ORIGINAL ARTICLE

Creativity Stimulation by Idea Generation: A Resting-state fMRI Study on Effective Connectivity

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ABSTRAK

Kajian ke atas kreativiti telah berkembang semenjak sedekad yang lalu. Walau bagaimanapun hanya sedikit diketahui mengenai kesalinghubungan berkesan (EC) di antara kawasan jaringan mod lalai (DMN) selepas rangsangan kreativiti. Kajian ini bermatlamat untuk mengukur kesalinghubungan otak yang diaruh oleh rangsangan kreativti dan mengaitkannya dengan skor kreativiti. Seramai 50 peserta direkrut dalam kajian ini dan dibahagikan kepada kumpulan kawalan dan uji kaji. Kumpulan uji kaji menjalani sesi rangsangan kreativiti selama dua hari. Imbasan pengimejan resonans magnet kefungsian keadaan rehat (rs-fMRI) dijalankan ke atas semua peserta kajian selepas sesi rangsangan. Data rs-fMRI dianalisis menggunakan pemetaan statistik berparameter dan pemodelan sebab dan akibat dinamik spektrum. Satu model bersalinghubungan penuh yang mengandungi girus angular (AG), korteks pre-fontal tengah (mPFC) dan pre-kuneus (PCU) sebagai kawasan yang menjadi keutamaan (ROI) dipadankan terhadap data setiap peserta kajian. Model tersebut menjalani pemurataan parameter Bayesian untuk menentukan purata kekuatan kesalinghubungan di antara ROI. Terdapat peningkatan skor kreativiti bagi kumpulan uji kaji dalam aspek kelancaran (p=0.018)

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dan keanjalan (p=0.048) kecuali keaslian (p>0.05). Tiada perbezaan dalam pengaktifan otak di antara dua kumpulan peserta kajian. Kesemua EC di antara ROI dalam hemisfera kiri dan kanan untuk kedua-dua kumpulan kajian adalah bererti (P>0.9). Kesimetrian jaringan EC bagi kumpulan uji kaji dapat diperhatikan dengan kesalinghubungan PCU→PCU, PCU→mPFC dan AG→PCU manakala ia lebih bererti dalam kumpulan uji kaji. Penemuan ini mencadangkan bahawa rangsangan kreativiti selama dua hari mampu menyebabkan perubahan dalam skor kreativiti dan jaringan kesalinghubungan tetapi tidak memberi keputusan yang meyakinkan dalam konteks perbezaan dalam pengaktifan otak.

Kata kunci: Jaringan mod lalai; keadaan rehat; kesalinghubungan berkesan; kreativiti; pemodelan sebab dan akibat dinamik spectrum

ABSTRACT

Studies on creativity have bloomed in the past decade. However, little is known about the effective connectivity (EC) between default-mode network (DMN) regions after creativity stimulation. This study aimed to measure the brain connectivity induced by creativity stimulation and to relate it with creativity score. A total of 50 participants were recruited and assigned to control and experimental groups. The experimental participants underwent a two-day creativity stimulation session. Resting state functional magnetic resonance imaging (rs-fMRI) scans were performed on all participants after the session. The rs-fMRI data were analysed using statistical parametric mapping and spectral dynamic causal modelling. A fully connected model comprising angular gyrus (AG), medial pre-frontal cortex (mPFC) and pre-cuneus (PCU) as regions-of-interest (ROIs) was fitted for every participant's data. The model underwent Bayesian parameter averaging to determine the average strength of connection between ROIs. There was a significant increase in creativity score for the experimental group in the aspect of fluency (p=0.018) and flexibility (p=0.048) except in originality (p>0.05). No difference in brain activation was observed between groups. All the EC between ROIs in the left and right hemisphere for both groups were significant (P>0.9). Symmetrical EC networks for the experimental group were observed with left hemisphere PCU→PCU, PCU→mPFC and AG→PCU connections which were more significant in the experimental group. These findings suggested that creativity stimulation as short as two days was able to evoke changes in creativity score and network connectivity but insufficient to cause convincing differences in the brain activation.

Keywords: Creativity; default mode network; effective connectivity; resting state; spectral dynamic causal modelling

INTRODUCTION

Divergent thinking is defined as the ability for the mind to generate multiple possible solutions to a single problem (Abraham 2016). For the past decade, many studies have been conducted in the fields of cognitive neuroscience, establishing core nodes in different domains of creativity (Abdul Hamid et al. 2019; Beaty et al. 2016; Cousijn et al. 2014). For instance, divergent thinking seems to be associated with activation in the central, temporal and parietal regions of the brain (Abdul Hamid et al. 2019). The study of divergent thinking mainly revolves around three main characteristics, which are fluency - retrieval of associates from memory; flexibility - ability to switch broad semantic categories; and originality - novelty of the ideas being produced (Beaty et al. 2014). These three domains encompass the extraction and combination of knowledge or ideas to generate multiple solutions, which is what creativity is all about (Runco & Acar 2012).

