NEUROSCIENCE
RESEARCH ARTICLE

S. Zhou et al. / Neuroscience 371 (2018) 268–276

Temporal and Spatial Patterns of Neural Activity Associated with Information Selection in Open-ended Creativity

Siyuan Zhou, [a,b,c†] **Shi Chen,** [a,b†] **Shuang Wang,** [a,b,d] **Qingbai Zhao,** [a,b*] **Zhijin Zhou** [a,b*] **and Chunming Lu** [c*]

[a] *Key Laboratory of Adolescent CyberPsychology and Behavior (CCNU), Ministry of Education, Central China Normal University, Wuhan 430079, China*

[b] *National Experimental Teaching Demonstrating Center of Psychology, School of Psychology, Central China Normal University, Wuhan 430079, China*

[c] *State Key Laboratory of Cognitive Neuroscience and Learning and IDG/McGovern Institute for Brain Research, Beijing Normal University, Beijing 100875, China*

[d] *Collaborative Innovation Center of Assessment Toward Basic Education Quality, Beijing Normal University, Beijing 100875, China*

Abstract—Novel information selection is a crucial process in creativity and was found to be associated with frontal–temporal functional connectivity in the right brain in closed-ended creativity. Since it has distinct cognitive processing from closed-ended creativity, the information selection in open-ended creativity might be underlain by different neural activity. To address this issue, a creative generation task of Chinese two-part allegorical sayings was adopted, and the trials were classified into novel and normal solutions according to participants' self-ratings. The results showed that (1) novel solutions induced a higher lower alpha power in the temporal area, which might be associated with the automatic, unconscious mental process of retrieving extensive semantic information, and (2) upper alpha power in both frontal and temporal areas and frontal–temporal alpha coherence were higher in novel solutions than in normal solutions, which might reflect the selective inhibition of semantic information. Furthermore, lower alpha power in the temporal area showed a reduction with time, while the frontal–temporal and temporal–temporal coherence in the upper alpha band appeared to increase from the early to the middle phase. These dynamic changes in neural activity might reflect the transformation from divergent thinking to convergent thinking in the creative progress. The advantage of the right brain in frontal–temporal connectivity was not found in the present work, which might result from the diversity of solutions in open-ended creativity.

Key words: information selection, open-ended creativity, EEG power, EEG coherence, lower and upper alpha.

INTRODUCTION

Research on creativity has attracted great attention in psychology, education and management, which mainly focus on the characteristics of creative persons, the mental processes of creating ideas, the ecological press on the person and his mental processes, and the products of recording creative thoughts (Rhodes, 1961). Among them, the creative process is the core, without which all the others cannot work by themselves.

Finke et al. (1992) indicated that creative cognition consisted of two key processes that generated some incomplete mental representations and then refined or regenerated them to meet the requirements of problem solving. Furthermore, Bink and Marsh (2000) suggested a more integrated theoretical framework for creative cognition. In the beginning, creators retrieve the relevant information from long-term memory over an extensive range and then combine the information pieces with distant or implicit associations into some subsets of information. Then, these combinations of information are selected according to their availability for the task. Creative cognition shares similar common cognitive processes with non-creative cognition but selects the novel rather than the normal information. Therefore, information selection is the key process in creative activities.

As cognitive neuroscience develops rapidly, researchers employed various neuroimaging and electrophysiological technologies such as electroencephalograph (EEG) and functional magnetic

*Corresponding authors. Address: Key Laboratory of Adolescent CyberPsychology and Behavior (CCNU), Ministry of Education, Central China Normal University, Wuhan 430079, China (Q. Zhao and Z. Zhou).
E-mail addresses: zqbznr@mail.ccnu.edu.cn (Q. Zhao), zhouzj@mail.ccnu.edu.cn (Z. Zhou), luchunming@bnu.edu.cn (C. Lu).
† The first two authors contributed equally to this work.
Abbreviations: ANOVA, analysis of variance; EEG, electroencephalograph; fMRI, functional magnetic resonance imaging.

https://doi.org/10.1016/j.neuroscience.2017.12.006
0306-4522/

resonance imaging (fMRI) to figure out the mental processes of creative cognition. Studies have concentrated mainly on insight problem solving and divergent thinking.

Compound remote associate problems have been frequently used to explore the cognitive and neural mechanisms of insight (Bowden et al., 2005). Studies have revealed that the anterior superior temporal gyrus in the right brain was more activated for insight than non-insight solutions (Jung-Beeman et al., 2004). Due to its role in coarse semantic coding (Jung-Beeman, 2005), the right temporal cortex was regarded as the key area for establishing distant semantic associations. The crucial role of the right cortex in insight was also supported by the electrophysiological findings that the gamma wave suddenly increased over right temporal sites 0.3 s prior to insight solutions (Jung-Beeman et al., 2004). Furthermore, compared with the trials in which problems were unsolved throughout, a larger upper alpha activity was detected over the temporal sites for the trials in which problems were solved after hint presentation (Sandkuhler and Bhattacharya, 2008).

In addition, research using riddles and logogriphs also revealed several key brain areas involved in insight solution. The anterior cingulate cortex was proposed to detect and monitor cognitive conflicts in insight (Mai et al., 2004; Qiu et al., 2008a,b; Zhao et al., 2014b), the lateral prefrontal cortices might be responsible for resolving conflict (Luo, 2004; Qiu et al., 2010), the bilateral temporal areas were activated to retrieve semantic information over an extensive range (Luo and Niki, 2003; Zhao et al., 2013), and the hippocampus might underlie the formation of novel semantic associations (Luo and Niki, 2003; Qiu and Zhang, 2008; Zhao et al., 2013). Through the analysis of functional connectivity, Zhao et al. (2014b) suggested that the right lateral prefrontal cortex and right temporal area as well as their interaction might underlie the selection of novel information.

