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Neural correlates of serial order effect in verbal divergent thinking

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ABSTRACT

During the course of divergent thinking (DT), the number of generated ideas decreases while the originality of ideas increases. This phenomenon is labeled as serial order effect in DT. The present study investigated whether different executive processes (i.e., updating, shifting, and inhibition) specifically contribute to the serial order effect in DT. Participants' executive functions were measured by corresponding experimental tasks outside of the EEG lab. They were required to generate original uses of conventional objects (alternative uses task) during EEG recording. The behavioral results revealed that the originality of ideas was higher in later stage of DT (i.e., Epoch 2) than in its earlier stage (i.e., Epoch 1) for higher-shifting individuals, but showed no difference between two epochs for lower-shifting individuals. The EEG results revealed that lower-inhibition individuals showed stronger upper alpha (10–13 Hz) synchronization in left frontal areas during Epoch 1 compared to during Epoch 2. For higher-inhibition individuals, no changes in upper alpha activity from Epoch 1 to Epoch 2 were found. These findings indicated that shifting and inhibition contributed to create a serial order effect in DT, perhaps because individuals suppress interference from obvious ideas and switch to new idea categories during DT, thus more original ideas appear as time passes by.

1. Introduction

Divergent thinking (DT) is a facet of cognition that leads in various directions (Runco, 1999). It is usually referred to as a thought process used to generate original ideas by exploring diverse possible solutions, which is involved in many creative efforts (Kaufman et al., 2008). It was demonstrated that during the course of DT, the number of ideas decreases while the originality of ideas increases (Johns et al., 2001; Milgram and Rabkin, 1980; Phillips and Torrance, 1977; Runco, 1986; Ward, 1968). This phenomenon has been labeled as *serial order effect* and was first introduced by Christensen and his colleagues (Christensen et al., 1957). The present study aimed to investigate whether different executive processes specifically contribute to the serial order effect in DT, and explore electroencephaographical (EEG) correlates underlying the effects of executive processes on the serial order effect in DT.

1.1. Executive processes and divergent thinking

Divergent thinking is, according to the *controlled-attention theory of creative cognition* (Beaty et al., 2014b), a top-down process that involves executive processes (see also Runco, 1994). Previous studies revealed that some control processes affected DT performance, such as fluid intelligence (Beaty et al., 2014b; Jauk et al., 2013, 2014) and working memory capacity (De Dreu et al., 2012; Hao et al., 2015; Lee and Therriault, 2013). Recent psychometric studies demonstrated that inhibitory function had positive correlation with DT performance (Benedek et al., 2012), and DT performance was positively predicted by both inhibitory and updating functions (Benedek et al., 2014a). Furthermore, more creative individuals exhibited higher levels of inhibition than less creative individuals (Edl et al., 2014).

Plenty of EEG studies revealed that EEG activity in the alpha band was highly sensitive to certain creativity-related factors (see Fink and Benedek, 2014). First, the performance of creativity-demanding tasks induces stronger event-related synchronization of alpha (ERS; i.e., task-related band power increases relative to baseline) than the performance of "convergent" or intelligence-related tasks (Bazanova and Aftanas, 2008; Fink et al., 2007, 2009a; Martindale and Hasenfus, 1978). Likewise, alpha ERS was found to be related to divergent rather than convergent modes of thinking within the same task (Jauk et al., 2012). Second, more original ideas were accompanied by a stronger alpha activity at the central-parietal (and to some minor extent also at the anterior-frontal) sites (Fink and Neubauer, 2006; Grabner et al., 2007). Third, alpha ERS correlated with an individual's creative level (i.e., more creative individuals showing stronger alpha power than less creative ones when performing creativity tasks) (Fink et al., 2009a,

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2009b; Jausovec and Jausovec, 2000; Martindale et al., 1984). Fourth, alpha ERS was sensitive to a verbal creativity training (Fink et al., 2006) and to short-lasting creativity interventions (i.e., exposure to other people's ideas and induction of positive affection) (Fink et al., 2011). Fifth, enhancing alpha power of the frontal cortex using 10 Hz transcranial alternating current stimulation (10 Hz-tACS) increased facets of creativity, but 40 Hz-tACS unfolded no effects, which suggests that alpha activity in frontal brain areas is selectively involved in creativity (Lustenberger et al., 2015). Notably, Alpha ERS has traditionally been considered to reflect cortical deactivation (Pfurtscheller and da Silva, 1999), whereas alpha event-related de-synchronization (ERD; i.e., band power decreases) reflects cortical activation (Klimesch, 1999). However, alpha ERS has recently been found to reflect a form of top-down activity (Payne and Sekuler, 2014; von Stein and Sarnthein, 2000), such as the inhibition of interfering memories (Hanslmayr et al., 2011; Jensen and Mazaheri, 2010; Klimesch et al., 2007), or a state of heightened internal attention (Benedek et al., 2011, 2014b; Fink and Woschnjak, 2011; Handel et al., 2011; Jaarsveld et al., 2015; Klimesch et al., 2007). Hence, the aforementioned EEG researches support the important roles of executive processes in DT.