Divergent thinking is governed by the ability to; (i) forge associations between distinct memory representations; and (ii) execute functions that act on these associations. The associative processing or linking of ideas is crucial to generate potential solutions for a given problem (Benedek et al. 2012), in which at the neuronal level, this episodic associative process spreads through the semantic networks and is independent of the cognitive control (Mednick 1962). In terms of executive processing, recent evidence supports that higher executive control is positively associated with creative abilities (Beaty et al. 2015; Beaty et al. 2016; Gilhooly et al. 2007) and executive switching have been shown to have temporal advantage in divergent thinking, generating novel and original ideas at a faster rate (Nusbaum & Silvia 2011).

Findings of these two processes indicate that creative cognition involves a 'dual process' model that accounts for the interaction between associative and executive processes in the generation of novel ideas, that can be seen in divergent thinking (Allen & Thomas 2011; Ellamil et al. 2012; Mok 2014). Evolution of new techniques in neuroscientific methods, especially in functional magnetic resonance imaging (fMRI) and data analysis have succeeded to uncover patterns of neural activity across multiple brain regions during performance of creative tasks (Abdul Hamid et al. 2019). Three large-scale brain systems have been conclusively studied to interact dynamically during creative task performances which are default mode network (DMN), executive control network (ECN) and salience network (Beaty et al. 2018). Based on the dual-process model of creative cognition, DMN supports idea generation, while ECN supports idea evaluation (Beaty et al. 2016; Jung et al. 2013). On the other hand, salience network facilitates the dynamic transitions between the previously mentioned two network systems (Beaty et al. 2018) while contributing to the detection of behaviourally relevant stimulation.

Of all the three brain networks above, DMN was found to be the most prominently associated network with divergent thinking (Beaty et al. 2015). The core nodes of DMN comprises of the posterior cingulate cortices (PCC) and precuneus (PCU), the medial prefrontal cortices (mPFC) and bilateral inferior parietal lobules (IPL), along with the relevant areas for memory processing, which are medial temporal gyrus (MTG) and medial temporal lobe (MTL) (Binder et al. 2009; Buckner et al. 2008). DMN can be regarded as the inward-thinking brain network, which has been consistently shown to activate in the absence of external task stimulation (Buckner & Carroll 2007) and is related to mind-wandering, internal mentation and unconstrained thinking (Shapira-Lichter et al. 2013). A number of findings have correlated DMN with creative abilities. For instance, Wei et al. (2014) reported positive correlation between fluency and flexibility scores, with resting state functional connectivity between mPFC and MTG. High flexibility scores were also related to high cerebral blood flow in the left inferior frontal gyrus (IFG), right middle frontal gyrus (MFG) and right orbitofrontal areas (Chávez-Eakle et al. 2007). In terms of originality, enhanced scores after training were observed with enhancement in resting state functional connectivity between mPFC and MTG (Wei et al. 2014) along with enhanced activity in PCC, PCU, right MTG and right IPL (Fink et al. 2010). In summary, divergent thinking is represented by enhanced activity and connectivity in DMN and memory area, in which coupled with inhibition of irrelevant or common responses, contribute to the production of unusual ideas.

Most studies on default mode network and creativity reported on functional connectivity between the core regions, which reflects the temporal correlations between the brain regions. However, the correlation parameters are unable to represent the causal influence of one neural system over another i.e. effective connectivity (EC). EC between the regions of DMN has been mostly studied in a single population but rarely across groups. Although the signal from the resting brain is considered as low frequency fluctuations (LFF), significant difference in the strength of intrinsic connectivity between groups or across measurement can still be observed as shown in the studies on DMN in auditory working memory (Othman et al. 2019) and clinical areas (Li et al. 2017; Zhao et al. 2018). The dynamic causal modeling (DCM) uses the fMRI time series and explicitly models the neuronal dynamics according to the underlying EC, in which DCM has been proven to be a consistent and explanatory approach (David et al. 2008; Friston 2009). DCM treats the brain as a black box which receives input and produces output. For task-related responses, this explanation is met due to having a stimulus-driven input that elicits the causal influence of a neural system over another. However, to study resting state network, the stochastic modelling seems plausible, but one can dispute that the spontaneous mental state and fMRI signals during rest are not just random noise. In conjunction with this notion, spectral DCM (sp-DCM) was introduced (Friston et al. 2014). A sp-

DCM is based on a generative model of cross spectra between regional brain signals and uses a power law function in the spectral domain to model both random and endogenous neural fluctuation (Almgren et al. 2018). In contrast to the traditional stochastic DCM, sp-DCM has lower computation complexity because of its feature of fitting spectral second order data, as compared to the fitting of first order time series data in stochastic DCM (Li et al. 2011).

In the present study, it is hypothesised that the EC between nodes of DMN changes due to the creativity stimulation. Thus, the increase in the magnitude of the EC between these cortical nodes due to creativity stimulation might disclose new information that can be used to explain the related processes caused by creativity stimulation.

MATERIALS AND METHODS

Participants

A total of 50 students were conveniently recruited from the Faculty of Medicine of a public university in Malaysia. All of them were physically and mentally healthy with no reported history of neurological or psychiatric disorders. They also had no history of surgeries involving metallic implantation, making them eligible for rs-fMRI scans. All participants were explained the research details and had understood and voluntarily participated in the study after the informed consent was given. This study had been approved by the institutional ethics committee (IEC) of the university (reference number: PPI/111/8/JEP-2016-307). Among the 50 participants, 26 were randomly assigned into the control group (13 females), while the remaining 24 were in the experimental group (19 females). To minimise the variability of baseline data, the participants from these two groups were matched in terms of their age and were from the same cohort of 2nd year enrolment of the same bachelor program.

