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Influence of Creativity Stimulation on Brain Connectivity during Divergent Thinking Tasks

Abdul Hamid K[a,e], Rahman S[b], Sharis Osman S[c], Surat S[b], Ahmad Marzuki M[d], Yusoff AN[e]

[a]School of Health Sciences, KPJ Healthcare University College, Negeri Sembilan, Malaysia
[b]Department of Innovation in Teaching and Learning, Faculty of Education, Universiti Kebangsaan Malaysia, Selangor, Malaysia
[c]Radiology Department, An-Nur Specialist Hospital, Bandar Baru Bangi, Selangor, Malaysia
[d]Department of Nursing, Faculty of Medicine, Hospital Canselor Tuanku Muhriz, Wilayah Persekutuan Kuala Lumpur, Malaysia
[e]Center for Diagnostic, Therapeutic and Investigative Studies, Faculty of Health Science, Universiti Kebangsaan Malaysia, Kuala Lumpur, Malaysia

ABSTRACT

INTRODUCTION: Different facets of divergent thinking (DT) are associated with connectivity between different cerebral areas. However, the causal interactions between the key DT nodes have yet to be explored. It is hypothesised that with creativity stimulation, changes in effective connectivity among regions will be observed. **MATERIALS AND METHODS:** By using control (n=26) and experimental (n=24) participants, this study aimed to investigate the effective connectivity between brain areas associated with divergent thinking that accentuate fluency, flexibility, and originality. The experimental participants attended a two-day creativity stimulation, followed by three task-based fMRI sessions for all participants, which included basic use (BU) identification, alternative use (AU) generation and unusual use (UU) determination tasks. Dynamic causal modelling (DCM) was used to determine the most optimal causal model representing the most possible modulatory influence on the connections between medial prefrontal cortices (mPFC), inferior frontal gyrus (IFG), and inferior parietal lobule (IPL). **RESULTS:** The experimental participants scored higher fluency and flexibility than the controls ($p<0.05$). At neuronal level, the control group showed similar intrinsic connections receiving modulatory influence for AU and UU tasks, while the experimental group preferred a different perturbation of connection between both tasks. These intergroup differences may be caused by different thinking strategies involving semantic and episodic memory retrieval, and integration of remotely associated ideas to construct new combination among the experimental participants. **CONCLUSION:** Different DT demands may influence the effective connectivity between mPFC, IFG and IPL especially among individuals with higher DT abilities, especially in fluency and flexibility versus originality.

Keywords
Alternative uses task, bayesian, divergent thinking, dynamic causal modelling, effective connectivity

Corresponding Author
Dr. Ahmad Nazlim Yusoff
Center for Diagnostic, Therapeutic and Investigative Studies, Faculty of Health Science, Universiti Kebangsaan Malaysia, 50300 Kuala Lumpur, Malaysia
Email: nazlimtrw@ukm.edu.my

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INTRODUCTION

Creativity is often indicated by means of divergent thinking skill, which is fluency, flexibility, originality, and elaboration. Fluency accounts for the number of relevant solutions, flexibility refers to the number of categories of productions, while originality is judged by the number of unusual but useful solutions. These three categories are often assessed in various behavioural and neuroscientific studies of divergent thinking. To increase the probability of generating creative solution to a problem, divergent thinking involves simultaneous exploration of different options of distant and unusual connections between different semantic information.[1] A classic assessment which is broadly used to measure divergent thinking ability is the Alternate Uses Task (AUT), in which participants aim to generate as many interesting and unusual uses of a common object as possible, such as brick or a newspaper. Several executive functions are important processes of creativity, such as cognitive flexibility, fluency, planning and working memory.[2] To execute creative tasks, a range of controlled processes take place, such as fluency, cognitive flexibility, switching and inhibition, working memory and retrieval.[3,4] Cognitive flexibility is associated with increased divergent thinking ability, which is defined by how rapid an individual can generate an idea or solution of different categories in a short period of time.[5,6] Fluency performance, on the other hand, depends on a combination of several cognitive processes, including self-initiation of action, semantic retrieval, cognitive switching and inhibition, and monitoring of working memory contents.[7] Increased working memory ability increases fluency and the originality of responses. At the same time, increased cognitive switching eventually increases different categories of responses thus increase the flexibility of responses. Individuals with more flexible associations often regarded as more creative than their counterparts, as they can see the similarities or analogies between distinct concepts or situations.[8] Creativity training enhances one's divergent thinking skills in terms of ideational fluency, cognitive flexibility, and idea originality.