However, the process detected in the above studies was solving insight problems rather than solving general problems in an insightful way, because the experimental materials used were all the insight problems, which were some special artificial problems whose solutions involve insightful processes for ordinary beings (Ohlsson, 2011). Generally, the insight problem has a unique solution, and the solution of these problems belongs to closed-ended creativity. Comparatively, the general problem might have several solutions, even more than one novel solution. Therefore, solving general problems in a creative way is more likely open-ended creativity. Although both of these problems are creative problem solving, they might have distinct cognitive processing. According to the dual process account (Allen and Thomas, 2011), creative thinking includes automatic thinking and effortful thinking, which may play crucial roles in different phases of the creative process. Open-ended creativity is considered to mainly depend on automatic, intuitive thinking, while closed-ended creativity involves both automatic, intuitive thinking and effortful, analytical thinking (Lin and Shih, 2016). Therefore, it is hypothesized that the processes of information selection in open- and closed-ended creativity might be distinct from each other.

Divergent thinking is a typical open-ended creativity, and studies usually employ tasks such as the alternative uses test or creative sentence or story generation to explore the cognitive process (Wu et al., 2015). In the alternative uses test, fMRI results showed that the left frontal cortex was associated with divergent thinking (Fink et al., 2009; Abraham et al., 2012), and EEG recordings further revealed the alpha synchronization over the frontal scalp was associated with the generation of original uses, which might reflect a selective top-down inhibition process in creative thinking (Fink et al., 2009; Fink and Benedek, 2014; Benedek et al., 2014c). Different from these studies in which the originality of the uses was rated by others rather than the participants, Benedek et al. (2014b) distinguished the generation of genuinely new creative ideas and the mere recollection of old ideas from memory according to participants' self-report. The results showed brain activation in the orbital part of the inferior frontal cortex increased as a function of the creativity, which might be associated with executive processes for overcoming dominant but uncreative responses.

The role of the lateral frontal cortex in divergent thinking was also supported by the studies on creative sentence or story generation. It was found that the right prefrontal cortex acted critically in retrieving divergent semantic information when generating creative stories (Howard-Jones et al., 2005). Moreover, Benedek et al. (2014a) found that brain activation in the left anterior dorsomedial prefrontal cortex and the right middle temporal gyrus was linearly correlated with the creativity rating of generated metaphors, which might reflect executive control and the activation of novel semantic information, respectively.

Although the previous studies came to an agreement about the key brain area in divergent thinking, that is the frontal cortex playing a crucial role in open-ended creativity, there were some issues to solve yet. On the one hand, the above studies treated the creative process as a unitary construct and did not subdivide it into detailed mental components or stages through the experimental design or data analysis. Therefore, the dynamic neural activity of the key mental subprocesses, such as information selection in creativity, was not revealed. Although Schwab et al. (2014) and Wang et al. (2017) reported investigations of the temporal course of alpha power/synchronization during generation of creative ideas, the time window they chose was the whole duration of generating multiple uses of an object, which included several complete processes of creativity. Therefore, what they subdivided into different stages was one task rather than a single trial of creativity. On the other hand, the brain areas associated with creative thinking do not work independently but cooperate with each other to support creativity (Zhao et al., 2014b; Beaty et al., 2015, 2016). Nevertheless, the studies on divergent thinking did not take into account the interaction between the brain areas of executive control and visual or semantic information activation, although they had identified these areas as associated with information selection.

The current study was conducted to figure out the temporal and spatial patterns of neural activity associated with information selection in open-ended creativity. According to the previous studies, it was hypothesized that the neural activity of the frontal and temporal cortices as well as their interaction would underlie information selection in creativity.

METHOD

Participants

Twenty-three adults (12 females and 11 males; mean age: 21.1 years, ranging from 19 to 26 years) participated in this experiment. All were healthy, right-handed, native Chinese speakers and had normal or correct-to-normal vision and no report of neurological disease. All participants were asked to sign an informed consent to meet the ethics requirements of Institutional Review Board of Central China Normal University. Three participants were excluded due to too many EEG artifacts.

Materials and experimental paradigm

In the current study, we adopted a creative generation task of Chinese two-part allegorical sayings, which is a type of Chinese proverb consisting of two parts. The first segment is the descriptive part, consisting of a short phrase that portrays a novel scenario, and the second segment is the explanatory part made of a few words, providing the rationale. The two parts are implicitly associated with each other, usually in way of semantic pun or homophonic pun. For example, 'kuang feng zhong de la zhu, nan dian' (狂风中的蜡烛, 难点) is a semantic pun Chinese two-part allegorical saying. The first part means a candle in a wild wind, while the second part means a difficult point. They seem mismatched. However, if decomposing the 'nan dian' (难点) into two separate characters—'nan' (难, means difficult) and 'dian' (点, one meaning is igniting), the first and second parts would be matched. Another example is a homophonic pun Chinese two-part allegorical saying, such as 'xia yu tian dai shou biao, lin shi' (下雨天戴手表, 临时). The first part means wearing a watch on a rainy day, while the second part means temporary. The key is to replace the character "临" with "淋" which means pouring. Then, the second part would be 'lin shi' (淋时, which means pouring some water on time (watch)) and is associated with the meaning of the first segment.