Creativity Stimulation Training

The experimental participants underwent creativity stimulation training. The two-day training delivered activities using the alternative use task (AUT), in which the participants were taught to maximise the generation of appropriate but unusual alternative uses of common objects (Azmi et al. 2018). The content validity index of the tools employed in the training was 0.83 which was feasible to be used. The techniques were being taught included brainstorming, imagination and Cognitive Research Trust (CoRT) 1 and CoRT 4 tools that were adapted from de Bono CoRT Thinking Program (de Bono 2000). These tools included Other People's View (OPV), Consider All Factors (CAF), Plus, Minus, Interesting (PMI), Alternative Possibilities and Choices (APC) and Yes Po No methods. The training was conducted approximately 6 hours per day, with a 10 minutes break after each activity. The objects used in the creativity stimulation training were different from the objects used in the cognitive assessment (Abdul Hamid et al. 2019). All experimental participants attended the training without absence. On the other hand, the control participants were void of any creativity stimulation training.

Cognitive Assessment

Both groups underwent a cognitive assessment two weeks after creativity stimulation training for the experimental group. The assessment used an adapted version of AUT (Guilford 1967) on the participants to quantify their respective divergent thinking skills in three domains which were fluency, flexibility and originality. Participants were instructed to generate as many appropriate alternative and unusual uses of six common daily objects as possible, which were *shoe*, *button*, *key*, *pencil*, *automobile*, *tire* and *spectacles*. For an individual participant, the number of answers generated reflected the ideational fluency, the number of groups of answers under the same category reflected the cognitive flexibility and the answers constituting less than 1% of the whole number of answers by all participants reflected the originality. In terms of scoring scheme, fluency scores were calculated by 1 mark for each answer, flexibility scores were calculated by 2 marks for each category presented and originality scores were calculated by 2 marks for each unique useful answer generated. The duration to complete the cognitive assessment was limited to 30 minutes per participant. Independent *t*-test was done to compare mean behavioural score between both groups of participants ($p = 0.05$; 95% confidence interval (CI))

rs-fMRI Scans

All participants underwent rs-fMRI scans which started two weeks after creativity stimulation training. Due to the availability of only one 3-T MRI machine, the scans on all participants can only be completed in the interval of four weeks. The scans were conducted using a 3-T MRI scanner (Siemens Magnetom Verio, USA) in the Universiti Kebangsaan Malaysia Medical Centre (UKMMC). A fixation '+' sign was placed to be viewed by the participants during the resting state scan. The imaging protocol used gradient echo-echo planar imaging (GRE-EPI) sequence to acquire functional T2* images with the following parameters: echo time (TE) = 29 ms, repetition time (TR) = 2 s, flip angle (α) = 75°, slice thickness = 3.5 mm, slice gap = 1.05 mm, field of view (FOV) = 240 mm, matrix size = 64 x 64, voxel size = 3.75 x 3.75 x 4.55 mm and number of scans = 200, with the total imaging time of 9 minutes and 33 seconds (Abbott et al. 2013). During the scan, participants were instructed to empty their mind and passively focus on the fixation without thinking of anything. Participants were also told to stay awake and not to dream or mind-wander during the scan.

rs-fMRI Data Analysis

The fMRI data were analysed using Matlab 9.2.0 (R2018b) (Mathworks Inc. MA, USA) and statistical parametric mapping (SPM) (Functional Imaging Laboratory (FIL), the Wellcome Trust Centre for NeuroImaging, in the Institute of Neurology at University College London (UCL), UK.) version 12 (SPM12). The first 5 scans were discarded to minimise the magnetic saturation effect. The 195 T2* functional images underwent slice timing correction, followed by realignment to the first slice using 6-parameter affine transformation in translational (*x*, *y* and *z*) and rotational (pitch, roll and yaw) direction to undo the effects of participant's movements. The data were then subsequently normalised to the MNI stereotaxic space template implemented in SPM12 using a 12-parameter affine transformation, before undergoing smoothing via 8 mm full-width-at-half-maximum (FWHM) isotropic Gaussian kernel.

During the rest, the human brain had been found to display low frequency fluctuations (LFF) that range from 0.01 to 0.008 Hz (Cordes et al. 2001) which is associated with state of consciousness. To model the signal, a combination of sine and cosine functions of different frequencies that resembles the LFF can be employed, which is also known as the Fourier basis set (Glaser & Friston 2014). This function can be incorporated into the general linear model and was shown by the design matrix in Figure 1a. The methodology used to model this signal followed previous studies (Di & Biswal 2014; Nawi et al. 2020; Yusoff et al. 2018). According to Di & Biswal (2014), a set of 4 functions is deemed suitable to model resting state brain responses which oscillate between 0.01 to 0.08 Hz. In the design matrix shown in Figure 1a, the horizontal lines represented the number of scans, which in this study, was 195 functional scans for each participant. Referring to the vertical columns, the Fourier basis set was parameterised with 90 phase delay oscillating at 0.01 Hz (column 1 and 2), 0.02 Hz (column 3 and 4), 0.04 Hz (column 5 and 6) and 0.08 Hz (column 7 and 8). The next column (column 9 to 14) represented six realignment parameters, in translation and rotation; while column 15 represented effects caused by other baseline factors. The design matrix shown in Fig. 1(a) was then estimated and the images of the parameter estimation for the model known as ESS images were obtained for individual participants using the *F* statistics.

