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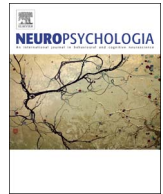
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Widespread neural oscillations in the delta band dissociate rule convergence from rule divergence during creative idea generation



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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’,

'krapi'), and then generate as many new pasta names as possible within one minute. From their responses, indices for rule convergent thinking (the number of items ending with an 'i', the cue given in the instructions) and rule divergent thinking (the number of items not ending with an 'i') could be created. In addition, we created indices for category repetitions (the number of times in which participants consecutively generated pasta names with the same ending), category switches (number of times in which participants switched from one ending, e.g., 'i', to another ending, e.g., 'a'), the number of unique name endings, and creative fluency (the total number of generated names) (De Dreu et al., 2014). To be able to use this task in a neuroimaging setting, we generated 39 additional categories (e.g., pain killers) with three examples (e.g., 'paradon', 'maladon', 'haptadon'), all three ending with the same letter(s). After pretesting these new categories in a sample of 116 students, we selected the 29 categories that produced the most variable responses in terms of participants' divergence from the examples and used these in the present EEG experiment, in addition to the original pasta category. All categories and their examples are shown in the Appendix A.

In the resulting Alternate Names Task (ANT), participants generated new names for 30 categories during separate 30-second segments, while we recorded EEG. Participants were seated in front of a computer and could type their new names on the screen. To prevent the EEG signal associated with the generation of ideas from being contaminated by brain activity associated with the typing of ideas and other artifacts (e.g., muscle artifacts), we divided the 30-second intervals into self-paced *idea generation intervals* and *typing intervals* (Fig. 1; see Fink et al., 2007, for a similar task procedure). At the beginning of each category segment, the category and three examples of new names were displayed on the screen. Participants were instructed to "think of new names for [category] such as [examples]". After reading the category and examples, participants could press a key to start thinking about potential new names, upon which a fixation cross appeared on the screen, indicating the start of the *idea generation interval*. We instructed participants to press the space bar as soon as they had generated a new name that they wanted to type in. Then, a typing window would appear in which the participant could enter the new name (i.e., the *typing interval*). After pressing 'enter' to finalize the response, the fixation cross would reappear and participants could continue to generate new names in the same category until the end of the category segment. Importantly, time stopped running during typing intervals to make sure that the number of possible ideas that participants could generate for

each category would not be influenced by individual differences in typing speed. To ensure that the 1.5 s generation interval that we used in the EEG analyses would not overlap with the preceding typing interval, participants could not respond within 1.5 s after ending the previous typing interval. On average, category segments (including both idea generation and typing intervals) lasted 55.80 s ($SD = 7.88$). To get used to the separation between idea generation and idea typing, participants first completed two practice category segments. The task was divided into six blocks of five category segments. After each block, we asked participants to indicate on a 7-point scale how motivated they were (1 = *not motivated at all*; 7 = *very motivated*) and how difficult they found the task (1 = *not difficult at all*; 7 = *very difficult*) during the preceding block. Subsequently, participants could take a break from the task if desired.

We removed duplicate names and existing names from the data prior to the analysis. Switch and repetition trials were defined as trials on which participants switched to a different name ending compared to the previous trial or repeated the same ending, respectively, regardless of whether that trial was a rule convergent or a rule divergent trial. Thus, switch trials included both trials on which participants switched from a rule convergent to a rule divergent name and vice versa. Similarly, repetition trials included both repetitions of rule convergent name endings and rule divergent name endings. Because switches and repetitions were determined with respect to the previously generated name, these indices could not be determined for the very first name that participants generated for a particular category. Therefore, the maximum number of switches and repetitions was always one less than the total number of new names. Unique name endings were defined based on the name ending shared by the examples for a certain category, which could consist of either one or multiple letters (see Appendix A; name endings shared by the examples of each category are printed in bold). Because we were interested in participants' relative (in)flexibility in generating names, we calculated proportions for the number of rule convergent and rule divergent names by dividing these indices by the total number of generated names (reflecting participants' relative tendency to follow the rule set by the examples vs. breaking the rule). Similarly, we calculated proportions for the number of repetitions and switches (reflecting participants' tendency to repeat the same name ending vs. to switch to another name ending), and the number of unique name endings that participants used (reflecting participants' relative flexibility in generating names with different endings).

