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Widespread neural oscillations in the delta band dissociate rule convergence from rule divergence during creative idea generation

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ABSTRACT

Critical to creative cognition and performance is both the generation of multiple alternative solutions in response to open-ended problems (divergent thinking) and a series of cognitive operations that converges on the correct or best possible answer (convergent thinking). Although the neural underpinnings of divergent and convergent thinking are still poorly understood, several electroencephalography (EEG) studies point to differences in alpha-band oscillations between these thinking modes. We reason that, because most previous studies employed typical block designs, these pioneering findings may mainly reflect the more sustained aspects of creative processes that extend over longer time periods, and that still much is unknown about the faster-acting neural mechanisms that dissociate divergent from convergent thinking during idea generation. To this end, we developed a new event-related paradigm, in which we measured participants' tendency to implicitly follow a rule set by examples, versus breaking that rule, during the generation of novel names for specific categories (e.g., pasta, planets). This approach allowed us to compare the oscillatory dynamics of rule convergent and rule divergent idea generation and at the same time enabled us to measure spontaneous switching between these thinking modes on a trial-to-trial basis. We found that, relative to more systematic, rule convergent thinking, rule divergent thinking was associated with widespread decreases in delta band activity. Therefore, this study contributes to advancing our understanding of the neural underpinnings of creativity by addressing some methodological challenges that neuroscientific creativity research faces.

1. Introduction

Creativity, the ability to generate ideas that are not just novel and original but also potentially useful (Amabile, 1996), allows us to adapt to a constantly changing environment and is arguably the hallmark of human mental capacity. Creativity is a complex construct that encompasses a range of different cognitive processes, such as the inhibition of mundane ideas, cognitive flexibility, and the recombination of information into new patterns (Dietrich, 2004; Nijstad et al., 2010). Laboratory studies have typically focused on a subset of the underlying processes, such as the difference between divergent and convergent thinking (e.g., Chermahini and Hommel, 2010). Divergent thinking is defined as the generation of multiple alternative solutions in response to open-ended problems (Guilford, 1967). For example, in the Alternate Uses Task, participants are asked to generate as many new uses for a common object (such as a brick) as they can think of. Divergent thinking performance benefits from a lack of inhibition between alternative thoughts, the quick abandoning of (implicit) rules and examples, approaching a problem from several different angles, and the forming of associations on the basis of remotely related knowledge (Chermahini and Hommel, 2010; Cropley, 2006; Larey and Paulus, 1999; Nijstad et al., 2010).

The definition and operationalization of convergent thinking varies considerably across studies. Some authors have equated convergent thinking with intelligence-related, as opposed to creativity-related, cognitive processes and measure convergent thinking with anagram tasks (Benedek et al., 2011), or tasks that require people to report common, as opposed to original, uses for specific objects (Jauk et al., 2012). Others have defined convergent thinking as a series of cognitive operations that converges on the correct or best possible answer

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(Cropley, 2006; Krug et al., 2003) and have measured convergent thinking with arithmetic tasks (Krug et al., 2003) or tasks in which people evaluate and choose the best solution from a pool of candidate solutions for implementation (Basadur et al., 2000; Runco, 2008). Yet other researchers propose that convergent thinking involves the recombination of familiar and closely related knowledge into multiple ideas, with convergent thinking being expressed in a limited range of semantic categories that are considered during idea generation (Larey and Paulus, 1999; Nijstad and Stroebe, 2006; Rietzschel et al., 2007). To accommodate these different treatments of convergent thinking, Cropley (2006) proposed that convergent thinking can best be understood as a syndrome of more or less related processes, including combining what "belongs" together, achieving accuracy and correctness and homing in on the single best answer, reapplying set techniques, sticking to the rules, sticking to a narrow range of obviously relevant information, and the forming of associations from adjacent fields. Just like divergent ideation, convergent idea generation may lead to creative ideas, but this happens in small, incremental steps (Finke, 1996; Kohn and Smith, 2010; Nijstad and Stroebe, 2006; Rietzschel et al., 2007).

Studies in social and cognitive psychology have greatly advanced our understanding of the contextual factors, personality characteristics, and cognitive mechanisms associated with divergent and convergent thinking (e.g., Baas et al., 2011; Carson et al., 2003; De Dreu et al., 2012; Hommel, 2012; Zabelina et al., 2016). These studies combined provide a solid body of knowledge from which the next generation of questions can be approached. One such next step is to uncover the neural substrates of creative performance in general, and divergent and convergent thinking in particular. However, this endeavor is methodologically challenging for two main reasons. First, tracking the neural substrates of divergent and convergent thinking requires repeated testing of time-locked divergent and convergent processes in a large number of trials. Second, it requires the selection of suitable comparison tasks (Abraham and Windmann, 2007; Fink et al., 2007).