The ESS images obtained from individual-subject analysis were then entered into a differential group analysis conducted using an independent sample *t*-test to compare between the control and experimental groups. The design matrix used was shown in Figure 1b. The area, sub-area, anatomical functions, voxel value and peak coordinates of the activations for comparisons of control to experimental and experimental to control, thresholded at corrected and uncorrected *p* values were recorded and tabulated. The confirmation of the areas of activation, if any, was obtained from an ROI analysis using a MATLAB-based WFU PickAtlas toolbox (Wake Forest University, North Carolina, USA).

Five regions-of-interest (ROIs) were

selected in this study due to their known involvement in the default mode network and creativity. The ROIs were left and right hemisphere angular gyrus (AG), medial pre-frontal cortex (mPFC) and left and right hemisphere pre-cuneus (PCU). Random-effects analysis (RFX) that considered within- and between-subject variability were performed to obtain group activation at a corrected significance level (p_{FWE} = 0.05). By using WFU Pickatlas toolbox (Wake Forest University, North Carolina, USA) (Maldijan et al. 2003), the activation from the ROIs were obtained by masking the whole brain activation with the automated anatomical labelling (AAL) atlas for each region. The coordinates of maximum intensity for these five ROIs were determined from control and experimental group activation results respectively and were used as the reference coordinates.

The following DCM analyses were conducted based on the methods described by Ashburner et al. (2014). A general linear model (GLM) containing the time corrected, realigned, normalised and smoothed images were defined again for each particular participant and a new design matrix was constructed as shown in Figure 1c. This design matrix was estimated and was used in the extraction of the LFF from cerebrospinal fluid (CSF) and white matter (WM) centred at (0, -40, -5) and (0, -24, -33) of a 6-mm radius volume-of-interest (VOI) respectively. The extracted LFF from the two regions together with the six realignment parameters were then used to construct a design matrix as shown in Figure 1d. These LFF from WM, CSF and realignment parameters were used as confounds. This design matrix was then estimated. The design matrix in Figure 1d was later used to extract LFF from the five ROIs mentioned above. An 8-mm radius VOI was specified for each ROI using the respective centre coordinates. By doing this, the LFF obtained from each VOI was expected to contain signals exclusive of confounds i.e. WM, CSF and participant's movement.

At this point, data from 19 participants (38%) had to be excluded for not meeting the eligibility of several requirements for SPM and sp-DCM data analyses i.e. head movement exceeding 1 mm and/or 1° in translational and rotational directions, absence of activation in the ROIs at a corrected significance level ($p_{FWE} < 0.05$) and the maximum activation intensity of the ROIs at coordinates located more than 16 mm from the referenced group coordinates. Thus, only the data from 16 control participants and 15 experimental participants (a total of 62% of the initial number of participants) had the eligibility to contribute to the EC results.

Spectral Dynamic Causal Modelling

The analysis of sp-DCM was separated according to brain hemispheres. Using the extracted LFF from individual activation, a fully connecting model was constructed consisting of AG, mPFC and PCU for each hemisphere using DCM version 12.5 (DCM12.5), as shown in Figure 2. In the model, both

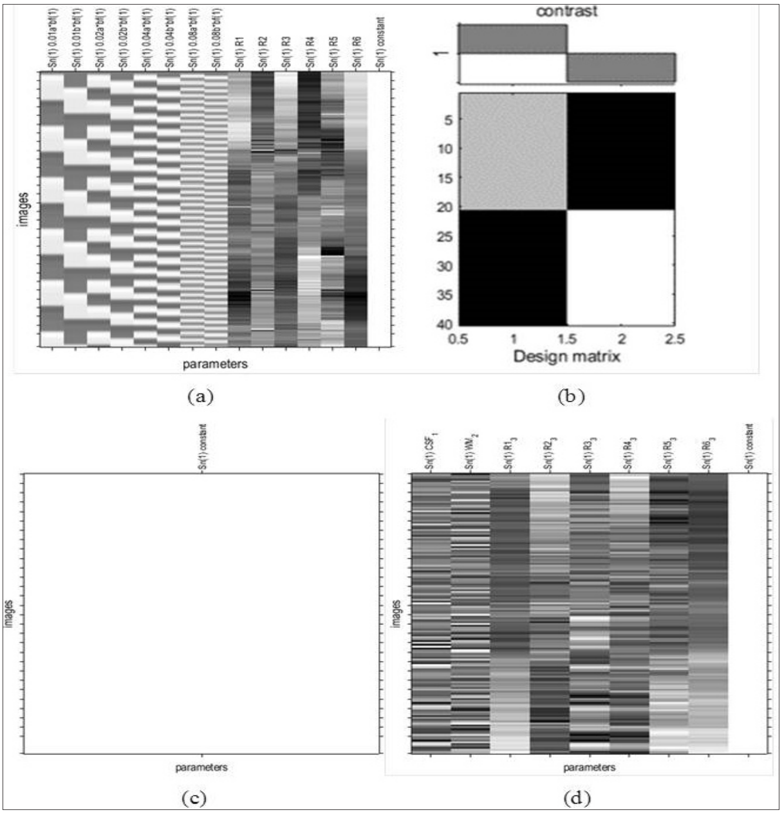

FIGURE 1: Designs matrix used in SPM analyses for (a) obtaining individual brain activation from LFF, (b) obtaining group differential activation between control and experimental groups, (c) extracting LFF from CSF, WM and realignment parameters to be used as confound and (d) extracting LFF from AG, mPFC and PCU