In conversation, people often only state the first part, expecting the listener to know the second. Therefore, Chinese two-part allegorical sayings are also called Xiehouyu (歇后语, means a saying with the latter-part suspended). However, in the creation of a Chinese two-part allegorical saying, the second part is generated at first because it is what people want to say, and then the second part is created as a semantic pun or homophonic pun. For example, for the second part, 'gao zhao' (高招, means brilliant idea) may be decomposed into 'gao' (高, means high) and 'zhao' (招, means beckoning), and then create a short phrase to describe a corresponding scenario, such as 'shan ding shang hui shou' (山顶上挥手, means waving the hand on the top of mountain). Alternatively, people may replace the character 'zhao (招)' with 'zhao (照)', which means lighting, and create the first part of 'fei ji shang de deng guang' (飞机上的灯光, means lamplight on flying plane). Another possibility is that people may produce the first part with a similar meaning to the second part, such as 'wan li tiao yi de dian zi' (万里挑一的点子, means a good idea that is one in a million). This process shows that the generation of a Chinese two-part allegorical saying can be completed in different ways and lead to more than one solution. Therefore, the creation of Chinese two-part allegorical sayings is open-ended creativity.

A pre-experiment was conducted to choose the materials for the formal experiment. Ninety-second segments with two characters were derived from a corpus of existing Chinese two-part allegorical sayings, and none of the materials overlapped in character with the others. Thirty-eight participants were required to generate a novel and appropriate first segment to each second segment. Since the task was difficult, worked examples (a second segment with both a novel first segment and a normal first segment) were provided at the beginning of the pre-experiment to help participants learn some strategies. After that, participants generated a solution to each item within 3 min and rated each solution as 'novel' or 'normal' by themselves. The results of the pre-experiment showed that the mean generating time was 26.37 s, and the mean rate of novel solutions was 49.26%. To ensure that the novel and normal solutions would be comparable in number in the formal experiment, thirty-two items were chosen, and the rate of novel solutions was in the range of 40–60%.

The formal experiment consisted of the practice stage and the experiment stage. The practice included two trials in which participants were asked to generate a novel and appropriate first segment to each second segment. No matter what the participants worked out, a novel and a normal solution were presented as worked examples to help them learn the strategies. The procedure of each trial in the experimental stage is shown in Fig. 1. First, a cross sign was presented at the center of the screen for 1 s. Subsequently, a second segment was presented at the same position, and participants were asked to generate a novel and appropriate first segment for the presented second segment within 40 s. Once they came out with an optimal solution, they pressed the "ENTER" key and spoke it out loudly within 10 s. Then, participants were instructed to rate their solution as 'normal' or 'novel' by pressing the '1' key or '2' key, respectively. Note that the appropriateness of the solutions was not rated here because all the solutions generated should make sense first to be an answer. The next trial came after a –4 s blank. During the entire

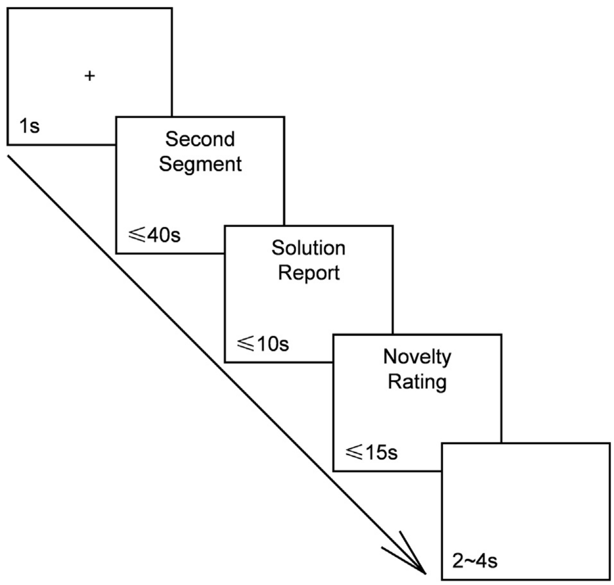

Fig. 1. The procedure of a trial in the formal experiment.

experiment, participants were asked to stay still in order to minimize the interruption of EEG signals.

EEG recording and analysis

The EEGs were recorded using a 64-channel elastic cap by Brain Product, Gilching, Germany, according to the International 10–20 system. The reference and ground electrode were located at FCz and a site between AF3 and AF4, respectively. The electrooculogram (EOG) consisted of the vertical EOG and horizontal EOG, which were recorded by electrodes placed above the left eye and at the outer corner of the right eye. The impedance of all electrodes was below 5 kΩ over the whole period of the experiment. The EEG signals were amplified and bandpass filtered between 0.05 and 100 Hz, and the continuously sampled frequency was 500 Hz/channel.

EEG data were analyzed offline using Analyzer 2.0 software (Brain Product, Gilching, Germany). EEG data were re-referenced by the average signals of Tp9 and Tp10, which were located at left and right ear mastoids. A filter was adopted with a bandpass of 0.1–35 Hz. Eye movement artifacts were rejected using Independent Component Analysis (ICA), and other artifacts (voltage exceeds ± 100 μV in any channel) were also eliminated. The trials were classified into novel and normal solutions according to participants' self-rating. Because the solution times for different trials were very different, ranging from 3.82 s to 39.95 s, we could not average the neural signals of different trials in accurate time segmentation like ERPs. Moreover, the calculation of EEG power and coherence required data with a long enough time epoch, which was 2 s in the current study. To make sure that most trials were usable, three epochs in each trial were extracted to display a rough changing trend of neural activity: (1) early phase, which was 0 to 2 s after the second segment was presented, (2) middle phase, which was −1 to 1 s centered at the midpoint of the whole generation period, and (3) late phase, which was −2 to 0 s before participants pressed the key to report. The trials with solving time lower than 6 s were excluded.