This challenge has been taken up in several pioneering EEG studies that have contrasted divergent with convergent thinking. The common and key finding in these studies is the observation of higher alpha-band activity over frontal and parietal areas during divergent as compared to convergent thinking, which is broadly interpreted as reflecting higher internal processing demands for divergent thinking (Fink and Benedek, 2014; Jauk et al., 2012; Klimesch et al., 2007; Krug et al., 2003). In these studies, divergent thinking was typically measured with open-ended idea generation tasks, such as the Alternate Uses Task (Guilford, 1967). As discussed above, convergent thinking was measured with very different tasks, including anagram tasks (Benedek et al., 2011), arithmetic tasks (Krug et al., 2003), or tasks that require people to report common, as opposed to original, uses for specific objects (Jauk et al., 2012). These experimental designs can therefore be considered as typical *block designs* in which divergent and convergent thinking are measured across separate tasks or blocks of trials. While such designs can provide valuable information about the more sustained aspects of these creative processes, extending over several trials, we were here interested in the neural mechanisms that dissociate the switch from divergent to convergent thinking, and vice versa, on a trial-to-trial basis. When measuring divergent and convergent thinking in separate blocks of trials, block-related differences relating to changes in motivation and attention may influence findings. Further, the tasks that have been used to measure divergent and convergent thinking so far likely rely upon different strategies for successful task performance and may differ on several crucial aspects, besides the variable of interest (i.e., convergent vs. divergent thinking). These relatively unspecific factors may include the overall difficulty level of the tasks and the extent to which the tasks rely on existing knowledge. Thus, if one is interested in directly comparing divergent and convergent thinking, an *event-related design* that can track fast changes in thinking mode is desirable. Here we present such a novel task.

Our aim was to unravel the unique oscillatory mechanisms underlying specific cognitive processes that are part of the broader psychological constructs convergent thinking and divergent thinking in idea generation. To do so, we measured EEG in a new event-related design in which subjects engaged in idea generation dynamically across time and within a single task. In our adapted version of the *Pasta task* (De Dreu et al., 2014; Dijksterhuis and Meurs, 2006; Gocłowska et al., 2014; Marsh et al., 1999), participants were given three examples of non-existing category names, for example pasta names all ending with an 'i' (e.g., 'fussilini, 'falucci, 'krapi'). Participants were then asked to generate as many new pasta names as possible within a 30-second time period. Their responses could be scored as being rule convergent (number of names ending with an 'i', following the implicit rule given in the instructions) and rule divergent (number of names not ending with an 'i', diverging from the implicit rule in the instructions) (De Dreu et al., 2014). Previous studies have validated the original Pasta task by showing that the outcome measures of this task are influenced by factors that enhance structured or flexible thinking in predictable ways (Boot et al., 2017b; De Dreu et al., 2014; Dijksterhuis and Meurs, 2006; Gocłowska et al., 2014). Crucially, our new task allowed us to assess "rule convergent" and "rule divergent" ideation retrospectively, based on the single-trial output that participants generated while they were performing the same task. Also, it allowed us to measure spontaneous switching between these thinking modes on a trial-to-trial basis. Independent of the implicit rule in the instructions, the names that participants generated on a particular trial could be classified as a repetition or a switch with respect to the ending of the generated name in the previous trial.

In addition, we manipulated participants' motivation across the different blocks of the idea generation task, because previous studies showed that a motivation to attain positive outcomes is associated with more flexible idea generation than a motivation to avoid negative outcomes (Roskes et al., 2012). By providing participants with an opportunity to win a bonus during this task, we aimed to explore the possibility that a focus on possible gains vs. losses would influence behavioral and EEG indices of creative idea generation. Also, previous studies have associated spontaneous eye blink rate, an indirect marker of dopaminergic activity (Groman et al., 2014), with improved divergent but not convergent thinking (Chermahini and Hommel, 2010, 2012), suggesting that convergent and divergent processes in creativity are differently modulated by dopamine. To assess whether these findings extend to the more specific rule convergent and rule divergent processes measured in the present study, we recorded participants' eye blink rate during a resting-state period prior to the idea generation task.

2. Methods

2.1. Participants and procedure

We recruited 37 students at the University of Amsterdam to participate in this study for money or course credit. Six participants were excluded, because they generated an insufficient number of divergent names (< 20) for reliable analysis of the EEG signal, resulting in a final sample of 31 participants (22 females; $M_{\text{age}} = 21.4$ years, $SD = 2.3$). During the experimental session, we first measured spontaneous eye blink rate during a five-minute resting-state period. Subsequently, participants engaged in a creative idea generation task while we recorded EEG. In total, the session took approximately two hours. Informed consent was obtained from all participants, and the study was approved by the Ethics Committee of the University of Amsterdam.

2.2. Task

We measured rule convergent and rule divergent thinking using an adaptation of the *Pasta task* (Dijksterhuis and Meurs, 2006; Marsh et al., 1999). In the original task, participants are given three examples of non-existing pasta names all ending with an 'i' (e.g., 'fussilini, 'falucci,