the AG and PCU were separated in the left and right hemispheres while mPFC was shared by both hemispheres. No input was specified in the modelling because the neuronal network was assumed to be perturbed by the resting state activity inside the brain (Razi et al. 2015). The causal model was then estimated using the analysis of cross spectra (Friston et al. 2014) for the determination of the EC between the regions. The estimated models then underwent Bayesian parameter averaging (BPA) to determine the average EC between the ROIs (Nawi

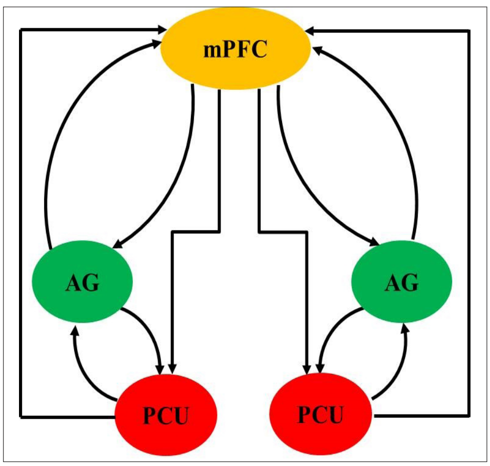

FIGURE 2: A fully connecting model constructed for sp-DCM analysis

et al. 2020). An EC is considered significant if it has a non-zero value with a posterior probability (P) of equal or larger than 0.9 (Penny et al. 2004). A posterior probability of a connection is a probability of that connection to occur given the data and the model. A Mann-Whitney U test using Statistical Packages for Social Sciences (SPSS) was further implemented to determine the difference in each EC between control and experimental groups.

RESULTS

Behavioural Results

Cognitive assessment results revealed that the experimental group achieved significantly higher mean ± SD behavioural score of 84.75 ± 33.97 as compared to control group of 67.81 ± 25.12 ($p = 0.048$). Independent sample *t*-test done on the behavioural scores of the three elements of divergent thinking tasks obtained from cognitive assessment showed significant difference between experimental and control groups in both fluency and flexibility but not in originality (Table 1).

Differential Brain Activations

Based on the group differential random-effects analysis (RFX) using a control to experimental contrast and experimental to control contrast, no cluster of voxels survived the corrected ($p = 0.05$) thresholds. At an uncorrected threshold ($p<0.001$), four clusters of activation survived the threshold for control to experimental contrast which were superior parietal lobe (SPL) and inferior frontal gyrus (IFG) in the right hemisphere as well as superior frontal gyrus (SFG) and middle occipital gyrus (MOG) in the left hemisphere, as a maximum intensity projection in Figure 3 in three different orientations was observed. Their statistical data were tabulated in Table 2. All voxels in all clusters were significant at peak level ($p<0.001$) but the clusters were not significant at cluster and set level. Nevertheless, these clusters appeared to be more active in the control group as they were in the experimental group during the resting state. The right hemisphere SPL appeared to show highest activation intensity and area among the four. Surprisingly, for experimental to control group contrast, no voxel survived even at

TABLE 1: Comparisons of cognitive assessment results between control and experimental group in terms of fluency, flexibility and originality using independent t-test (α = 0.05)

Assessed element of divergent thinking	Mean behavioural score (SD)		p-value
	Control Group	Experimental Group	
Fluency	25.42 (9.01)	33.67 (14.30)	0.018
Flexibility	36.23 (11.16)	42.67 (11.32)	0.048
Originality	6.15 (6.47)	8.42 (9.89)	0.339

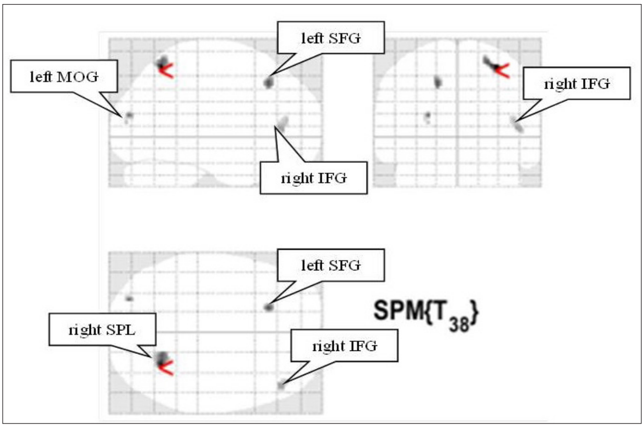

FIGURE 3: Maximum intensity projection profile (p<0.001 uncorrected for multiple comparisons) obtained from group differential analysis using contrast control group > experimental group (clusters containing number of voxels of less than 11 were removed to exclude trivial effects)

the uncorrected threshold despite the creative training undergone by the experimental group. Due to the weak activation profile obtained from group differential analysis, further analysis i.e. the analysis of EC will be based on group activation profile for control and experimental groups separately.