For EEG analysis, a fast Fourier transformation was adopted on time-domain signals of all selected epochs to obtain the frequency-domain signals of EEG activity. The lower alpha (8–10 Hz) band and the upper alpha (10–12 Hz) band were chosen for analysis (Fink et al., 2009). As mentioned in the Introduction, the lateral frontal cortex and temporal areas played a crucial role in information selection, and then frontal area electrodes (AF3, AF7, F3, F5, F7, AF4, AF8, F4, F6, and F8) and temporal area electrodes (FT7, T7, TP7, FT8, T8, and TP8) were selected for the following analysis. The power value of each electrode in each band was calculated using Analyze r2.0 software, and then was log-transformed for inclusion in an ANOVA. In EEG coherence analysis, EEG coherence between all pairs of electrodes was calculated by cross-spectrum analysis in Analyzer 2.0 software for both lower and upper alpha bands, and then four groups of electrode pairs were selected, as shown in Fig. 2, including 15 frontal–temporal pairs in each hemisphere, 5 interhemispheric frontal–frontal pairs and 3 interhemispheric temporal–temporal pairs. Then, the frontal–temporal coherence in each hemisphere and the interhemispheric frontal–frontal and temporal–temporal coherence for each participant were obtained by averaging the coherence values in each group. All the coherence values were Fisher-Z transformed for ANOVA, and *p* values were corrected using the Greenhouse-Geisser correction for all repeated-measures ANOVAs.

RESULTS

Behavioral results

The average solution rate of all participants was (90.62 ± 7.45)%. The mean percentage of novel solutions was (39.96 ± 12.56)% according to participants' self-rating. Paired-samples *t*-test showed that the mean solving time for novel solutions (19.23 ± 4.60 s) was significantly shorter than that for normal solutions (21.0 6 ± 4.00 s) [$t(19) = 2.11$, $p < 0.05$].

EEG power results

Alpha power in the frontal area. Both the lower and upper alpha power over the frontal scalp were analyzed using a 2 (novelty: novel, normal) × 2 (hemisphere: left [AF3, AF7, F3, F5, F7], right [AF4, AF8, F4, F6, F8]) × 3 (time epoch: early phase, middle phase, late phase) repeated-measures ANOVA.

For lower alpha power, none of the main effects or interactions was significant.

For upper alpha power, a significant main effect of novelty [$F(1, 19) = 2.59$, $p < 0.05$, $\eta^2_{partial} = 0.23$] was found, in which the upper alpha power induced by the novel solution (0.13 ± 0.08 μV^2) was significantly higher than that by the normal solution (0.11 ± 0.07 μV^2). As shown in Fig. 3, there was also a significant interaction

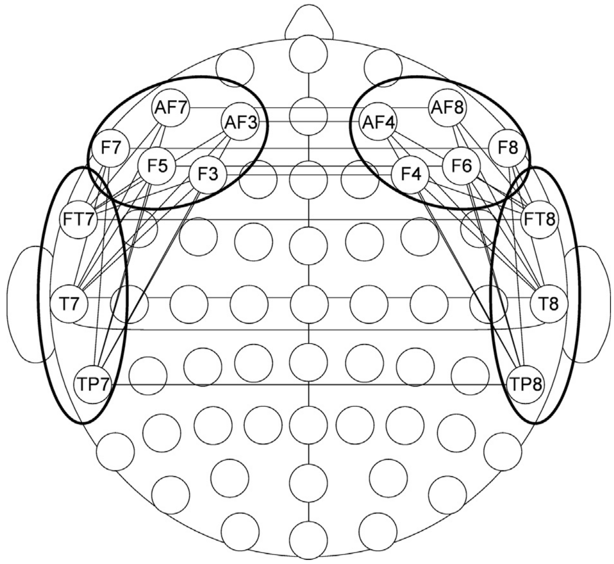

Fig. 2. The sketch map of the selected electrodes for EEG power analysis and electrode pairs for coherence analysis.

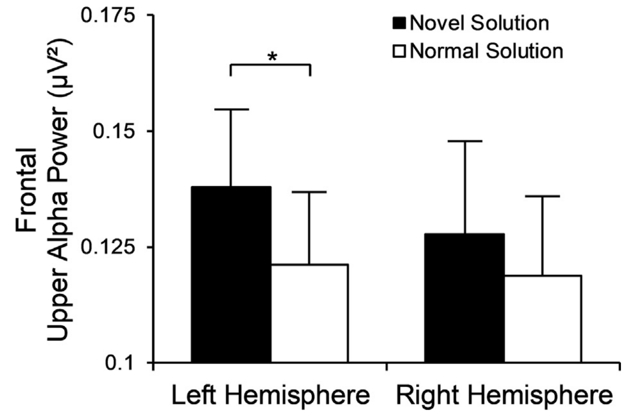

Fig. 3. The comparison of the frontal upper alpha power between the novel and normal solution in each hemisphere. Error bars were standard error of the mean ($^{*}p$ = 0.072).

between novelty and hemisphere in the upper alpha band [$F(2, 38) = 5.54$, $p < 0.05$, $\eta^2_{partial} = 0.23$]. The simple effects test showed that the upper alpha power induced by the novel solution (0.14 ± 0.08 μV^2) was marginally significant higher than that by the normal solution (0.12 ± 0.07 μV^2) in the left hemisphere [$p = 0.072$], while the difference in the right hemisphere was not significant [$p > 0.05$].

Alpha power in the temporal area. A 2 (novelty: novel, normal) × 2 (hemisphere: left [FT7, T7, TP7], right [FT8, T8, TP8]) × 3 (time epoch: early phase, middle phase, late phase) repeated-measures ANOVA was conducted in analysis of the lower and upper alpha power over the temporal scalp.

