.57	0.858	0.012	0.000
	38	4	38	Right	Middle frontal gyrus	6	43	3.38	0.835	0.020	0.000
	10	10	-20	Right	Rectal gyrus	11	78	3.13	0.801	0.036	0.001

The results are shown for each of the creativity dimensions obtained with the TTCT verbal. Coordinates correspond to the Montreal Neurological Institute (MNI) system. Regions were obtained converting coordinates to the Talairach–Tornoux system. Z values correspond to the maximal voxel of each cluster. *r* is Pearson’s correlation coefficient between the normalized cerebral flow and the scores on each creativity dimension. BA, Brodmann Area. Cluster size corresponds to the number of voxels in the cluster.

relevant to the creative process. They had greater right and left prefrontal activation; left temporal lobes and right cerebellum regions also showed significantly higher CBF. In our study highly

creative subjects had greater CBF in BA 10, 11, and 47 which have consistently showed higher activation during the performance of creative tasks (Bekhtereva et al., 2001, Goel and Vartanian, 2005,

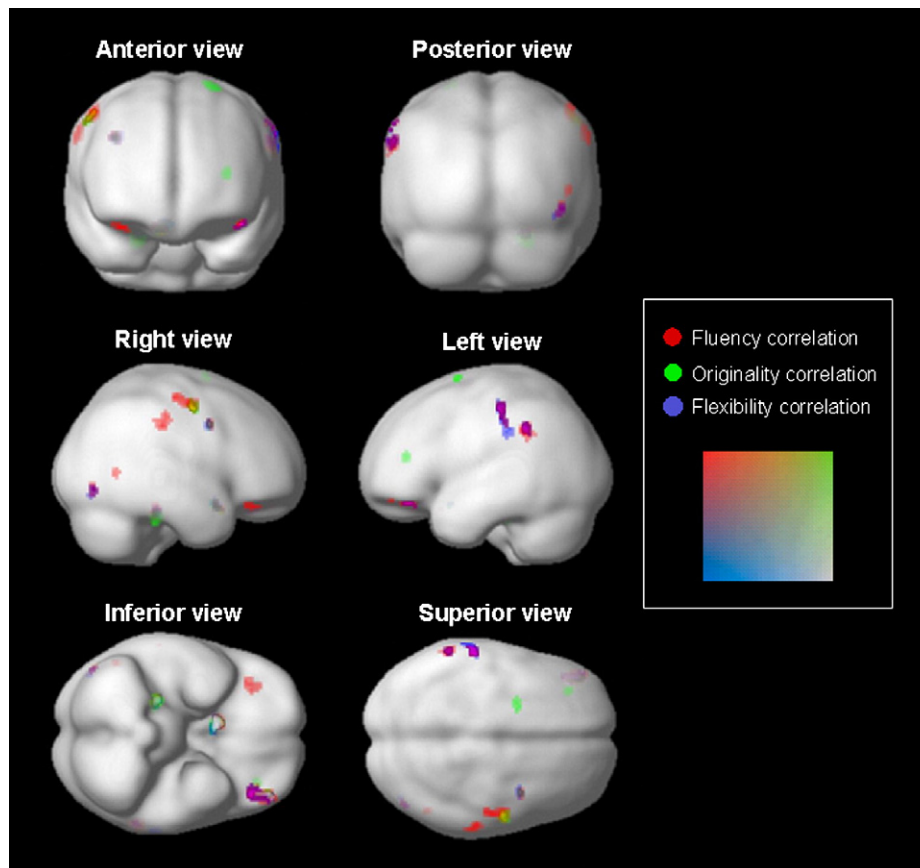


Fig. 2. Regions of correlation between CBF and the scores in the creativity dimensions. Regions of correlation are shown superimposed on the MNI average T1 magnetic resonance render template. Correlations with fluency are shown in red ($r > 0.779$, $p < 0.001$). Correlations with originality are shown in green ($r > 0.691$, $p < 0.001$). Correlations with flexibility are shown in blue ($r > 0.801$, $p < 0.001$). The pallet of colors illustrates the three creativity dimensions’ overlaps with the CBF correlations. For details of localization, cluster size, and significance, see Table 3.

