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

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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

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Abbreviations: ANOVA, analysis of variance; EEG, electroencephalograph; fMRI, functional magnetic resonance imaging.

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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