For the lower alpha power, the ANOVA showed a significant main effect of novelty [$F(1, 19) = 5.98$, $p < 0.05$, $\eta^2_{partial} = 0.24$], in which the lower alpha power induced by the novel solution (0.11 ± 0.13 μV^2) was higher than that induced by the normal solution (0.09 ± 0.09 μV^2). The significant main effect of time epoch was also found [$F(2, 38) = 6.52$, $p < 0.01$, $\eta^2_{partial} = 0.26$] as shown in Fig. 4A. Post-hoc analyses showed that the lower alpha power in the early phase (0.12 ± 0.13 μV^2) was significantly higher than that in the middle (0.10 ± 0.11 μV^2) and late phase (0.09 ± 0.09 μV^2) [$p < 0.05$], while no difference was found between middle and late phases [$p > 0.05$].

For the upper alpha power, there was a significant main effect of novelty [$F(1, 19) = 2.59$, $p < 0.05$, $\eta^2_{partial} = 0.23$], in which the upper alpha power induced by the novel solution (0.10 ± 0.08 μV^2) was higher than that induced by the normal solution (0.09 ± 0.06 μV^2).

EEG coherence results

Frontal–temporal coherence. The frontal–temporal coherence in both lower and upper alpha band were analyzed using a 2 (novelty: novel, normal) × 2 (hemisphere: left, right) × 3 (time epoch: early phase, middle phase, late phase) repeated-measures ANOVA.

For the lower alpha coherence, the ANOVA showed a significant main effect of novelty [$F(1, 19) = 7.29$, $p < 0.05$, $\eta^2_{partial} = 0.28$], in which the lower alpha frontal–temporal coherence in the novel solution (0.30 ± 0.07) was higher than that in the normal solution (0.26 ± 0.05).

For the upper alpha coherence, the main effect of novelty was significant [$F(1, 19) = 4.79$, $p < 0.05$, $\eta^2_{partial} = 0.20$], in which the upper alpha frontal–temporal coherence in the novel solution (0.30 ± 0.08) was higher than that in the normal solution (0.26 ± 0.05). As shown in Fig. 4B, there was a significant main effect of time epoch [$F(2, 38) = 5.47$, $p < 0.01$, $\eta^2_{partial} = 0.22$]. Post-hoc analyses revealed that the upper alpha frontal–temporal coherence in the middle phase (0.30 ± 0.07) was significantly higher than that in the early phase (0.26 ± 0.05) [$p < 0.05$].

Interhemispheric coherence. The frontal–frontal coherence and temporal–temporal coherence were separately analyzed using a 2 (novelty: novel, normal) × 3 (time epoch: early phase, middle phase, late phase) repeated-measures ANOVA.

For frontal–frontal coherence, none of the main effects or interactions were found to be significant in either the lower or upper alpha band.

For temporal–temporal coherence in the lower alpha band, the main effect of novelty was significant [$F(1, 19) = 5.45$, $p < 0.05$, $\eta^2_{partial} = 0.22$], in which the lower alpha bilateral temporal coherence in the novel solution (0.20 ± 0.07) was higher than that in the normal solution (0.16 ± 0.07). For temporal–temporal coherence in the upper alpha band, the main effect of time epoch was significant [$F(2, 38) = 5.11$, $p < 0.05$, $\eta^2_{partial} = 0.21$] as shown in Fig. 4C. Post-hoc analyses showed that the upper alpha bilateral temporal coherence in the middle phase (0.20 ± 0.08) was significantly higher than that in the early phase (0.15 ± 0.06) [$p < 0.05$].

