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Authors: Gavin D. Tempest, Rémi Radel

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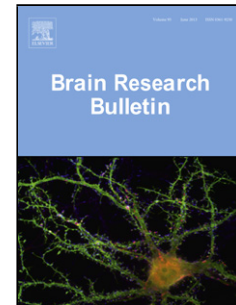
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Put on your (fNIRS) thinking cap: Frontopolar activation during augmented state creativity

Authors

Gavin D. Tempest^{1,2}, Rémi Radel¹

Institutions

¹Université Côte d'Azur, Laboratoire Motricité Humaine Expertise Sport Santé (LAMHESS), Nice, France.

²Stanford University, Center for Interdisciplinary Brain Sciences Research, Stanford, USA.

Highlights

- To 'think creatively' on demand is an augmented state of creativity
- Creativity can be indicated using the semantic distance between noun-verb pairs
- When cued to 'think creatively', semantic distance scores are higher than when uncued
- Cued and uncued responses indicate regional left frontopolar activity using fNIRS
- Use of fNIRS during augmented creativity states in naturalistic settings is supported

Abstract

Thinking creatively requires the ability to consciously augment creative insight through processes such as analogical reasoning and relational cognition. Prior work has examined augmented states of creativity using a modified verb generation task which requires brief engagement in attempts to think creatively during MRI. In this study, we employed the verb generation task to examine augmented creative states and frontopolar cortex activation in a less-constrained setting using functional near infrared spectroscopy (fNIRS). Participants (n=29) were presented with a noun and were required to think of an associated verb. In 50% of the trials, participants were instructed to ‘think creatively’ (cued condition) as opposed to stating the first or most prominent verb that came to mind (uncued condition). The task was administered in French to native speakers. Hemodynamic responses were recorded over the frontopolar cortex using fNIRS. The relatedness of the noun-verb pairs was calculated and other measures of creativity (the Alternate Uses Test, Compound Remote Associate Test and the Biographical Inventory of Creative Behaviors) were recorded. We showed that in the cued condition, semantic scores were higher (indicating more creative responses), positively associated with other measures of creativity, and changes in oxygenated hemoglobin were larger and more extensive in the left frontopolar cortex, than in the uncued condition. Our findings support the use of the verb generation task (administered in French) to augment creative states and provides further validation of the use of the task to capture creativity (i.e., processes involved in generating creative responses through distant associations). We highlight the use of fNIRS to measure associated regional changes in frontopolar cortex activity during augmented states of creativity.

Keywords: near infrared spectroscopy, cerebral cortex, cortical activity

Introduction

In an increasingly competitive society, the ability to think creatively is a key asset for innovation and success. The process of creativity involves connecting and synthesizing information through processes such as relational cognition and analogical reasoning (Holyoak & Thagard, 1995). Relational cognition and analogical reasoning are not required for creative cognition, yet they contribute to the processes involved in creative thinking. In addition, relational cognition is distinguishable from, but incorporates, semantic processes employed in analogical reasoning (Green et al., 2017; Green, Kraemer, Fugelsang, Gray, & Dunbar, 2010), integrating near and distant targets to form new connections resulting in novel ‘creative’ thoughts and insights (Holyoak & Thagard, 1995). The ability to ‘think creatively’ on demand, has been described as an augmented state of creativity (Prabhakaran, Green, & Gray (2014)). Capturing augmented creative states is challenging as it requires turning ‘on’ and ‘off’ responses without explicitly knowing the processes involved, or interfering with or inhibiting the outcome. To examine neural correlates of creativity, Prabhakaran, Green, & Gray (2014) developed a paradigm to induce states of relational creative responses using a modification of the classic verb-generation task (Petersen, Fox, Posner, Mintun, & Raichle, 1989). In real-time, participants were required to generate a verb related to a given noun. The open-ended responses (i.e. verb generation) were quantitatively measured using latent semantic analysis providing the semantic distance between noun-verb pairs (Landauer, Foltz, Laham, & Laham, 1998). When participants were instructed to *think creatively*, semantic distance scores were higher (meaning the verb was less related to the noun). Semantic distance scores accurately reflect semantic proximity between a pair of words and represent analogical reasoning (Green et al., 2010). Although not a direct measure of