Previous studies on creativity training that employed different target of cognitive processes have shown to enhance creative performance, in imagery, idea production, cognitive and thinking skills.[9, 10] However, most training to impact changes at the neuronal level creative task performance[11-13] were lengthy and elaborated, which could pose a disadvantage that limits its implementation in an educational setting. Thus, the present study applied a different and shorter approach as the cognitive stimulation that intended to improve ideational fluency, cognitive flexibility and possibly the originality of ideas generated. For the past decade, numerous studies have explored the neuronal mechanisms underlying creative cognition training and its training-related changes in the brain.[14-16]

The findings from these studies are able to assist the direction of training program to improve our understanding of specific neuronal functions that include working memory, executive attention, cognitive inhibition, and task switching (from process-based training); and even metacognitive evaluation and skill improvement (from strategy-based training). The neuronal changes associated with different divergent thinking domain has also yet to be studied, especially in terms of its functional connectivity and the causal interactions between the key brain regions. To explain the changes in brain responses in relation to fluency and flexibility, and originality of those ideas between these groups of individuals, a specific fMRI paradigm was constructed to achieve maximal segregation of task fluency and flexibility, from originality. Based on the assumption that improvement of divergent thinking at the behavioral level can be related to changes in neuronal activity[17], a shorter length of cognitive stimulation than two weeks which has been proven to improve ideational fluency[18] and cognitive flexibility[19] is able to exhibit difference of brain responses, especially on how activity in the cerebral region is affected by the activity in another region of cognition and creativity. Thus, the present study aims to compare the effective connectivity of several established cerebral regions of divergent thinking during the performance of alternative uses tasks (AUT) between individuals who did and did not undergo creativity stimulation, through functional magnetic resonance imaging (fMRI) acquisition.

MATERIALS AND METHODS

Participants

The study employed a quasi-experimental design. Based on the optimal sample size calculation by Desmond & Glover[20] to achieve 80% power of the study, 50 students were conveniently recruited from the Faculty of Medicine, Universiti Kebangsaan Malaysia. All participants were currently enrolled in their second and third year during the study recruitment. They were physically healthy, had no previous surgeries of metallic implantation and had no history of mental disorders, thus were deemed eligible for functional magnetic resonance imaging (fMRI) procedure.

Research procedures and requirements were briefed to the participants and all participants understood and provided informed consent to voluntarily participate in the study. This study is approved by the institutional ethics committee (IEC) of the university (reference number: PPI/111/8/JEP-2016-307).The participants were randomly assigned to experimental (EG) and control group (CG). The EG which consisted of 24 participants (5 male) received creativity stimulation prior to the fMRI procedure, in which the 26 CG participants (13 male) did not. The average age for the participants is 21.58(0.64) years for CG and 21.36(0.59) years for EG.

Pre-fMRI Cognitive Assessment

All participants underwent a pre-fMRI cognitive test as the psychometric assessment using an adapted version of Alternative Use Task (AUT) by J. P. Guilford[21] which is also used in previous studies[12,22] to quantify their divergent thinking skills. In the 30-minute test, they were required to generate as many appropriate alternatives and unusual uses of 6 common daily objects as possible. The objects are shoe, pencil, umbrella, key, tire, and spectacles. The score for each participant was given based on fluency, flexibility, and originality of the responses generated. This scoring system was based on the Runco Creativity Assessment Battery.[23] One (1) mark was computed for every useful idea generated and every category assignable to every useful idea, respectively.