Recent fMRI studies also indicated that executive processes were involved in DT. Beaty et al. (2015) assessed dynamic interactions between brain regions (e.g., the default-mode, control, and salience networks) during DT. The results revealed that the posterior cingulate cortex (PCC) showed increased coupling with regions of the control network (i.e., dorsolateral prefrontal cortex, DLPFC) and salience network (i.e., bilateral insula). Moreover, the dynamic interaction between these networks depended on the stage of DT; that is, the PCC showed early coupling with the right anterior insula and later coupling with the right DLPFC. Similarly, Beaty et al. (2017) investigated dynamic interactions between the default-mode, control and salience networks in solving a verb generation task (a DT task). They found that the default-mode and control networks exhibited strong functional connectivity when participants solving task in the high-constraint (i.e., high semantic interference) condition. These findings suggest that interactions between the default and control networks may underlie response inhibition during constrained idea production. Another fMRI study demonstrated that the originality of DT responses (accessed by trained raters) predicted increased functional coupling of the ventral ACC and the left angular gyrus (Mayseless et al., 2015), which are regions involved in cognitive control and self-generated thoughts, respectively. The important roles of the control network in DT are also supported by the resting-state fMRI studies. Beaty et al. (2014a) examined resting-state network patterns in people with better DT ability. The results revealed that highly creative participants showed increased coupling of default network regions with the left inferior frontal gyrus, a region associated with cognitive control that is widely implicated in studies of DT. Zhu et al. (2017) used functional connectivity analysis of resting-state fMRI data to investigate visual and verbal creativity-related regions and networks. They found the strength of connectivity between the default network and the control network was positively related to both creative domains. In a recent review, Beaty and his colleagues (Beaty et al., 2016) proposed that the default network contribute to the generation of candidate ideas (potentially useful information derived from long-term memory) in light of its role in self-generated cognition, while the control network would often be required to evaluate the efficacy of candidate ideas and modify them to meet the constraints of task-specific goals. Such a proposal was highlighted in another review (Zabelina and Andrews-Hanna, 2016), in which it suggests DT, especially its later stages, may benefit from the dynamic cooperation of the default network and control network.

1.2. Possible effects of executive processes on the serial order effect in DT

Why does the number of ideas decrease but the originality of ideas increase during the course of DT? According to the associative model of creativity (Mednick, 1962), DT is considered as a process of spreading activation through related semantic networks. The neighboring ideas in the semantic network are usually thought as being common and less creative, while the more remote ideas are regarded to be more unusual and creative. Understandably, it takes some time for distant associations or concepts to be activated and connected; creative ideas may hence emerge later than more common ideas, and ideas become increasingly sparse as time passes by. In this vein, the serial order effect in DT reflects the gradual spreading of activation towards increasingly remote associations (Beaty and Silvia, 2012; Wallach and Kogan, 1965).

However, some executive processes may also account for the serial order effect in DT. First, executive switching helps individuals stop generating ideas in one category and switch to another category, which could create a serial effect. More specifically, people typically start with a salient and obvious category in solving the DT problems. Once the category is exhausted, they need to stop the search process, switch to a new category, and then construct responses within it. Previous studies revealed that some people (those with lower intelligence and working memory span) had difficulties in such deliberate control of cognition; they switch less often and hence have fewer ideas in verbal fluency tasks (Unsworth et al., 2011) and less creative ideas in DT tasks (Nusbaum and Silvia, 2011a). Understandably, if people first exhaust an obvious category and then stop and switch to new idea categories, their later responses will be better than their earlier responses. Second, executive inhibition helps suppress task-irrelevant information (Carson et al., 2003; Klimesch, 2012), which could also create a serial order effect. That is, obvious, common ideas come to mind first; as time passes, more original ideas appear when people overcome interference from obvious ideas and early responses. This proposal was supported by a recent study (Beaty and Silvia, 2012), in which participants were asked to solve a verbal DT problem in 10 min. The results showed that compared to participants with lower fluid intelligence (i.e., Gf), participants with higher Gf started with more original ideas, and the originality of their ideas remained at a high level of quality across time. The authors suggested that this effect might be driven by executive mechanisms; that is, participants with higher Gf can inhibit the salient but unoriginal ideas that typically come to mind at the beginning of DT (Beaty and Silvia, 2012). Third, updating supports the active maintenance of task-relevant information and the controlled search from memory (Unsworth and Engle, 2007), which could create a serial order effect as well. It is known that creative ideas originate from the successful association of previously unrelated concepts taken from memory (Mednick, 1962). Fertile strategies for idea generation involve the controlled search and selective retrieval from memory. Updating is involved in the identification and maintenance of relevant cues that help delimiting the actual search set (Unsworth and Engle, 2007). From the point of view, updating may help people continue to retrieve semantically remote but useful concepts from memory, and then produce more creative ideas as time passes by.

1.3. The present study

Up to now, it is still an open question how executive processes play roles in the serial order effect in DT. The present study aimed to investigate whether different executive processes (i.e., updating, shifting, and inhibition) specifically contribute to the serial order effect in DT, and explore the EEG correlates underlying the effects of executive processes on the serial order effect in DT. We particularly addressed two questions. First, are brain activity patterns different between the earlier and later stages of DT, which may reflect different roles of