2.3. Incentivizing performance: gains versus losses

We incentivized performance by providing participants with an opportunity to earn a bonus during the ANT. At the start of each block, we asked participants to memorize a randomly selected two-digit number that they had to report back at the end of that block. At the start of gain blocks, we told participants that they could earn one euro during that block by remembering the number during the five category segments of that particular block. At the start of loss blocks, we informed participants that they would lose one euro if they would not be able to correctly report the number at the end of the block. Memorizing a two digit number is relatively easy and does not detectably affect performance on a concurrent cognitive task (Baddeley and Hitch, 1974; De Dreu et al., 2012), so we reasoned that this manipulation would not influence idea generation. To make clear that participants' performance on the idea generation task was the main focus of this study, we emphasized that participants were not to prioritize the memorization of the numbers over the generation of new names at the end of the task instructions, right before participants started generating new names: "Finally: try to memorize the numbers as well as possible, but at the same time do not let this distract you from the task in which you are required to think of new names. This task is crucial for the success of this research project". All but two participants (who failed to memorize the number on one occasion) correctly reported the two-digit number

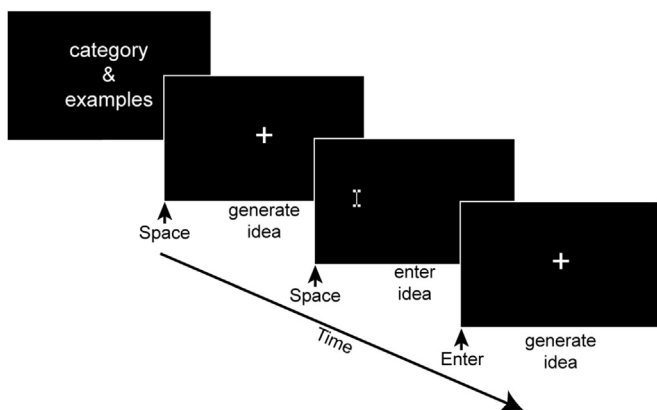


Fig. 1. Example of a category segment from the Alternate Names Task. At the start of each category segment, participants read the category that they had to generate new names for and three examples of such names. After participants pressed a key to start the self-paced *idea generation interval*. Participants pressed the space bar whenever they had generated a new name that they wanted to type in, upon which a new window would appear in which the participant could enter the new name (i.e., the *typing interval*). After pressing 'enter' to finalize the response, the fixation cross would reappear and participants could continue to generate new names in the same category until the end of the category segment.

Table 1
Correlations between the different ANT creativity indicators.

	1.	2.	3.	4.	5.	6.	7.	8.
1. Fluency								
2. Rule convergent names	.90**							
3. Rule divergent names	.27	-.17						
4. Repetitions	.72**	.85**	-.26					
5. Switches	.03	-.37*	.90**	-.42*				
6. Number of unique endings	.01	-.41*	.94**	-.47**	.96**			
7. Proportion of rule divergent names	-.43*	-.74**	.73**	-.68**	.82**	.85**		
8. Proportion of switches	-.59**	-.78**	.45*	-.65**	.73**	.65**	.87**	
9. Proportion of unique endings	-.79**	-.92**	.30	-.74**	.54**	.55**	.84**	.93**

Note.

* $p < .05$.

** $p < .01$.

after each block, indicating that participants had no difficulty memorizing the numbers. The average difficulty that participants reported at the end of each block was 3.00 on a 7-point scale ($SD = .66$), further suggesting that memorizing the numbers while generating new names was not too difficult. To make sure that participants would never lose money, each participant's bonus was set to three euros at the beginning of the experiment. Gain and loss blocks alternated over the course of the experiment and the type of block presented first was counterbalanced across participants.