Two (2) marks were computed for every original answer that constituted less than 1% of the whole number of uses for an object from all participants. The psychometric scores of participants ranged from 36 to 195. The EG then attended a two-day creativity stimulation session, after which a series of fMRI scans were conducted. The session was done for 6 hours with a 1-hour gap in one day, for two days. The creativity stimulation session incorporated creative activities using various techniques that have been described in Azmi et al.[24] and Rahman et al.[25] The techniques employed were brainstorming, imagination, and de Bono CoRT I and IV which included Plus, Minus, Interesting (PMI), Other People's View (OPV), Consider All Factors (CAF), Alternative, Possibilities and Choices (APV), and Yes Po No methods.

The content validity index (CVI) of the module employed in the creativity stimulation was 0.833, which is deemed feasible to be used on the targeted demographics. Wilcoxon's signed-rank test was used to compare the psychometric scores between pre- and post fMRI for both groups. An independent sample t-test and Mann-Whitney U test were also done on those scores for the pre- and post-fMRI cognitive assessment to compare between control and experimental group.

fMRI Data Acquisition and Procedure

Three sessions of fMRI scan were conducted using a 3-tesla MRI scanner (Siemens Magnetom Verio) in Universiti Kebangsaan Malaysia Medical Centre (UKMMC). The explanation on the fMRI paradigm and respective imaging parameters of those sessions have been described in Abdul Hamid et al.[26]

fMRI Data Analysis

The fMRI data were analysed using Matlab 9.2.0 (R2018b) (Mathworks Inc. MA, USA) and Statistical Parametric Mapping (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 pre-processing of all T2* functional images was described in Abdul Hamid et al.[26]

The pre-processed data underwent general linear model (GLM) analysis for generation of group brain activation via random-effect analysis (RFX), in which the group cortical activation of BU, AU and UU tasks were height-thresholded at a=0.05 corrected to account for family-wise error (FWE) for both groups of participants. All participants exhibited significant activation in visual cortices, inferior frontal gyrus (opercular part) (IFGop), inferior parietal lobule (IPL), medial prefrontal cortices (mPFC) and precuneus of both hemispheres, in addition to other cortical areas. These 5 regions were selected for the following connectivity analysis due to their involvement in divergent thinking and creative tasks, other than their significant activation in the group results, especially for AU and UU tasks.

Extraction of ROIs and Construction of Dynamic Causal Models (DCMs)

The peak coordinates for these five regions for all tasks were selected from group results using the WFU Pickatlas toolbox (Wake Forest University, North Carolina, USA).[27] These coordinates acted as the reference for extraction of individual coordinates following several DCM criteria.

Firstly, the center of the 6-mm sphere of volume in respective individual coordinates should be within 16 mm distance from reference coordinates. Secondly, the coordinates must reside in the correct anatomical region. Thirdly, these coordinates should survive as significant activation at uncorrected significance level (p<0.01). The respective group coordinates from each task for each selected ROIs are tabulated in Table I.

Table I: Analysis of brain activation in secondary visual cortices, medial prefontal cortices, inferior frontal gyrus, inferior parietal lobule and precuneus related to divergent thinking tasks in control and experimental groups ($p < 0.001$)

a) Control group

Location	BU				AU				UU			
	Coordinate			t-value	Coordinate			t-value	Coordinate			t-value
	x	y	z		x	y	z		x	y	z	
mPFC	-2	18	50	3.57	-4	20	42	7.78	-10	16	44	6.17
L IFG	-52	16	2	6.33	-48	4	16	4.46	-36	10	32	6.11
R IFG	50	24	-4	5.77	40	18	6	3.67	56	14	32	4.55
L IPL	-60	-36	44	4.58	-50	-30	48	9.87	-50	-30	46	7.21
R IPL	48	-36	60	1.65	26.	-56	52	5.03	26	-56	52	4.55
Precuneus	-16	-62	66	3.41	-14	-56	44	1.48	-10	-56	72	6.64
L V2	-28	-88	8	7.59	-20	-92	2	6.85	-20	-92	4	4.79
R V2	24	-84	-10	7.29	28	-88	8	5.56	28	-88	8	4.31