creativity, but rather a process involved in generating creative responses, semantic distance is positively correlated with primary measures of creativity (verbal, non-verbal and achievement-based) such as divergent thinking (Prabhakaran et al., 2014). In a follow-up study, Green, Cohen, Raab, Yedibalian, & Gray, (2015) administered the verb generation task during functional magnetic resonance imaging (fMRI). The authors showed that repeatedly engaging (i.e. cued) versus disengaging (i.e. uncued) in brief augmented creative states (during standard noun-verb generation) led to regional changes in cortical activity and connectivity of the frontopolar cortex. The authors concluded that the frontopolar regions of the brain (specifically, left inferior frontopolar cortex) contributes to the capacity of an individual to deliberately become a more 'distant thinker' during augmented creative states.

The modified verb generation task has primarily been studied by Green and colleagues (Green et al., 2017, 2015; Prabhakaran et al., 2014; Weinberger, Iyer, & Green, 2016) to measure neural correlates of creativity using MRI. An advantage of the verb generation task is that it provides a reliable measure of creative abilities (through semantic distance associations) and its administration is compatible with event-related neuroimaging study designs requiring multiple trials (Fink et al., 2009). Yet, the verb generation task has not been administered using other neuroimaging methods and outside of the constraints of the MRI environment. In addition, the task has only been administered in the English Language to native speakers and the findings (verb responses and neural correlates) have not been replicated using another language. In our study, we aimed to (i) independently investigate creativity using the modified verb generation task (cued vs. uncued conditions) administered in French, (ii) assess the validity of task responses with additional measures of creativity, and (iii) determine the utility of functional near infrared spectroscopy (fNIRS) to measure changes in the frontopolar cortex during augmented

states of creativity. Functional NIRS is a non-invasive neuroimaging technique that uses near infrared light to measure changes in oxygenated (HbO) and deoxygenated hemoglobin (HbR) concentration in regions of the cerebral cortex. Changes in the hemodynamic response are correlated with the blood-oxygen-level-dependent (BOLD) signal using fMRI and serve as a proxy for cortical activation (Cui, Bray, Bryant, Glover, & Reiss, 2011). Functional NIRS can be used in naturalistic settings (e.g., sat upright in a chair) that are less restrictive and anxiety provoking compared to the environment required for fMRI, which could potentially dampen creative responses. Therefore, the combined use of the verb generation task (developed by Prabhakaran et al., 2014) and fNIRS offers the advantage of being able to induce and assess augmented creative states in different environments. We expected that in the cued condition (whereby participants are instructed to think creatively) semantic distance is higher and positively correlates with additional measures of creativity (capturing divergent thinking and creativity achievement), and cortical activity (i.e. changes in the hemodynamic response) is larger in frontopolar regions of the brain (measured using fNIRS), than in the uncued condition.

Methods

Participants

Twenty-nine native French speakers (20 male, age, $M=22.9 \pm 3.5$ years, height $M=174.9 \pm 10.9$ cm, weight, $M=68.9 \pm 11.9$ kg) were recruited from Université Côte d'Azur. Prior to participation, the volunteers signed an informed consent form approved by the University Ethics Committee and received course credits upon completion of the study. Participants completed the Alternate Uses Task (AUT; Guilford, 1967), Compound Remote Associates Test (CRAT; Bowden & Jung-Beeman, 2003) and the Biographical Inventory of Creative Behaviors (BICB;

Batey, 2007). Subsequently, the participants completed the (un)cued conditions of verb generation task during concurrent recording of fNIRS signals (approx. 15 minutes).

Measures

Alternate Uses Test. The AUT (Guilford, 1967) indicates divergent thinking whereby the participant is instructed to list all of the possible uses they can think of for a specific item. In our study, three items (shoe, bucket, newspaper) were presented to the participants. The word representing each item was displayed for two minutes on a computer screen. During this time, participants were instructed to write down all of the possible uses they could think of for the item. Four sub-categories were recorded. Fluency, the number of alternate uses per item.