2.4. EEG recording

We recorded EEG at 1024 Hz using a BioSemi ActiveTwo 64 channels system, with electrodes placed according to the international 10–20 system. Two reference electrodes were placed at the earlobes. The horizontal and vertical electrooculogram (EOG) were measured using bipolar recordings from two electrodes placed approximately 1 cm lateral of the outer canthi of the eyes and two electrodes placed approximately 2 cm above and below the participant's right eye.

2.5. EEG preprocessing and data analysis

The raw EEG data was downsampled to 512 Hz and rereferenced to the average signal from the earlobe electrodes. We applied a high-pass and low-pass filtered at .5 and 100 Hz, respectively. The continuous EEG data was epoched into intervals of -2.5 to $+1.5$ s surrounding the response indicating the end of the idea generation interval to prevent edge artifacts from contaminating the oscillatory activity in the idea generation interval. Bad channels were identified through visual inspection of the data and replaced by interpolation. Epochs containing artifacts were discarded. We computed an independent component analysis using EEGLAB software (Delorme and Makeig, 2004) and removed components containing eye blinks, oculomotor artifacts, and other artifacts that could be clearly distinguished from the brain-driven EEG signal. On average, 122.55 rule convergent epochs ($SD = 75.84$), 64.13 rule divergent epochs ($SD = 33.37$), 102.19 repetition epochs ($SD = 77.75$), and 58.29 switching epochs ($SD = 30.05$) were available for each participant.

Time-frequency analyses were performed in Matlab. We applied complex wavelet convolution with frequencies ranging from 1 to 40 Hz in 30 linearly spaced steps. Power was normalized using a decibel (dB) transform ($10 \times \log_{10}[\text{power}/\text{baseline}]$). Because our task did not include a pre-stimulus baseline period, we used the average power across all trials and conditions during the 1.5 s interval prior to the response indicating the end of the idea generation interval as a baseline for each frequency and each individual. Thus, the EEG power signal that we used in the analyses reflects the relative power differences across conditions between conditions rather than the power relative to a baseline period. Subsequently, we calculated a difference signal by subtracting the power for rule convergent trials from the power in rule divergent

trials over the entire time window and used four t -tests to determine whether this difference signal was significantly different from zero in four predefined frequency bands (delta: 1–4 Hz, theta: 4–8 Hz, alpha: 8–12 Hz; beta: 12–25 Hz). Similarly, we calculated the difference signal for trials associated with repetitions and switches with respect to the previously generated name ending and tested the significance of this difference.

2.6. Eye blink rate

We recorded eye blink rates from the vertical EOG channels during a five-minute resting-state period in which participants passively viewed a fixation cross on the screen. We standardized signal amplitude at each time point and defined blinks as the signal amplitude exceeding the mean amplitude by 2 standard deviations, following the previous blink by at least 390 ms (based on visual inspection of the data).

3. Results

3.1. Descriptive statistics

On average, participants generated 6.41 ideas ($SD = 2.69$) per category in 30 s. On average, 4.41 (68.8%) of those ideas were rule convergent ($SD = 2.61$) and 2 (31.2%) of those ideas were rule divergent ($SD = 1.31$). On average, participants generated names with 1.99 different endings in each category ($SD = .71$).

Table 1 displays the correlations between the different ANT outcome measures (both absolute numbers and proportions). Fluency correlated with the total number of convergent names and repetitions, but not the total number of rule divergent names, switches, and unique name endings. However, fluency correlated negatively with the proportion of rule divergent names, switches and unique name endings, indicating that participants who generated many new names were generally less flexible in doing so. Indicators of flexible idea generation (i.e., rule divergent names, switches, and unique endings) were correlated among each other. These flexible creativity indicators were negatively correlated with rule convergent idea generation and the number of repetitions.