b) Experimental group

Location	BU				AU				UU			
	Coordinate			t-value	Coordinate			t-value	Coordinate			t-value
	x	y	z		x	y	z		x	y	z	
mPFC	2	22	40	3.04	-2	24	44	8.18	-2	24	44	7.05
L IFG	-56	18	0	6.05	-44	10	24	9.21	-52	16	22	7.80
R IFG	50	16	-4	5.74	60	14	26	4.61	58	14	28	9.73
L IPL	-56	-32	50	3.31	-58	-28	44	9.93	-58	-28	44	8.80
R IPL	52	-36	56	1.55	26	-56	52	4.24	42	-34	48	4.55
Precuneus	-8	-66	66	3.25	-16	-58	68	7.59	-14	-66	62	6.03
L V2	-26	-92	6	9.75	-16	-96	6	5.85	-26	-90	6	8.36
R V2	22	-94	-2	7.38	28	-90	-2	8.97	24	-90	0	7.10

The extracted signals were then entered into the analysis of dynamic causal modeling (DCM). Extrinsic input was presumed to enter bilateral secondary visual cortices (V2) following the visual stimulus employed during the functional data acquisition. A different number of models were constructed for each divergent thinking task, as shown in Figure 1. Model00 is a full-connected model without any modulatory input pertubations, while Model01 is almost like Model00, with voided IFG-precuneus connectivity. ModelB01 to ModelB05 depicts full intrinsic connectivity with different various modulatory input perturbations. For BU, only Model00, Model01 and ModelB01 were considered for DCM analysis. DCM analysis for AU models involved addition of ModelB02 and ModelB03 from the similar models in BU, while UU involves all 7 models for DCM analysis. The constructed models differ in intrinsic connectivity perturbed by modulatory input between different tasks, hypothetically influenced by the different level of fluency, flexibility, and originality demand. For AU and UU tasks, the construction of added models from set of models for BU task was based on several conditions. Firstly, all models have a one-way connection from V2 to mPFC and precuneus, due to their involvement in visuospatial processing.[28] Secondly, these models have full connectivity between mPFC, precuneus, IFG and IPL, based on a few assumptions as followed: (1) there are strong communication between mPFC and precuneus as the nodes of default mode network (DMN), which is highly associated with creativity[29]; (2) due to the involvement of precuneus in various cognitive processing[30,31], a reciprocal connectivity between PCU-IFG and PCU-IPL is almost certain, and (3) due to the established role of IFG and IPL in cognitive and executive processes, such as memory retrieval[31], pre-potent response inhibition[32] and novel response generation[33], these regions may exert reciprocal connectivity to mPFC and precuneus, along with each other.

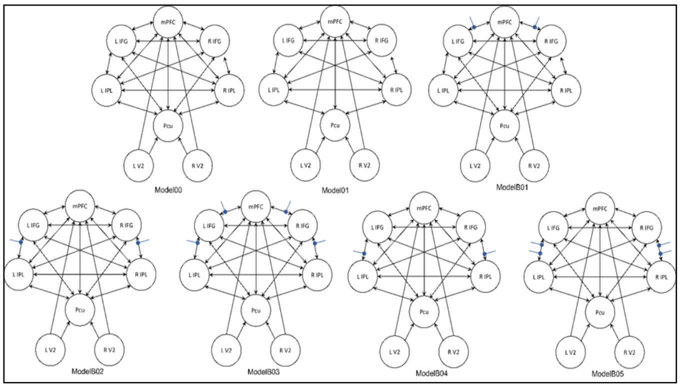

Figure 1: Schematic diagram of constructed dynamic causal models for all divergent thinking task (IFG: inferior frontal gyrus, IPL: inferior parietal lobule, L: left, mPFC: medial prefrontal cortices, Pcu: precuneus, R: right, V2: secondary visual cortex)