Originality, how common the use was reported within the study sample. Each response was compared to the total amount of responses from all of the subjects. Responses that were given by only 5% of the group counted as unusual (1 point) and responses given by only 1% of them counted as unique (2 points). This score was then divided by the fluency score to represent the average originality level of an idea. Flexibility, the number of different categories used.

Elaboration, a rating of the level of detail provided (from 0 to 2). This score was then divided by the fluency score to represent the average elaboration level for each response. Two independent raters scored participants' responses. The inter-rater agreement was satisfactory (Krippendorff's alphas = 1 for fluency, 0.92 for originality, 0.79 for flexibility, and 0.80 for elaboration).

Compound Remote Associate Test. The CRAT (Bowden & Beeman, 2003) was used to determine creative convergent thinking and problem solving. In this test, three unrelated words were presented on a computer screen and the participant was asked to find a common word that is associated with each of the three words to form a compound word (e.g., the word "stone" is the solution of "age/mile/sand" as the compounds "stone-age", "milestone", and "sandstone" can

be formed). Following two examples, participants had to solve 20 problems. For each trial, the set of three words was displayed on the screen for 30s. At any moment during this time limit, participants pressed a button to indicate that they had an answer. This triggered a 3s recording window where participants provided their responses vocally. Responses were later transcribed and accuracy and response time were analyzed.

Biographical Inventory of Creative Behaviors. A self-reported measure of creativity was used to assess creative personality trait. The BICB (Batey, 2007; Batey & Furnham, 2008) was used for this purpose. The BICB includes a list of 34 behaviors and the participant is required to answer if they engaged in such behavior in the last 12 months using a *Yes* or *No* forced choice response format. The list of behaviors covers a broad range of creative activities (e.g., arts, crafts, writing, software or game development). The list of behaviors was translated into French for our study. A recent review of creativity measures provides good support for the validity of the BICB noting a solid factor structure and internal consistency (Silvia, Wigert, Reiter-Palmon, & Kaufman, 2012).

Verb generation task. The verb generation task (described and validated by Prabhakaran et al., 2014) suitable for neuroimaging study designs (Green et al., 2015) was used to assess augmented state creativity. Singular nouns ($n=300$) in French were selected based on word length (3-7 letters) and frequency (30-1300 per million) from an online (movie) database (<http://www.lexique.org>). A univariate analysis confirmed that the nouns employed in the uncued ($n=30$) and cued ($n=30$) conditions were equal for word length (uncued, $M = 5.1$, $SD = 1.2$; cued, $M = 5.3$, $SD = 1.2$; $F(1,58) = .171$, $p=.680$) and frequency (uncued, $M = 131.0$, $SD = 186.5$; cued, $M = 113.6$, $SD = 134.9$; $F(1,58) = .555$, $p=.459$). Nouns were presented on a computer screen and participants were required to think of a verb related to the noun (duration 8s) and then

prompted to state the verb aloud. In the uncued condition, depicted by a noun in purple font, participants had to state the first verb that came to mind. In the cued condition, depicted by a noun in green font, participants were instructed to *think creatively* (i.e. a verb that is less obvious). There were 60 trials (30 uncued and 30 cued) alternating randomly between conditions every two trials. The task was conducted using the E-prime software (E-Prime 2.074, PST, Sharpsburg, USA) and vocal responses to the tasks were recorded using a microphone. An inter-trial interval of 4-6 seconds was applied. The verbal responses were transcribed offline. Verbs were screened and duplicates and slang words were removed. The semantic distance between the noun-verb pairs was indexed by latent semantic analysis using topic space “Francais-total (300 factors)” and term-to-term (pairwise) comparison (Landauer, Foltz, & Laham, 1998; <http://lsa.colorado.edu>). Latent semantic analysis is a measure of the semantic relatedness of word pairs calculated by subtracting the index of semantic similarity for each pair from one. In our study, a high score indicates that the verb is less related to the noun and a more creative response. Prior to the analysis, non-verbs or verbs not included in the topic database were excluded. This method has been validated and used in previous studies examining creativity (for details see Green et al., 2014; Prabhakaran et al., 2014).