3.2. EEG results

3.2.1. Rule convergent versus rule divergent processes

To explore the EEG activity associated with the rule divergence effect (breaking the implicit rule set by the examples vs. following the rule), we first calculated the power difference between rule divergent and rule convergent ideation in the four predefined frequency bands averaged across all electrodes (Bonferroni-corrected for multiple comparisons due to the four frequency bands). We focused our analyses on the idea generation interval just prior to the response (see Methods). We were interested in the creative processes preceding a new name and this

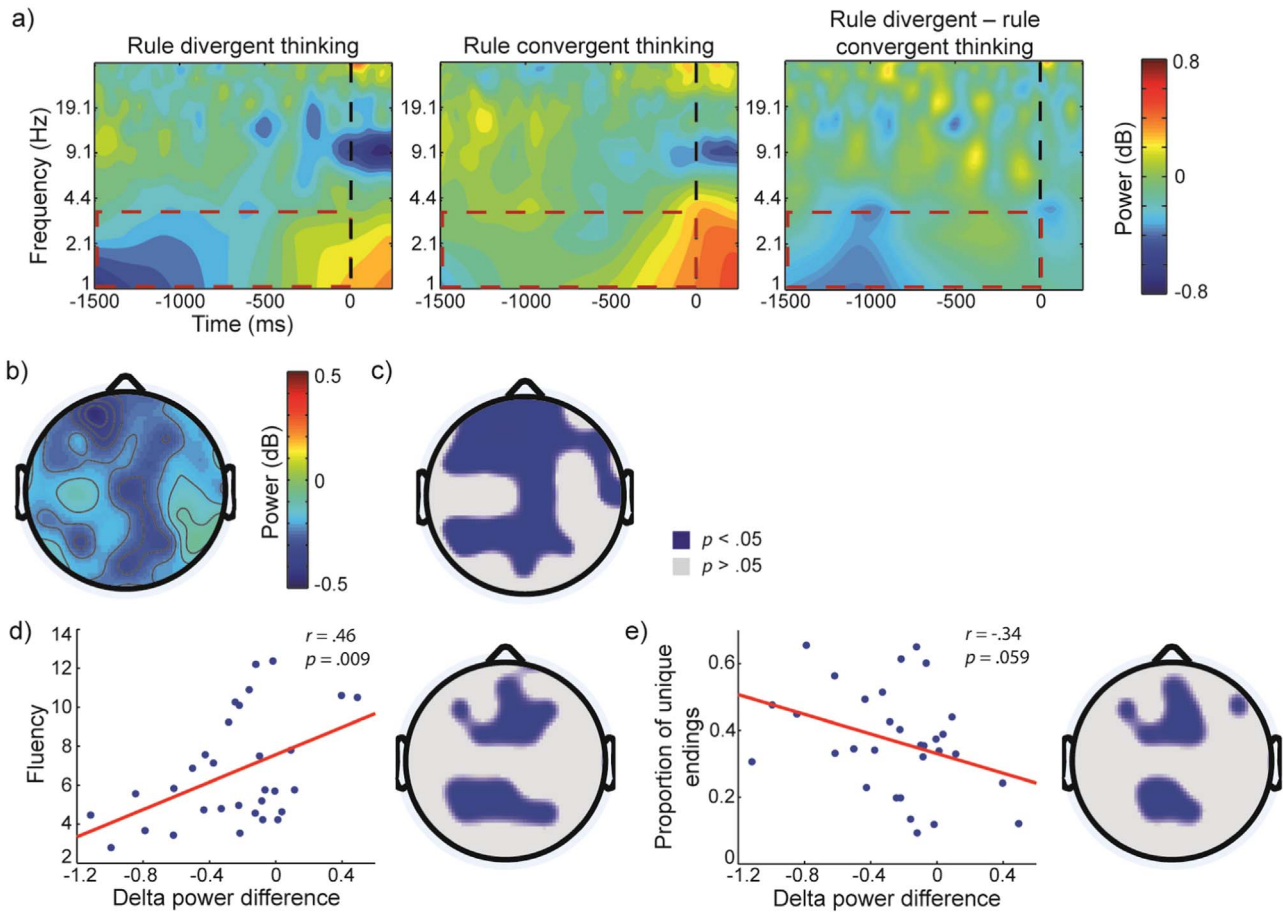


Fig. 2. Rule divergence effect in the delta band and correlations with creative idea generation. (a) Time-frequency maps of the rule divergent and rule convergent conditions and their difference, averaged across all electrodes. (b) Topographical distribution of the rule divergence effect in the delta band and (c) a thresholded headmap showing all electrodes with a $p < .05$ in blue. (d and e) Scatterplots of the association between the rule divergence delta band effect (averaged over all significant electrodes shown in 2c) and fluency (d) and the proportion of unique name endings (e), across all participants. For display purposes, thresholded headmaps of the electrode sites where the correlation with these behavioral indices was significant, masked by the electrodes in which the rule divergence effect was significant (from c), are also shown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

process is arguably less time-locked than traditional stimulus-locked processes in typical neuroscience tasks, so the processes may vary in time. Therefore, we defined the idea generation interval as the window of 1.5 s prior to the response indicating that the participant had generated a new name and tested the average power difference in this 1.5-second time window.

Fig. 2a displays the time-frequency maps of the rule divergent and rule convergent conditions separately, as well as their difference, averaged across all electrodes. The power difference in the idea generation window differed significantly from zero in the delta band only ($t_{30} = 3.31$, $p = .003$; all p s $> .085$ for the other three frequency bands). We then explored the topographical distribution of this effect and observed that it was relatively broadly distributed, as shown in Fig. 2b. For display purposes, Fig. 2c displays a thresholded headmap showing all electrodes with a $p < .05$ (in blue).