All the specified models then underwent Bayesian estimation of model parameters and compared using Bayesian model selection via fixed-effect analysis (FFX) for group results to determine the best causal model that depicts the intrinsic connectivity that is balanced between accuracy and complexity. The aim of the model comparison is to determine the presence of modulatory input perturbation on the connectivity between mPFC and IFG, and between IFG and IPL that best explains the underlying network that could relate with fluency, flexibility, and originality aspect of divergent thinking.

RESULTS

Psychometric Results

The range of the number of ideas generated by the participants for all six common household items were 36 to 195. A significant difference between pre- and post-fMRI psychometric performance in CG was found in originality (p=0.014) (refer Table II), but not in fluency and flexibility (p>0.05). The EG showed significantly higher post-fMRI scores in fluency (p=0.001) and flexibility (p<0.001) as compared to pre-fMRI scores, but not in originality (p>0.05).

Table II: Comparison results between pre- and post-fMRI psychometric scores for creativity categories of fluency, flexibility and originality using Wilcoxon signed-rank test in (a) control group and (b) experimental group

(a) Control group

Creativity category	Median (IQR)		Z-statistics	p-value
	Pre-fMRI scores	Post-fMRI scores		
Fluency	25.0 (12.0)	24.0 (15.0)	-0.343	0.731
Flexibility	34.0 (18.0)	34.0 (18.0)	-1.000	0.317
Originality	4.0 (8.0)	5.0 (10.0)	-2.456	0.014

(b) Experimental group

Creativity category	Median (IQR)		Z-statistics	p-value
	Pre-fMRI scores	Post-fMRI scores		
Fluency	31.0 (14.0)	31.000 (15.0)	-3.226	0.001
Flexibility	39.0 (10.0)	42.000 (10.0)	-3.491	< 0.001
Originality	6.0 (10.0)	6.000 (10.0)	-1.826	0.068

For the influence of creative stimulation, the pre-fMRI psychometric scores in the three domains were not significantly different between both group participants (p>0.05). However, the EG achieved higher mean (SD) score in fluency (p=0.022, d=0.47) and flexibility (p=0.049, d=0.55), but not in originality (p>0.05) for post-fMRI psychometric performance. The effect size for fluency and flexibility as measured by Cohen's d indicate a moderate and large effect , respectively.

Dynamic Causal Modeling

The brain activation results have been described in Abdul Hamid et al.[26] Data from a few participants had to be excluded for further analysis for not fulfilling the DCM criteria. The number of participants whose data succeeded through DCM analysis is 11 for BU, 15 for AU and 13 for UU tasks from CG, and 9 for BU, 15 for AU, and 16 for UU tasks from EG. The chosen model network using Bayesian model selection (BMS) via fixed-effect analysis (FFX) for all tasks is shown in Figure 2. A clear selection was observed for all preferred model for all tasks in both groups, in which each winning model has the highest relative log evidence ($p(y|m)$) among all models being compared, with the posterior probability of more than 0.9000 (refer Table III).