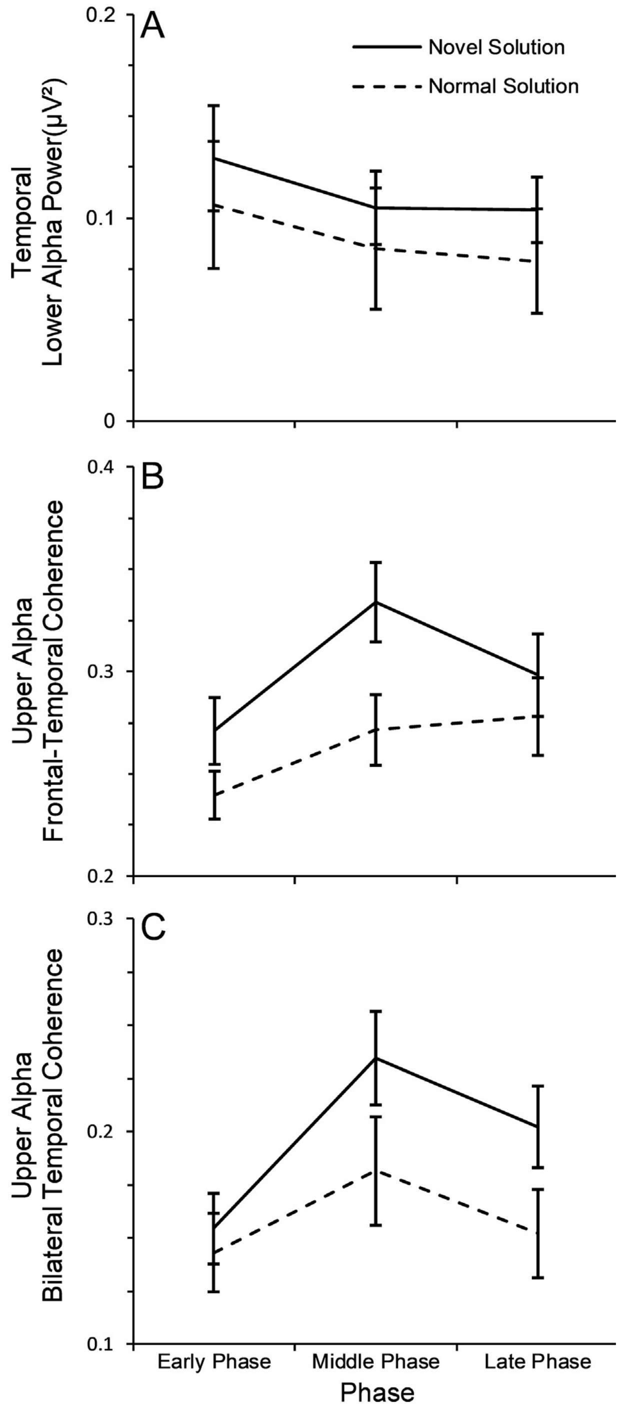

Fig. 4. (A) The dynamic change of lower alpha power in temporal area in which the power value in early phase was significantly higher than that in middle and late phase. (B) The dynamic change of frontal–temporal coherence in upper alpha band in which the coherence value in middle phase was significantly higher than that in early phase. (C) The dynamic change of temporal–temporal coherence in upper alpha band where the coherence value in middle phase was significantly higher than that in early phase. Error bars were standard error of the mean.

DISCUSSION

The current study focused on the cognitive and neural processing of information selection in open-ended creativity. Generally, when engaging in open-ended creativity, people retrieved extensive information closely and remotely related to the question, and then inhibited the common information and activated the novel information to produce the novel solution. These processes might be reflected by the alpha activity of the frontal and temporal cortex as well as their interaction.

Possible integrations of alpha activity in creativity

In the previous studies, the findings of alpha activity for creativity did not agree. Some researchers found lower alpha activity increased in creativity (Fink et al., 2006; Razumnikova, 2007; Razumnikova et al., 2009), while some other studies reported an increase in upper alpha activity (Sandkuhler and Bhattacharya, 2008; Fink et al., 2011). In addition, there were some studies that found increased activity of both lower and upper alpha band or did not discriminate the two types of alpha waves (Jausovec, 2000; Fink et al., 2009; Benedek et al., 2014c). Although the previous studies provided no clear evidence of the specific roles of lower and upper alpha activity in creative cognition (Fink and Benedek, 2014), the lower and upper alpha activity might still reflect different cognitive processing in creativity.

Generally, the increase in alpha power or synchrony in creativity had two interpretations. One was defocused attention (Dietrich and Kanso, 2010), which meant a state of automatic processing that facilitated the sorts of associative processes (Zabelina and Robinson, 2010). Since lower alpha activity was found to be more likely to be associated with general cognitive process such as arousal or alertness (Fink and Benedek, 2014), it might reflect automatic, intuitive or unconscious processing in creativity. The other was selective inhibition (Fink et al., 2009), which suggested an active top-down control of brain activity. Given that more activity during cognitive processes was associated with specific task demands (Klimesch et al., 2000; Doppelmayr et al., 2005), the upper alpha activity might be involved in the process of information selection in creativity.

Alpha power in the frontal and temporal cortex

In the current study, the results showed that compared with that of the normal solution, the lower alpha activity of the creative solution was increased over the bilateral temporal sites. Due to the typical function of the temporal cortex in language, the increased lower alpha activity might be associated with the automatic, unconscious mental process of retrieving extensive semantic information. Furthermore, the lower alpha activity showed a reduction with time. This result might reflect the dynamic change from divergent thinking to convergent thinking in the creative process, in which the automatic and unconscious semantic retrieval decreased and the problem space was compressed.

To come to a novel solution, semantic information that is closely related and information that is unrelated to the problem should be abandoned. As discussed above, the upper alpha activity in temporal areas might be involved in the inhibition of the common or unrelated information. Additionally, selective inhibition was also underlain by the increased upper activity over the frontal scalp. The current results indicated a dominance of upper alpha activity in the left frontal area. This result might reflect stronger inhibition of common semantic information since the left brain was responsible for the fine and close semantic processing (Jung-Beeman, 2005). Thinking from another perspective, stronger inhibition suggested more activation of semantic information, which meant a larger problem space for open-ended creativity.

Alpha coherence between frontal and temporal area

Information selection in creativity was not supported by the frontal or temporal area separately. Studies on closed-ended creativity showed that it was the functional connectivity between the frontal and temporal areas in the right brain that underlay the selection of novel information (Zhao et al., 2014b). Similar results were found in the current study compared with that in the normal solution, EEG coherence of both lower and upper alpha bands between the frontal and temporal area was higher in the creative solution. According to the different functions of the left and right brain in fine and coarse semantic processing (Jung-Beeman, 2005), it was suggested that alpha coherence in left brain might reflect inhibition of common semantic processing, while that in the right brain might be associated with the selection of novel semantic information.

Additionally, the frontal–temporal upper alpha coherence was lowest in the early phase of problem solving and then increased to the top of the middle phase. Since the neural interaction between the frontal and temporal area underlies the selection of information, this result might indicate that creative cognition took automatic and unconscious information retrieval as the principal thing in the beginning, and the selective inhibition increased afterward. This result was consistent with the interpretation of the dynamic change in lower alpha activity in the temporal area. Furthermore, upper alpha coherence between the bilateral temporal areas showed a similar change curve with the bottom at the beginning and the top in the middle. Given that neural coherence meant the functional cooperation between two areas, this result meant that the various semantic information was retrieved randomly and uncontrollably at the beginning, and then came into integration gradually.

Note that because there was no significant interaction between novelty and time epoch, the normal solution had similar curves as the novel solution. According to the model by Bink and Marsh (2000), creative cognition shared similar processes with non-creative cognition, and the crucial difference between them is the selection of novel information. Therefore, the similar change curves might reflect the common dynamic processes of open-ended problem solving, while the higher alpha power in frontal and temporal areas as well as the stronger frontal–temporal alpha coherence underlay the selection of normal information in the creative solution.