Group Activation

Figure 4 showed significant AAL-masked brain activation results for control group (top) and experimental group (bottom) that were obtained from RFX at a corrected (p_{FWE} < 0.05) significant level. The cross sectional view of the activation is shown next to the maximum intensity projection. From the results, both groups exhibited significant activation in the five selected regions, with a slight difference in the location of the coordinates of maximum intensity. For control group, the ROIs were centred at the following coordinates: left AG at (-40, -68, 30), right AG at (44, -60, 26), mPFC at (4, 22, 42), left PCU at (-12,

TABLE 2: Statistics (adjusted for search volume) of the activated regions obtained from group differential RFX for control to experimental contrast at set-, cluster- and peak-level. Maximum intensity coordinates and the name of the regions based on AAL were tabulated

Cluster	p set-level	$p_{FWE-corr.}$ cluster-level	$p_{FWE-corr.}$ cluster-level	$p_{corr.}$ peak-level	$p_{uncorr.}$ peak-level	t peak-level	NOV (k=10)	Peak x mm, y mm, z mm	Regions
1	0.756	0.192	0.015	0.451	<0.001	4.74	82	30, -60, 56	right SPL
2		0.783	0.105	0.932	<0.001	4.12	32	-18, 26, 44	left SFG
3		0.989	0.309	0.979	<0.001	3.96	12	-26, -86,16	left MOG
4		0.857	0.133	0.999	<0.001	3.67	27	48, 36, 6	right IFG

k = Extent threshold; FWE = Family-wise Error; corr. = Corrected; uncorr. = Uncorrected; NOV = Number of activated voxels

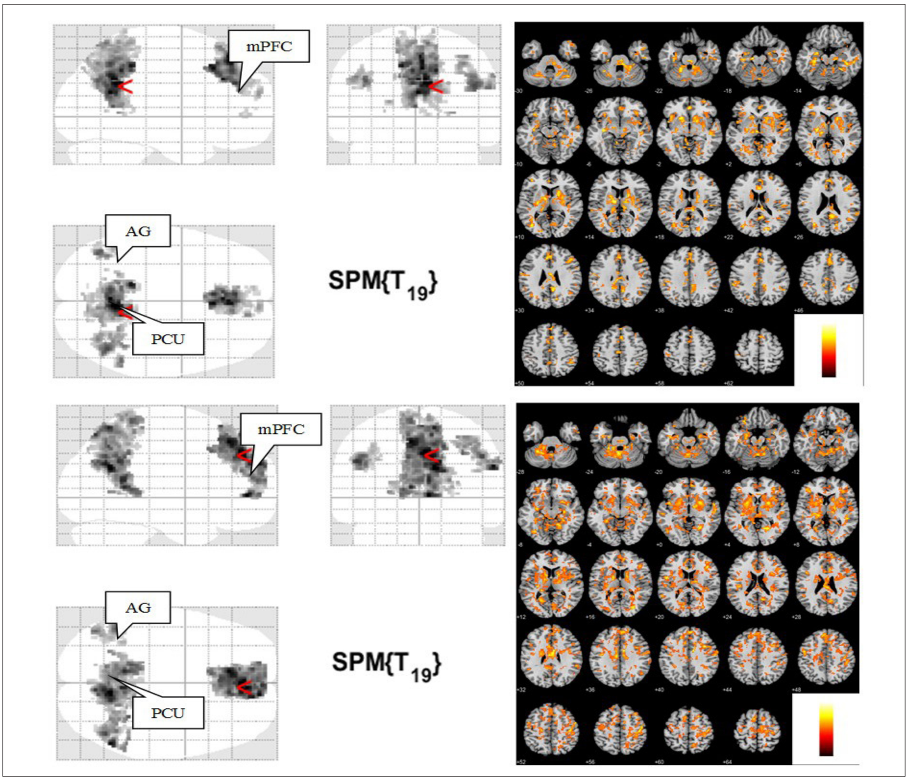

FIGURE 4: Maximum intensity projection (left) and axial view of group activation (right) in left and right AG, mPFC and left and right PCU for control group (top) and experimental group (bottom)

-42, 44) and right PCU at (10, -50, 28). For experimental group, the ROIs were centred at the following coordinates: left AG at (-50, -54, 30), right AG at (56, -60, 26), medial PFC at (4, 40, 38), left PCU at (-8, -50, 8) and right PCU at (10, -60, 24). The activation profile indicated left and right hemisphere AG, mPFC and left and right hemisphere PCU (Table 3).