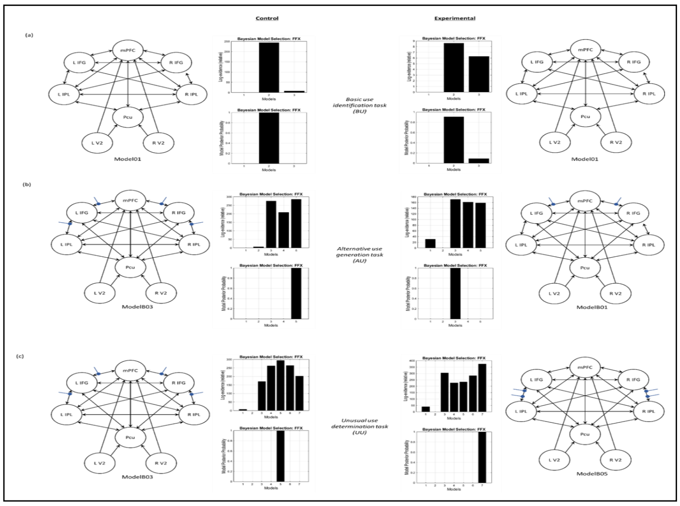

Figure 2: Winning model for (a) BU task, (b) and (c) AU taskand (d) UU task through Bayesian model selection for fixed-effect analysis (FFX)

Table III: Winning model and their respective relative log evidence and posterior probability from Bayesian model selection (FFX) for all divergent thinking tasks in (a) control group and (b) experimental group

(b) experimental group

	Task		
	Basic use identification (BU)	Alternative use generation (AU)	Unusual use determination (UU)
(a) Control group			
Winning model	Model01	ModelB03	ModelB03
Relative log evidence, $p(y|m)$	243.8	285.0	294.3
Posterior probability	1.000	1.000	1.000
(b) Experimental group			
Winning model	Model01	ModelB01	ModelB05
Relative log evidence, $p(y|m)$	8.6	171.2	374.2
Posterior probability	0.910	1.000	1.000

DISCUSSION

The main findings in the present study are (a) the experimental group performed better in AUT psychometric assessment as compared to the CG, in terms of task fluency and flexibility, and (b) there is a difference in the modulatory input pertubation between mPFC and bilateral IPL and IFG in the CG (a group with lower average DT score) and the EG (a group with higher average DT score) during alternative use generation and unusual use determination tasks. Holistically, a different network of connectivity was observed across the divergent thinking tasks of increasing difficulty, especially in the group with higher average of DT ability. No difference in terms of model preference was found during execution of BU between both groups due to low cognitive demand of the task, reflecting the same performance of basic use identification in both groups. Different explanation may imply for AU and UU tasks, in which the CG exhibited similar preference of connectivity model for AU and UU, but not for the EG. On another note, all winning models for both groups in all three tasks showed trivial mPFC-precuneus effective connectivity – supporting the previous functional connectivity findings on its involvement in creative tasks.[34,35]

The need for fluency and flexibility of ideas during AU execution acts as the modulation on mPFC→IFG and IPL→IFG connections in the CG. It seems that the same connections were also influenced by the need for idea originality as the modulatory influence. For EG, these modulatory influences have their effect on only the mPFC→IFG connections during AU, and on reciprocal ipsilateral IFG-IPL connections during UU. The findings may reflect the similar thinking strategies employed by the individuals with lower DT ability in generating as many alternative ideas as possible and in determining the best (most unusual) answer possible. On the other hand, a different thinking tool may be exploited by the individuals with higher DT ability benefited from the creativity stimulation session.

The mPFC has been specifically related to the semantic memory and its retrieval.[36,37] Previous studies have suggested that functional connectivity with the mPFC has shown significant relationship with divergent thinking which differs with individual creative abilities,[35,38] such as with lateral temporal cortex.[38,39] Psychophysiological interaction between mPFC and left IFG was also found to be positively correlated with creative use and creative metaphor generation tasks[40] which inferred that generation of creative ideas necessitates the making of remote semantic association and their conceptual integration. The present findings demonstrated causal connection from mPFC to bilateral IFG during the search and generation of alternative uses, regardless of individual DT ability. The IFG, especially the left, has been linked to divergent thinking in the aspect of cognitive control and response selection[33,41] and possibly metacontrol flexibility.[42] Bilateral activation of IFG is essential to improve AUT performance in divergent thinking,[43] although the left IFG is more strongly activated than the right. The causal connection between mPFC and IFG in the final winning model of both groups imply the need for semantic memory search and conceptual integration accompanied with cognitive control and inhibition to generate as many creative uses as possible to meet the demand of AU tasks.