Howard-Jones et al., 2005, Vartanian and Goel, 2005). The BA 47 has been associated to the formation of hypothesis that requires set shifts or “lateral transformations,” a key feature of creative cognition (Vartanian and Goel, 2007). On the other hand, the association areas from the dorsolateral prefrontal cortex and the cerebellum have been involved in working memory. Working memory allows us to keep a small amount of verbal information in mind for almost indefinite periods (Kandel et al., 2000); therefore, information remains in an accessible state, ready to be used, mixed, or carried out and emerges when performing simple or complex everyday cognitive and motor tasks during the process of incubation (Chavez-Eakle, 2007). Recently Vandervert, Schimpf, and Liu proposed a cognitive theory which combines the working memory model with dynamic models of the cerebellum for the study of creativity (Vandervert et al., 2007). The cerebellum makes cognitive functions faster, more efficient and adaptative, modulating language, attentional and visuospatial processes, and imagery (Chavez-Eakle, 2007, Vandervert et al., 2007). The right cerebellum is also involved in emotional reactions and is directly linked to the amygdala, hippocampus, temporal lobe, hypothalamus, thalamus, anterior cingulate, and orbital frontal lobes (Rhawn, 1996, Kandel et al., 2000, Mouras et al., 2003, Afifi and Bergman, 2005). Furthermore, it has been reported that individuals with lesions in right cerebellum have disturbances in verbal association and spatial tests (Rhawn, 1996) and show frontal hypoactivity (Arai et al., 2003). The dorsolateral prefrontal cortex has shown activation when participants have to name a word or series of words of their choice all beginning with a given letter or syllabi, which has been interpreted as an involvement in response selection and the internal generation of action (Spence and Frith, 1999). Interestingly, analyzing some tasks used by the researchers it became evident that they also involve the production of divergent thinking, a key component of creativity. Furthermore, damage in this area leads to a lack of spontaneous activity and produces repetitive and stereotypic responses to objects and their environment (Spence and Frith, 1999) and creativity involves spontaneity and the production of unusual and original responses to the environment. Highly creative individuals showed significantly greater activation of the right precentral gyrus (BA 6, premotor and supplementary motor cortex) which participates in the assimilation of sensory information, modulates the impulses transmitted to primary motor areas, and is involved in the learning of new motor programs and motor imagery (Malouin et al., 2003). Increased activity in this area has been observed even when subjects are only imagining complex movements in hands and fingers (Rhawn, 1996). The right precentral gyrus also can be activated by phantom-limb movements (Roux et al., 2003) and during sexual arousal (Mouras et al., 2003). The middle frontal gyrus (BA 6 and anterior prefrontal cortex BA 10) is a structure related to higher level processing of the emotional significance of complex stimuli. The middle frontal gyrus, in association with the medial frontal and anterior cingulate cortices, is a site of convergence for limbic inputs and is involved in the integration of cognition and emotion, affect, and meaning and also in the representation of the mental states of others (Berthoz et al., 2002). These areas maintain rich interconnections and have been related with the conscious experience of emotion (Lane, 1997). We suppose that higher activation in these areas could be related to the vivid conscious experience of feelings and perceptions described in highly creative individuals (Dabrowski et al., 1970, Camacho et al., 1983, Chavez and Lara, 2000). The latter combined with higher symbolic

abilities that are processed mainly in frontal lobes might enable highly creative individuals to translate their experiences into creative works.

In this study we were interested in assessing divergent thinking, a key component of creativity; therefore, we did not evaluate IQ in the participants. It has been described that IQ tests evaluate convergent thinking (Guilford, 1968). Furthermore, there is substantial evidence that creativity is essentially independent of IQ above 115 (Sternberg and O’Hara, 1999). However, in further research it would be interesting to compare the PFC involvement associated to different levels of divergent and convergent thinking.