Functional NIRS

A continuous-wave multi-channel NIRS (Oxymon Mk III, Artinis Medical Systems, Zetten, The Netherlands) was used to measure the hemodynamic response over bilateral frontopolar regions during the verb generation task. A headband containing 12 optodes (six light receivers and six detectors, the lowest and most central optodes aligned with FpZ) measuring 16 channels was placed on the participants head. The source-detector distance was fixed at 35 mm to ensure reasonable sensitivity to grey matter (Strangman, Zhang, & Li, 2014), except for two pairs over

the midline. These optode pairs had a short source-detector distance fixed at 10 mm and were used as reference channels to control for the influence of extra-cortical noise such as skin blood flow upon the NIRS signal (Gagnon et al., 2011; Scarpa et al., 2013). The head band included an accelerometer (ADXL335, Analog Devices, Norwood, USA) to measure head movement time-aligned with the NIRS data acquisition. The channel locations are shown in Figure 1. Data were sampled at 25 Hz and acquired with Oxysoft (version 3.0.43, Artinis Medical Systems, Zetten, the Netherlands).

Figure 1: Location of the source and detector optodes and channels

The fNIRS data processing was performed using Homer2 NIRS processing package (Huppert, Diamond, Franceschini, & Boas, 2009) based in MATLAB (2016b, MathWorks Inc). Raw optical data were converted to changes in optical density units, noisy channels were removed using the `enPruneChannels` function, and motion artefacts were identified and excluded using the `hmrMotionArtifactByChannel` function. The data were further motion corrected using wavelet motion correction and a band-pass filter (cut-off frequencies of 0.01 Hz and 0.5 Hz) was applied. Data were converted to HbO and HbR concentrations using the modified Beer-Lambert equation (see Brigadoi et al., 2014 for full details). Following pre-processing, a Gaussian based general linear model was performed to quantify the changes in HbO and HbR. Signals from the two short separation channels and the accelerometer data were included in the model as regressors. At the participant level, beta estimates per channel and condition (uncued, cued) were calculated.

Statistical analysis

Verb generation task. The semantic distance scores were positively skewed therefore a general linear mixed model (GLMM) suitable for a gamma function was employed. Linear mixed models (LMM) offer a higher level of statistical power compared to traditional repeated measures analysis of variance (Ma, Mazumdar, & Memtsoudis, 2013) and are recommended to prevent type-1 error (Boisgontier & Cheval, 2016). The noun was included as a factor in the model and a random intercept effect structured by subjects was included to control for the non-independence of data. A fixed factor of Condition (uncued, cued) was included.

Functional NIRS. The primary dependent variables were beta estimates for HbO and HbR during the uncued and cued conditions of the verb generation task. Task-related cortical activation is defined as a significant increase in HbO and/or a decrease in HbR. To identify task-related brain activation during the uncued and cued conditions, a permutation-test was conducted using MATLAB toolbox (Mensen & Khatami, 2013). The beta estimates for each channel per condition were entered into the mass-statistical testing procedure ($p < 0.05$, corrected for multiple comparisons per condition). In addition, the contrast (cued > uncued) was calculated and subject to the same statistical testing. Finally, Pearson correlations ($p < 0.05$, uncorrected) were conducted between channels showing a significant change in HbO or HbR and creativity measures (uncued and cued semantic distance [unadjusted], AUT, CRAT and BICB scores).

Results

The means and standard deviations of the creativity measures are shown in Table 1.

Verb generation task

A main effect of Condition for the semantic distance scores indicated a higher score in the cued than in the uncued condition, $F(1,1377) = 6.111, p=.014$ (see Figure 2).

Functional NIRS

In the uncued condition, significant activation (HbO) was observed in the left frontopolar region (channel 13, $t=3.53, p=.01$). In the cued condition, when instructed to “think creatively”, more extensive activation (HbO) was observed in the left frontopolar region (channel 10, $t=3.10, p=.041$, and channel 13, $t=3.06, p=.044$). The contrast between the two conditions (cued > uncued) indicated significant activation (HbO) in the left frontopolar region (channel 10, $t=4.01, p=.01$; see Figure 3). No significant main effect of condition was shown for HbR ($p>.05$).