During the execution of the most unusual use determination task, similar winning model for the CG to AU task has substantially shown that the individuals with lower DT abilities utilised a similar thinking strategy in searching and finalising for the most creative idea. This process primarily involves semantic memory search and retrieval due to the involvement of mPFC in the modulated causal connectivity. On the other hand, the individuals with higher DT abilities (the EG) exhibited that modulatory influence of idea originality has its effect on IFG-IPL ipsilateral connections, bilaterally. The IPL is a prominent node of DMN, which strengthens its role in internal mentation and mind wandering. A change in resting functional connectivity between IFG and IPL has been positively associated with AUT performance in fluency and originality aspect for high-creative group of individuals.[44]

The prefrontal and inferior parietal cortices support a flexible integration of previous knowledge in constructing new and novel ideas,[33] especially the left hemisphere. The IPL, specifically, has also been implicated in the production of original ideas,[45,46] episodic memory retrieval,[33] and consistently during conceptual expansion.[47] The modulatory influence in the winning model for the individuals with higher DT abilities (EG) has its effect on the back-and-forth connection between IFG and IPL. This finding presumes a more systematic approach employed by these individuals to achieve the best answer possible, by integrating old and new ideas from semantic and episodic memory for efficient conceptual expansion. These thinking processes may be triggered from the creativity stimulation. The different modulatory input perturbation between both groups also showed that individuals with different divergent thinking ability engage the modulatory influence on a different set of intrinsic connectivity between different cortical nodes to maximise the novelty of the ideas being generated, especially when only the best idea is considered for validity. There are several limitations to this study. The first limitation is the relatively small number of participants whose data underwent the analysis of dynamic causal modeling which deemed insufficient for random-effects analysis to be applied for the generalization of inference. Thus, a fixed-effect analysis was used for the modeling purposes using Bayesian model selection. Secondly, no pre-stimulation fMRI session was done to assess the matching extent of both groups in their brain activity.

However, the pre-stimulation cognitive assessment was done and ruled out no significant difference in the psychometric performance between both groups. This finding at behavioral level does not qualify to strengthen the differences in brain connectivity between the groups which could have been affected by the creativity stimulation. Thirdly, the IQ level and gender of participants were not controlled in this study. However, the cognitive assessment was done to certify the changes of divergent thinking performance affected by the creativity stimulation session. At the same time, gender variability was not being assessed under the scope of the present study. Fourthly, the length of the creativity stimulation session is too short to induce significant changes at the neuronal level.

Future studies should employ a longer session of stimulation, accompanied by several breaks to maximise memory encoding and retention from the training. Lastly, the elaboration domain of creativity was not included in this study. This limitation is due to the necessity of sophisticated fMRI paradigm and extended validation means of answers by the participants. The brain activation during elaboration period to generate creative uses of the object being shown reflects a mixture of regions that are engaged in strategy development in creative solution, along with those regions involved in the actual generation of creative solutions.

CONCLUSION

A two-day creativity stimulation session can exhibit differences in the divergent thinking ability between participants who attended the creativity stimulation session versus those who did not, with the difference most prominently seen in the aspects of task fluency and flexibility. The winning causal models exhibited differences in the network of effective connectivity during the execution of alternative use generation and unusual use determination tasks, but not in the basic use identification task. This finding is due to the different strategy employed with different divergent thinking ability, which exerted difference in the intrinsic connectivity and modulatory influence induced by the task demands, especially involving between mPFC with IFG and IPL.

Tasks with higher creative demands causes modulatory perturbations on reciprocal connections between IFG and IPL for higher-DT ability individuals, implying different thinking strategies among individuals with different divergent thinking ability to produce more novel and original ideas. This study confirms that different cognitive demands between fluency, flexibility and originality of ideas poses different causal perturbation on the intrinsic connection between key nodes of divergent thinking.

DECLARATION OF CONFLICT OF INTERESTS

This study declares no conflicts of interest.

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