The right frontal rectal gyrus and the left frontal orbital gyrus are other areas that presented higher CBF in highly creative individuals. These areas are intimately associated with the anterior cingulate, the amygdala, the ventral striatum, and the lateral hypothalamus and are related with emotion processing as well (Rhawn, 1996). CBF in these regions correlates inversely with depressive symptoms, and injury in these areas could result in manic-like excitement (Lane, 1997, Drevets et al., 1999). It is important to mention that several individuals experience a state phenomenologically similar to intense joy while developing creative products (Chávez, 2004). Higher CBF in these structures has also been related to complex cognitive tasks such as meditation (Newberg et al., 2001). The left inferior temporal gyrus (BA 20), which also showed higher CBF in highly creative subjects, participates in long term and complex memory, attention, processing of complex auditory and visual stimuli, and emotion (Rhawn, 1996).

It is interesting to note that alexithymia (the impairment of the ability to identify and communicate one’s emotional state) has phenomenological characteristics that are opposed to creativity. Alexithymic individuals show difficulty in describing feelings, impaired symbolization, and have a tendency to focus on external events rather than inner experiences, to be socially conforming, humorless, and experience meaningless (Pérez-Rincón, 1997), whereas highly creative individuals present highly expressive abilities, enhanced symbolization, and intense inner experience have a tendency to challenge the social status quo, to have great sense of humor, and to have multiple meaning experiences (Camacho et al., 1983, Torrance and Safter, 1999). Functional magnetic resonance imaging (fMRI) studies have shown that individuals suffering alexithymia show different cerebral activation (higher or lower depending if the emotion is positive or negative) in the right and left middle frontal gyrus, left mediofrontal cortex, and anterior cingulate when compared with healthy control individuals and when both groups were exposed to controlled emotional stimuli (Berthoz et al., 2002). Alexithymic individuals also show higher activation in left medial frontal, right inferior temporal, left superior temporal regions, left precentral gyrus, and in the cerebellum when compared to healthy control individuals during emotional autobiographic recall (Huber et al., 2002). We found these areas to be associated with creative achievement; we suppose that similitude or opposition in phenomenological characteristics might implicate that the same neural pathways are involved.

According to Arieti’s (1976) theory creativity occurs as an integration of primary and secondary processes. Interestingly in our study highly creative individuals showed greater activation in both frontal and temporal structures, whereas schizophrenic patients (who display high content of primary process) show hypofunction of the frontal cortex while temporal lobe activity is

increased, particularly left superior temporal cortex (Berman and Weinberger, 1999), suggesting abnormal interactions between these areas.

To our knowledge this is the first study probing differences in CBF between high and average creative performance involving participants socially recognized by their creative contributions to their fields. Other investigations have recruited students (Bekhtereva et al., 2001, Bekhtereva et al., 2004, Howard-Jones et al., 2005) or participants from the general population (Goel and Vartanian, 2005, Vartanian and Goel, 2007) where creativity exhibits normal distribution (Torrance, 1988, Torrance, 1990) or have compared the differences between high and low creative individuals from a given population (Martindale et al., 1984, Martindale, 1990, Carlsson et al., 2000). In addition, we used a standardized measure of creativity, the TTCT which have been proven to have high predictive validity and are the most used and cited creativity tests (Torrance, 1988, 1990, Cramond, 1999). The three creative dimension scores of in the verbal form of the TTCT (fluency, originality, and flexibility) had a significantly strong linear correlation with CBF in bilateral fronto-temporal areas and the cerebellum as well, as it was expected. In addition, it is interesting to point out that the three creativity dimensions had important overlaps with their CBF correlations. This could suggest that either a cerebral area could participate in the processing of more than two dimensions or the dimensions are components of a single broader “neuromental” process. In our findings, the three dimensions displayed a strong linear correlation with right and left middle frontal gyrus and with right rectal gyrus (BA 6 and 11). However, our results also indicate the existence of additional specific cerebral loci for specific creativity dimension processing. Both fluency and flexibility correlated with left inferior frontal gyrus. Nonetheless, fluency had a correlation with right and left inferior parietal lobule (BA 40), a multi-modal assimilation area (Rhawn, 1996), and the right postcentral gyrus, a primary sensory area (BA 1). These areas have been also related to motor imagery (Malouin et al., 2003) and sexual arousal (Mouras et al., 2003). Moreover the BA 40 is connected with all the sensory cortical areas and is involved in high order, complex, multisensory perception, integrating information from vision, touch, balance, and spatial orientation (Spence and Frith, 1999) and its relation with the speech areas in the temporal and frontal lobes gives it a critical role in communication skills (Afifi and Bergman, 2005). Left sided lesions in this area cause deficits in motor symbolism (apraxia) and the lose of the mental image of an act (Spence and Frith, 1999). As we previously mentioned, in our study the BA 40 showed significant correlations with creative fluency. This area has been associated to creative performance when composing stories using words from different semantic areas (Bekhtereva et al., 2004). Interestingly, this region was found to be 15% wider in Einstein’s brain when compared to control subjects (Afifi and Bergman, 2005). Originality had an independent correlation with the superior temporal gyrus (BA 38), which participates in complex auditory and linguistic functioning such as context processing (Rhawn, 1996) and has been related to the production of insight (Jung-Beeman et al., 2004). In addition, originality had a strong correlation with the right cerebellar tonsil, and as we previously referred the cerebellum has an important role in working memory, the modulation of ideas, language, and the processing of conceptual information when facing novelty (Vandervert et al., 2007). Even if flexibility is a clearly different construct (Torrance and Safter, 1999) it did not have additional