Association between fNIRS, semantic distance and creativity measures

No association between HbO (unadjusted means) in significant channels and semantic distance scores were observed ($p>.05$). However, significant positive associations between semantic distance scores (cued and uncued conditions) and fluency and flexibility of the alternate uses task were recorded. In the cued condition only, a significant positive association between semantic distance scores and the BICB was shown (see Table 2).

Discussion

The present study examined a verb-generation task to induce augmented states of creativity and cortical activity in the frontopolar region of the brain using fNIRS. The main findings show that (1) during augmented states of creativity (when instructed to think creatively; cued trials), participants generated verbs more semantically distant from the nouns presented, than when they were not instructed to think creatively (uncued trials); (2) the semantic distance scores from the

verb-generation task were positively correlated with other measures of creativity (fluency and flexibility in the AUT and total scores of the BICB); and (3) augmented states of creativity led to regional differences (indicated by increased HbO) in left frontopolar regions measured using fNIRS.

The difference between cued (higher) and uncued (lower) semantic distance scores was similar to prior studies employing a similar task (Green et al., 2017, 2015; Prabhakaran et al., 2014; Weinberger et al., 2016). When participants were instructed to think creatively, the verb-noun pairs were less related, indicating more creativity (through the ability to generate distant associations). The findings of this study support and extend previous work. For the first time, this study employed noun-verb pairs from a topic space other than English (i.e., Francais-total) indicating cross-cultural validity.

The semantic distance scores (uncued and cued) were positively correlated with fluency and flexibility of the AUT. Responses to the AUT involve elements of practical and creative thinking, both contributing to fluency and flexibility in response to the task. Given that both the uncued and cued conditions were associated with the AUT, the AUT was not sufficiently sensitive to distinguish between 'off' and 'on' (augmented) states during the verb generation task. Given that the primary purpose of the AUT is to measure creative thinking and the verb generation task is to measure semantic distance (associated with creative thinking), the positive association between the AUT and verb generation task may be due to more general processes involved in the semantic search of a noun. However, the positive, moderate effect sizes shown between the verb generation task and divergent thinking assessed using the Torrance tests (as shown elsewhere; Green et al., 2015) suggest that the measures tap into overlapping processes involved in creative thought. The verb-generation task was not associated with the CRAT, which

may be unsurprising given that the CRAT is a measure of convergent, as opposed to divergent thinking, and does not largely involve semantic relations (see Cortes, Weinberger, Daker, & Green, 2019).

No associations between the contrast of conditions (cued minus uncued semantic distance scores) and creativity measures were shown. In our study, the most robust index of creativity was in the cued condition. The strongest association was shown between semantic distance in the cued condition (only) and total BICB scores. The BCIB assesses creative achievements or outcomes (such as writing a short story, engaging in research or composing music), therefore the positive association with the verb generation task indicates that the ability to think distantly is associated with a higher level of creative achievement. In this study, only the total score was shown to be significantly associated with semantic distance; individual items of the BCIB were not examined which may provide more sensitivity to understanding to specific types of creative achievement. For example, Prabhakaran et al. (2014) similarly showed a positive correlation between responses in the cued condition (only) and responses to the Creativity Achievement Questionnaire, specifically in science and visual art domains (Carson et al., 2005). On the whole, our results provide further support and validity of the verb generation task, particularly when responses are cued, to appropriately measure semantically different verb-noun pairs associated with other validated creativity measures.

The use of fNIRS to measure augmented creativity states using the verb generation task is novel. Cortical activation using fNIRS is characterized by an increase in HbO and/or decrease in HbR (Obrig & Villringer, 2003). The findings indicate uniquely activated regions of the left frontopolar cortex during the cued and uncued conditions (indicated by HbO). Activation in the frontopolar cortex during the cued condition was more extensive than in the uncued condition (a

total of two significantly activated channels vs. one). In our study, we attribute more extensive activation in the cued condition as an increase in creative thought or at least an increase in cortical recruitment required to think more creatively. Task-evoked activation of the frontopolar cortex using fNIRS is consistent with the results of comparable semantic processing tasks for determining creativity using fMRI (Green et al., 2015; Howard-Jones, Blakemore, Samuel, Summers, & Claxton, 2005; Seger, Desmond, Glover, & Gabrieli, 2000). Furthermore, activation in the left frontopolar cortex is associated with multiple verbal tasks of creative-idea generation (see Fink et al., 2009). In a similar verb-generation task to the present study, Seger, Desmond, Glover, & Gabrieli (2000) showed significant activation of the left inferior prefrontal region when generating non-novel verbs and in the left middle frontal gyrus when generating unusual verbs. In addition, the authors showed activation in the right middle frontal gyrus when generating unusual verbs. We also showed activation in the right hemisphere in the cued condition, although this did not survive multiple corrections for significance testing (channel 2, $p < .05$, see Figure 3).