Difference between open-ended and closed-ended creativity

The advantage of the right brain in frontal–temporal connectivity was reported by a study on closed-ended creativity (Zhao et al., 2014b), while the current study on open-ended creativity did not find a hemispheric difference in frontal–temporal coherence. This difference might be due to the differences in cognitive processes between closed-ended and open-ended creativity.

Previous studies on closed-ended creativity mainly concentrated on insight problem solving, which included a stage of unconscious processing that emerged into consciousness in an all-or-nothing fashion (Salvi et al., 2016). Generally, the insight problem had a unique solution. Once the insight solution is clarified, novel information would be activated and common information would be inhibited. Accordingly, the neural activity of the right brain increased and that of the left brain decreased. The neuroimaging studies provided support for the idea that the right brain dominance in insight problem solving occurred in the time before the solution (Jung-Beeman et al., 2004; Zhang et al., 2011).

In comparison, in open-ended creativity, even though participants had generated an idea, there might be other solutions that were more in line with the problem. Therefore, the search and evaluation of ideas lasted until participants decided to report the solution. The behavioral result was that the solving time for the normal solution was longer than that in the novel solution, which might result from the continuous search process. Even when participants had come to a novel idea, the search might still continue to get a better one. This result meant the retrieval of both the novel and common information would continue until participants made a decision. In other words, compared with closed-ended creativity, open-ended creativity might be more dependent on the cooperation of the two hemispheres. In the current study, the higher coherence of lower alpha activity between the bilateral temporal areas in the novel solution might reflect more effective integration of close and remote semantic information in open-ended creativity.

CONCLUSION

Our results indicated that the alpha activities in frontal and temporal areas as well as their coherence were associated with information selection in open-ended creativity. Furthermore, the dynamic change in alpha power and coherence reflected the transformation from the divergent thinking to convergent thinking in creative progress. Finally, the result did not show a hemispheric difference in frontal–temporal alpha coherence, which might result from the non-uniqueness of the solution in open-ended creativity.

Acknowledgments—This study was supported by the National Natural Science Foundation of China (Grant No. 31400875 and 3147100), the Excellent Doctoral Student Support Project of Central China Normal University (Grant No. 2017YBZZ079), and the Open Research Fund of the State Key Laboratory of Cognitive Neuroscience and Learning (China) (Grant No. CNLZD1604).

REFERENCES

Abraham A, Pieritz K, Thybusch K, Rutter B, Kroger S, Schweckendiek J, Stark R, Windmann S, Hermann C (2012) Creativity and the brain: uncovering the neural signature of conceptual expansion. Neuropsychologia 50:1906–1917.

Allen AP, Thomas KE (2011) A dual process account of creative thinking. Creativity Res J 23:109–118.

Beaty RE, Benedek M, Kaufman SB, Silvia PJ (2015) Default and executive network coupling supports creative idea production. Sci Rep 5:10964.

Beaty RE, Benedek M, Silvia PJ, Schacter DL (2016) Creative cognition and brain network dynamics. Trends Cogn Sci 20:87–95.

Benedek M, Beaty R, Jauk E, Koschutnig K, Fink A, Silvia PJ, Dunst B, Neubauer AC (2014a) Creating metaphors: the neural basis of figurative language production. Neuroimage 90:99–106.

Benedek M, Jauk E, Fink A, Koschutnig K, Reishofer G, Ebner F, Neubauer AC (2014b) To create or to recall? Neural mechanisms underlying the generation of creative new ideas. Neuroimage 88:125–133.

Benedek M, Schickel RJ, Jauk E, Fink A, Neubauer AC (2014c) Alpha power increases in right parietal cortex reflects focused internal attention. Neuropsychologia 56:393–400.

Bink ML, Marsh RL (2000) Cognitive regularities in creative activity. Rev Gen Psychol 4:57–78.

Bowden EM, Jung-Beeman M, Fleck J, Kounios J (2005) New approaches to demystifying insight. Trends Cogn Sci 9:322–328.

Dietrich A, Kanso R (2010) A review of EEG, ERP, and neuroimaging studies of creativity and insight. Psychol Bull 136:822–848.

Doppelmayr M, Klimesch W, Hodlmoser K, Sauseng P, Gruber W (2005) Intelligence related upper alpha desynchronization in a semantic memory task. Brain Res Bull 66:171–177.

Fink A, Benedek M (2014) EEG alpha power and creative ideation. Neurosci Biobehav Rev 44:111–123.

Fink A, Grabner RH, Benedek M, Neubauer AC (2006) Divergent thinking training is related to frontal electroencephalogram alpha synchronization. Eur J Neurosci 23:2241–2246.

Fink A, Grabner RH, Benedek M, Reishofer G, Hauswirth V, Fally M, Neuper C, Ebner F, Neubauer AC (2009) The creative brain: investigation of brain activity during creative problem solving by means of EEG and fMRI. Hum Brain Mapp 30:734–748.

Fink A, Schwab D, Papousek I (2011) Sensitivity of EEG upper alpha activity to cognitive and affective creativity interventions. Int J Psychophysiol 82:233–239.

Finke RA, Ward TB, Smith SM (1992) Creative cognition: theory, research, and applications. Cambridge, MA: MIT Press.

Howard-Jones PA, Blakemore SJ, Samuel EA, Summers IR, Claxton G (2005) Semantic divergence and creative story generation: an fMRI investigation. Cognitive Brain Res 25:240–250.

Jausovec N (2000) Differences in cognitive processes between gifted, intelligent, creative, and average individuals while solving complex problems: an EEG study. Intelligence 28:213–237.

Jung-Beeman M (2005) Bilateral brain processes for comprehending natural language. Trends Cogn Sci 9:512–518.