areas of correlation with CBF, in this regard it is important to consider that in the verbal TTCT it has been reported a stronger correlation between fluency, originality, and flexibility when compared to the figural TTCT (Chávez-Eakle et al., 2006). One explanation could be that an individual who produces a large number of alternative responses (fluency) is more likely to change from one conceptual field to another (flexibility) or to produce uncommon responses (originality). However, the three dimensions have shown different developmental curves in longitudinal studies (Torrance and Safter, 1999). Developmental curves of originality tend to be more prolonged, which means that from early childhood to late adolescence there is a gradual increase in originality scores year by year, when compared with the other two dimensions.

One fundamental characteristic of mammalian behavior is the capacity to respond to unexpected stimuli or novelty detection. Novelty is a crucial component of creativity definitions and the main criteria to score originality. Prefrontal regions play an important role in novelty generation (Ganesan et al., 2005). Electrophysiological recordings of scalp and intracranial event related potentials have shown that novel stimuli trigger a positive brain potential over central frontal regions and activate a distributed network involving prefrontal, posterior association cortex, temporal cortical regions, cingulate areas, and right and left hippocampus (Knight, 1996). Prefrontal and temporal cortexes play an important role in long-term memory and in retrieving these memories (Simons and Spiers, 2003). These areas are intimately related to the hippocampal neural circuits that maintain a template of the past; the novel stimuli diverge from this template activating neocortical circuits that anticipate and facilitate behavioral response (Knight, 1996), evaluate emotional significance, and subsequently transform the template of previous experiences.

The frontal lobes, especially the prefrontal cortex areas, had a greater development in *Homo sapiens* than in other mammals, and the underlying connectivity is greater in our species (Simons and Spiers, 2003). However, the brain of other primates, in particularly that of the apes, still remains largely unknown and it has been suggested that the cognitive specialization, which includes creative thinking, could be related to other functional aspects other than the relative volume of frontal lobes (Semendeferi et al., 1997). Cognitive flexibility and cognitive fluidity have been increasing in mammals since 100 million years ago being more apparent in hominids. This enabled social language and tool making to arise (Mithen, 1996). To consider and to study creativity precursors in other species and to explore creativity from an evolutionary point of view are relevant matters, although this certainly is beyond the scope of this paper. Creativity is a trait that has been present in the human species, regardless of the ethnicity or the cultural group. Creativity transforms culture, and culture provides the elements of the existent (for example what is considered or not as original) shaping the destiny of creative products. The brain–culture interactions are a fascinating issue; creativity involves both cultural and neuromental complex processes, therefore the research on creativity could be a promising field that would lead us to increase our understanding of these topics.

Creativity is a complex, dynamic, multi-integrative process that simultaneously involves perceptual, volitional, cognitive, and emotional processes. The higher CBF we found in specific brain regions in highly creative individuals during the performance of verbal TTCT tasks provides evidence of a specific neural network related to the creative process. As it is shown in our study, right and left fronto-temporal, parietal, and cerebellar functioning are

crucial for creative achievement. Further research will be needed to investigate specific interactions between these structures during the different stages of the creative process.

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