Limitations of the current task include 1) the constraint level of the nouns administered, and 2) difficulty in distinguishing cortical activity associated with creativity versus mental effort. First, the constraint level of the noun prompts (indicating the association of the noun to highly prepotent verb responses; see Green et al., 2015) was not considered in this study. Future studies administering the task should control for the constraint level between task conditions (e.g., cued vs. uncued) to reduce the potential confounding effects it may have upon verb selection. Second, it is unclear if cortical activity shown during the task is explicitly associated with creativity processes or mental effort, however the latter is associated with more lateral than medial prefrontal regions (Duncan & Owen, 2000). In the current task participants had eight seconds to

think of a verb associated with the noun. In the uncued condition, after participants had selected a verb it is assumed, they stopped searching for a response. Whereas, in the cued condition, participants may have experienced longer and more intense rumination (for the full 8 s period). This could be argued as a creative effort – collecting and synthesizing information to produce a creative response (Holyoak & Thagard, 1995). We did not record the time from presentation of the noun to the (verb) response as in previous studies (Prabhakaran et al., 2014). Cortical activation during the uncued condition may be attributed to mental effort to perform the task as activation of the left frontopolar cortex is broadly attributed to cognitive demand, and is associated with intelligence (Duncan & Owen, 2000). In our study, more extensive activation of the left frontopolar cortex during the cued condition may reflect increased cognitive demand or increased task complexity. Never-the-less, we have shown that changes in frontopolar cortex activation during the verb generation task can be measured and differentiated (uncued vs. cued noun-verb pairs) using fNIRS in support of prior evidence indicating cortical correlates of creativity. We acknowledge the gender imbalance of the cohort examined and that we did not examine the effects of gender upon the main findings.

We attributed activation of frontopolar regions using only changes in HbO. The change in HbO concentration is three-fold that of HbR, providing a greater signal to noise ratio, and is the most common parameter reported using fNIRS (Obrig & Villringer, 2003). Significant task-evoked changes in HbR are not commonly found or reported in fNIRS studies. Although we examined HbR, this parameter failed to show significance. The development of universal standards of signal processing of fNIRS data (like fMRI) are emerging, including the increased use of common processing packages such as Homer2, improving the analysis and interpretation of fNIRS data. However, an advantage of fNIRS, in comparison to other neuroimaging techniques,

is that it can be used in naturalistic settings. For example, in attempts to measure creativity, fNIRS may be applied in an environment more encouraging of creativity, during more dynamic tasks or tasks involving multiple-individuals.

In conclusion, our findings support the use of the verb generation task (in French) to augment creative states and provides further validation of the use of the task to capture creativity (i.e., processes involved in generating creative responses through distant associations). This work highlights associated neural correlates of creative responses using fNIRS. The use and portability of fNIRS makes it a suitable tool to measure brain activity associated with aspects of creativity in less constrained and naturalistic environments or during less-stationary activities (e.g., sitting upright or moving around), which could help advance this field of research.

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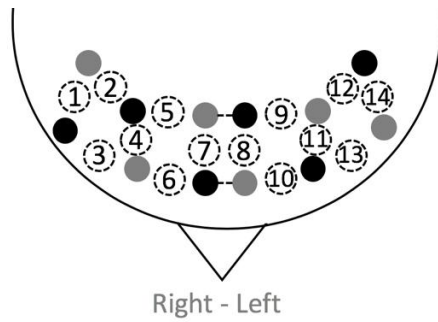


Figure 1: Birdseye view of the locations of the source (grey circles) and detector (black circles) optodes and channels (1-14) over the right and left frontal lobe. Two extra channels with a short separation distance (1cm) placed across the midline were included (black dotted lines).