Effective Connectivity

Figure 5 and 6 showed the EC between the three ROIs for the control and experimental group. The magnitude of self-connection for every region was also given. From the Bayesian perspective, all the self-connections and EC obtained from both groups were significant by having the posterior probability (P) of larger than 0.9. Both groups exhibited excitatory (positive) and inhibitory (negative) EC. Self-connections that were inhibitory in both groups were excluded, most of the EC were excitatory in the control group whereas for the experimental group, there were equal numbers of excitatory and inhibitory EC and with a symmetrical pattern (Figure 5 & 6). Even though the difference in brain activation between control and experimental group was small, it seemed that creativity training had caused a measurable change in the

TABLE 3: Group activation characteristics for mPFC, AG and PCU for control and experimental participants acquired at FWE = 0.05

Anatomical region	Cluster level		Peak level		MNI coordinates
	p_{FWE}-value	Number of voxels, k_E	p_{FWE}-value	t-value	
Control group					
mPFC	< 0.001	1609	< 0.001	10.65	(4, 22, 42)
Left AG	< 0.001	484	< 0.001	8.86	(-40, -68, 30)
Right AG	< 0.001	904	< 0.001	9.22	(44, -60, 26)
Left PCU	< 0.001	1755	< 0.001	10.52	(-12, -42, 44)
Right PCU	< 0.001	2019	< 0.001	11.23	(10, -50, 28)
Experimental group					
mPFC	< 0.001	2978	< 0.001	11.35	(4, 40, 38)
Left AG	< 0.001	565	< 0.001	9.87	(-50, -54, 30)
Right AG	< 0.001	725	< 0.001	10.70	(56, -60, 26)
Left PCU	< 0.001	1779	< 0.001	10.04	(-8, -50, 8)
Right PCU	< 0.001	2014	< 0.001	11.11	(10, -60, 24)

EC pattern of the experimental group, at least in the context of this study. This finding was supported by the results obtained from Mann Whitney U test in revealing the more significant connection between PCU, mPFC and AG in higher EC of experimental group (p<0.05) (Figure 7).

DISCUSSION

Experimental group of participants scored higher on average in the aspects of fluency and flexibility, potentially due to the creativity stimulation training they received in which the control group did not. This observation can be associated with more engagement

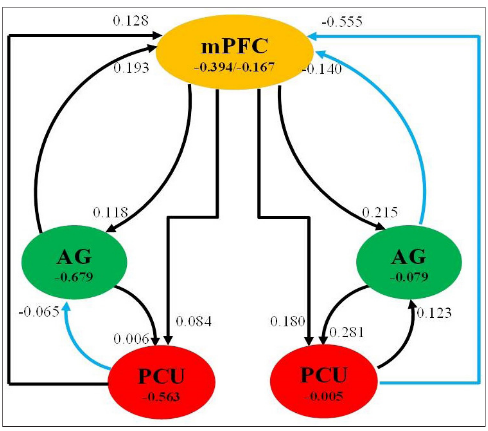

FIGURE 5: Average EC between mPFC, AG and PCU for control group (inhibitory connection in blue; number inside the region denoted the magnitude of self-connection)

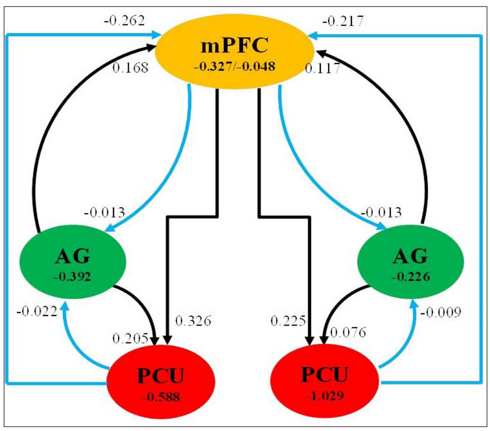

FIGURE 6: Average EC between mPFC, AG and PCU for experimental group (inhibitory connection in blue; number inside the region denoted the magnitude of self-connection)

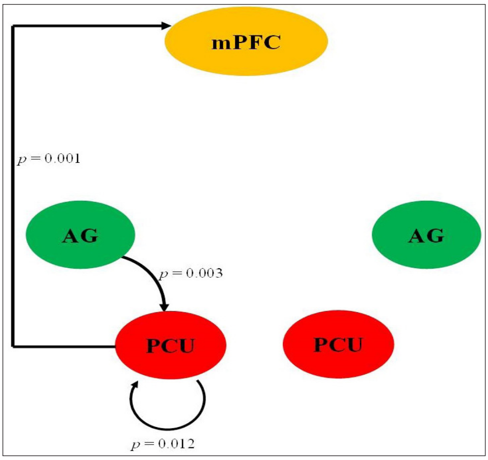

FIGURE 7: Connections that were significantly higher in experimental group as compared to in control group

of executive processes and cognitive strategies as employed in the training (Abdul Hamid et al. 2019). The same behavioural observation was reported in Ritter & Mostert (2017), in which a significant increase in behavioural performance was seen from pre- to post-training creativity assessment in a single group of participants.