Jung-Beeman M, Bowden EM, Haberman J, Frymiare JL, Arambel-Liu S, Greenblatt R, Reber PJ, Kounios J (2004) Neural activity when people solve verbal problems with insight. PLoS Biol 2:E97.

Klimesch W, Doppelmayr M, Rohm D, Pollhuber D, Stadler W (2000) Simultaneous desynchronization and synchronization of different alpha responses in the human electroencephalograph: a neglected paradox? Neurosci Lett 284:97–100.

Lin WL, Shih YL (2016) The developmental trends of different creative potentials in relation to children's reasoning abilities: From a cognitive theoretical perspective. Think Skills Creat 22:36–47.

Luo J (2004) Neural correlates of insight. Acta Psychol Sin 36:219–234.

Luo J, Niki K (2003) Function of hippocampus in "insight" of problem solving. Hippocampus 13:316–323.

Mai XQ, Luo J, Wu JH, Luo YJ (2004) "Aha!" effects in a guessing riddle task: an event-related potential study. Hum Brain Mapp 22:261–270.

Ohlsson S (2011) Deep learning: how the mind overrides experience. New York: Cambridge University Press.

Qiu J, Zhang QL (2008) "Aha!" effects in a guessing Chinese logogriph task: An event-related potential study. Chinese Sci Bull 53:384–392.

Qiu J, Li H, Jou J, Wu Z, Zhang Q (2008a) Spatiotemporal cortical activation underlies mental preparation for successful riddle solving: an event-related potential study. Exp Brain Res 186:629–634.

Qiu J, Li H, Yang D, Luo Y, Li Y, Wu Z, Zhang Q (2008b) The neural basis of insight problem solving: an event-related potential study. Brain Cognition 68:100–106.

Qiu J, Li H, Jou J, Liu J, Luo Y, Feng T, Wu Z, Zhang Q (2010) Neural correlates of the "Aha" experiences: evidence from an fMRI study of insight problem solving. Cortex 46:397–403.

Razumnikova OM (2007) Creativity related cortex activity in the remote associates task. Brain Res Bull 73:96–102.

Razumnikova OM, Tarasova IV, Vol'f NV (2009) Characteristics of cortical activity in persons with high and low verbal creativity: analysis of alpha1,2 rhythms. Zh Vyssh Nerv Deiat Im I P Pavlova 59:581–586.

Rhodes M (1961) An analysis of creativity. Phi Delta Kappan 42:305–310.

Salvi C, Bricolo E, Kounios J, Bowden E, Beeman M (2016) Insight solutions are correct more often than analytic solutions. Think Reasoning 22:443–460.

Sandkuhler S, Bhattacharya J (2008) Deconstructing insight: EEG correlates of insightful problem solving. PLoS One 3:e1459.

Schwab D, Benedek M, Papousek I, Weiss EM, Fink A (2014) The time-course of EEG alpha power changes in creative ideation. Front Hum Neurosci:8.

Wang M, Hao N, Ku Y, Grabner RH, Fink A (2017) Neural correlates of serial order effect in verbal divergent thinking. Neuropsychologia 99:92–100.

Wu X, Yang WJ, Tong DD, Sun JZ, Chen QL, Wei DT, Zhang QL, Zhang M, Qiu J (2015) A meta-analysis of neuroimaging studies on divergent thinking using activation likelihood estimation. Hum Brain Mapp 36:2703–2718.

Zabelina DL, Robinson MD (2010) Creativity as flexible cognitive control. Psychol Aesthet Crea 4:136–143.

Zhang M, Tian F, Wu X, Liao S, Qiu J (2011) The neural correlates of insight in Chinese verbal problems: an event related-potential study. Brain Res Bull 84:210–214.

Zhao QB, Zhou ZJ, Xu HB, Chen S, Xu F, Fan WL, Han L (2013) Dynamic neural network of insight: A functional magnetic resonance imaging study on solving Chinese 'chengyu' riddles. PLoS One 8:e59351.

Zhao QB, Zhou ZJ, Xu HB, Fan WL, Han L (2014b) Neural pathway in the right hemisphere underlies verbal insight problem solving. Neuroscience 256:334–341.

FURTHER READING

Fink A, Grabner RH, Gebauer D, Reishofer G, Koschutnig K, Ebner F (2010) Enhancing creativity by means of cognitive stimulation: Evidence from an fMRI study. Neuroimage 52:1687–1695.

Grabner RH, Fink A, Neubauer AC (2007) Brain correlates of self-rated originality of ideas: Evidence from event-related power and phase-locking changes in the EEG. Behav Neurosci 121:224–230.

Kaping D, Vinck M, Hutchison RM, Everling S, Womelsdorf T (2011) Specific contributions of ventromedial, anterior cingulate, and lateral prefrontal cortex for attentional selection and stimulus valuation. PloS Biol 9:e1001224.

Luo J, Niki K, Phillips S (2004) Neural correlates of the 'Aha! reaction'. NeuroReport 15:2013–2017.

Luo J, Niki K, Knoblich G (2006) Perceptual contributions to problem solving: Chunk decomposition of Chinese characters. Brain Res Bull 70:430–443.
Ragland JD, Ranganath C, Phillips J, Boudewyn MA, Kring AM, Lesh TA, Long DL, Luck SJ, Niendam TA, Solomon M, Swaab TY, Carter CS (2015) Cognitive control of episodic memory in Schizophrenia: differential role of dorsolateral and ventrolateral prefrontal cortex. Front Hum Neurosci 9:604.
Zhao QB, Li Y, Shang XL, Zhou ZJ, Han L (2014a) Uniformity and nonuniformity of neural activities correlated to different insight problems solving. Neuroscience 270:203–211.

(Received 20 July 2017, Accepted 6 December 2017)
(Available online 13 December 2017)