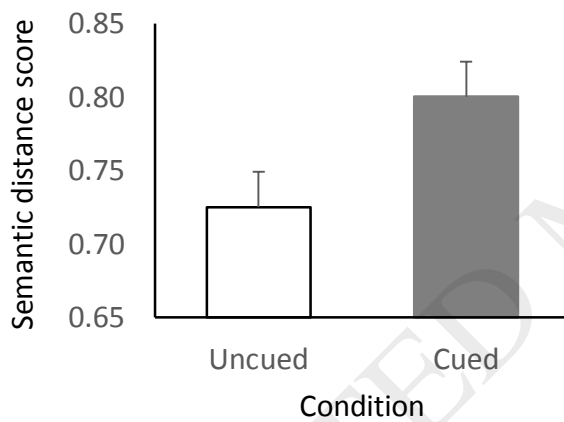


Figure 2: Semantic distance scores per uncued and cued conditions (M and SEM; $p < .05$).

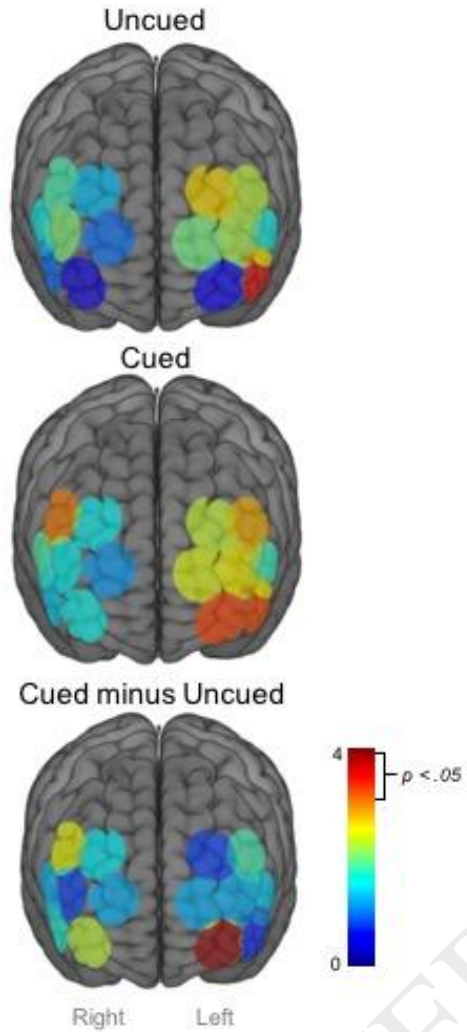


Figure 3: Task-related activation (increase in oxygenated hemoglobin; HbO; t-values) of the right and left frontopolar cortices during the verb generation task. Significant activation (increase in HbO) in the left frontopolar region(s) per condition (Uncued, Cued and contrast (Cued minus Uncued)) ($p < .05$).

Table 1: Measures of creativity

Measure	Mean	SD	Range
Alternate Uses Task			
Fluency	5.50	1.59	(1.33-9)
Flexibility	3.30	1.35	(1.0-7.0)
Originality	.29	.28	(0-1.17)
Elaboration	.32	.28	(0-1.14)

Compound Remote**Associate Task**

Correct (%)	62.7	20.6	(27.3-100)
Reaction time (s)	12.31	3.28	(5.94-19.20)

BICB

Total score	11.96	5.29	(4-24)
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Biographical Inventory of Creative Behaviors (BICB).

Table 2: Associations between creativity measures

Measure	Verb Generation Task (semantic distance scores)		
	Uncued	Cued	Contrast (Uncued-Cued)
Alternate Uses Task			
Fluency	*.449	** .524	.096
Flexibility	*.406	*.468	.078
Originality	.214	.322	.149
Elaboration	-.054	-.044	.015
Remote Associates Test			
Correct (%)	.035	-.086	-.174
Reaction time (s)	-.012	.175	.267
BICB			
Total score	.360	** .609	.346

Biographical Inventory of Creative Behaviors (BICB). * $p < .05$, ** $p < .01$.