However, no significant improvement was seen in the domain of originality. This result could be contributed by two factors. Firstly, the duration of training in the present study, which was only 2 days, is relatively short to enhance the creative ability in the originality domain. The shortest duration of training to cause a significant effect on originality in idea generation is 30-minute intervention with 7 sessions of training expanded over one week (Ding et al. 2014). Secondly, the present study employed a 2-day creativity stimulation with only 1 interleave period between the two days, which should be more. Longer duration of training enables multiple interleaves between the training sessions because it slows down the rate of learning but allows better encoding of information (Bjork & Bjork 2011). The progress of creative ability has to be incremented gradually over a period of time to harness its adaptability. A repetition of creative skills is necessary to increase focused attention. Due to these reasons, it is understood that a creativity or cognitive stimulation session need not be lengthy but adequate with 30-minute stimulation interleaved with sufficient time of rest. In addition, multiple sessions of intervention allow feedback and meta-cognitive evaluation among the trainees. Behavioral observation by Yang et al. (2016) showed that repetition learning of 3 to 6 times increases the object and information recognition performance significantly, thus increasing the memory retention. The development of creative ability needs to be gradual in a period of time to increase its adaptability. Repetition of creative tasks is a crucial element that needs to be employed to increase specific attention. At the same time, repetition of exposure to a certain stimulation increases the efficiency of detail encoding of the memory, thus increasing memory retention (Yang et al. 2016), especially in visuospatial working memory (Tagliabue et al. 2020). Thus, the rest interleaves and repetition of stimulation and learning are essential for an improved retention of memory and increased training efficiency.

At a corrected statistical threshold, rs-fMRI was not able to differentiate the brain activation in those who received creative training and those who did not. This finding most likely supports the above argument that creative training needs to be conducted over a longer period. Differences were observable only at an uncorrected threshold but the results showed a higher activity in control group involving areas not directly related to creativity i.e. SPL, IFG, SFG and MOG. Similar results were observed by Gafoor et al. (2021) from which the low working memory (WM) group showed higher activity in several brain areas as compared to the normal WM group.

In a dynamic system such as the human brain, excitatory and inhibitory neurons create balance in an EC network (Kajiwara et al. 2021). Inhibition is the capacity of an excited neuron to reduce the activity of its neighbours while excitation enables the excited neurons to act vice versa. In a human brain, the number of inhibitory neurons is relatively smaller than the excitatory neurons (Kajiwara et al. 2021). In DCM, inhibition was indicated by the negative value of the EC. A balance between excitation and inhibition is the key principle for neuronal network organisation and information processing (Bruining et al. 2020). According to DCM results obtained from this study, there were three aspects of hemispheric symmetry shown by the experimental group resting state network. First, connections that were inhibitory and excitatory were the same in the left and right hemispheres which implied the same number of inhibitory (or excitatory) connections in each hemisphere (6 vs. 6). Second, connectivity between any two ROIs was balanced in such a way that if one connection was excitatory, another was inhibitory. Third, it was region specific, for example connectivity from PCU to other regions was inhibitory while the incoming information was excitatory. The behaviour was the opposite for AG while mPFC had quite a mixed connectivity pattern. Similar results have been shown to occur for PCC in which PCC has been found to be the dominant node (Nawi et al. 2020). Creative training could have contributed at least partially to the more balanced EC patterns in the resting brain of the experimental group. For the control group, the number of inhibitory connections is less than the number of excitatory connections (3 vs. 9). This is in a good agreement with the current understanding with regards to inhibition-excitation relationship as mentioned in Kajiwara et al. (2021) and their distribution is not symmetry indicating a more natural distribution of inhibitory-excitatory connections. The fact that creative training had an enhanced effect on brain EC was also supported by a significantly ($p<0.05$) higher EC values for left hemisphere AG PCU, PCU mPFC and PCU PCU connections in the experimental group.

At the neuronal level, the strength of connections between mPFC and PCU (in both hemispheres) in the experimental group was mostly higher than those in the control group, which was possibly also an effect of creativity stimulation. A recent study on functional connectivity showed enhanced network of PCU in musicians as compared to non-musicians (Tanaka & Kirino 2016). In a resting state fMRI study by Takeuchi et al. (2012), functional connectivity between mPFC and PCC/PCU was found to be positively correlated with divergent thinking ability. These observations reflect that there is an increased engagement between the anterior and posterior subsystems of DMN in more creative individuals, during rest, as compared to less creative individuals.

Besides that, the connection strengths between regions within different hemispheres were higher in the right for the control group, but more symmetrical in the experimental group. This observation was also associated with creativity training, in which a robust connectivity between core executive regions of the right and left hemisphere was linked to higher creativity individuals. All domains of creative processes require inter-hemispheric interaction between multiple functionally specialised brain areas (Dietrich & Kanso 2010). In addition to that, Abraham (2016) revealed that interaction between cognitive control networks and default mode network is a function of creative ability. In this case, AG is more engaged in cognitive and executive processes than default-mode, while mPFC and precuneus are each established as the core hubs of DMN. In this study, symmetrical intrinsic connectivity and its respective strengths between all three nodes support previous conclusions.

There were limitations in this study that may affect the interpretation of results. The number of participants qualified for DCM analysis was relatively small as compared to previous studies on resting state effective connectivity e.g. Sharaev et al. (2016), Di & Biswal (2014) and Utevsky et al. (2014). Furthermore, to study the network of default-mode holistically, more than one dynamic causal model should be constructed so that model comparisons can be made for DCM to choose an optimum model. Extensive study that employs several methods of divergent thinking tasks can be conducted to further relate the effective connectivity between the DMN regions with various aspects of creativity.

CONCLUSION

The current findings revealed that a short session of creativity stimulation was able to significantly induce an increase in creativity behavioural performance as well as evoking a change in the EC network between AG, mPFC and PCU during rest. These three regions had been proven to be part of the default mode network (DMN). Furthermore, they also play important roles in creativity due to their involvement in internal and external information gathering during idea generation.

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