Subsequently, we assessed whether this widespread delta band modulation was related to behavioral outcomes of creativity (i.e., fluency, the proportion of rule divergent names, the proportion of switches, and the proportion of unique name endings). Therefore, we correlated the average delta power difference averaged over all significant electrodes (the cluster shown in blue in Fig. 2c) with participants' behavioral performance. The delta power difference correlated positively with fluency ($r = .46$, $p = .009$), indicating that a smaller (i.e., less negative) difference in delta power for rule divergent vs. rule convergent ideation was associated with enhanced fluency. Fig. 2d (left panel) shows the scatterplot of this correlation across subjects. To

visualize the topographical distribution of this correlation, Fig. 2d (right panel) also displays a thresholded headmap of all the individual electrodes in which this correlation was significant, masked by the electrodes in which the rule divergence effect was significant (all r s $> .393$, all p s $< .029$).

Moreover, we found a marginally significant negative correlation between the delta power difference in the cluster of significant electrodes (shown in Fig. 2c) and the proportion of the number of unique name endings that subjects used in this task (a measure that reflects flexible thinking; $r = -.34$; $p = .059$). This correlation indicates that larger (i.e., more negative) differences in delta power for rule divergent vs. rule convergent ideation were associated with greater flexibility in name generation. Fig. 2e (left panel) shows the scatterplot of this correlation across subjects. To visualize the topographical distribution of this correlation, Fig. 2e (right panel) also displays a thresholded map of all the individual electrodes in which this correlation was significant, masked by the electrodes in which the rule divergence effect was significant (all r s $> -.363$, all p s $< .05$).

Control analyses confirmed that these delta band results were not due to differences in trial number between conditions, because the rule divergence effect did not correlate consistently with the proportion of rule divergent names that people generated ($r = -.16$, $p = .383$; see Supplementary Fig. S1).

3.2.2. Trial-to-trial repetitions vs. switches

In addition to being rule convergent or rule divergent, the names

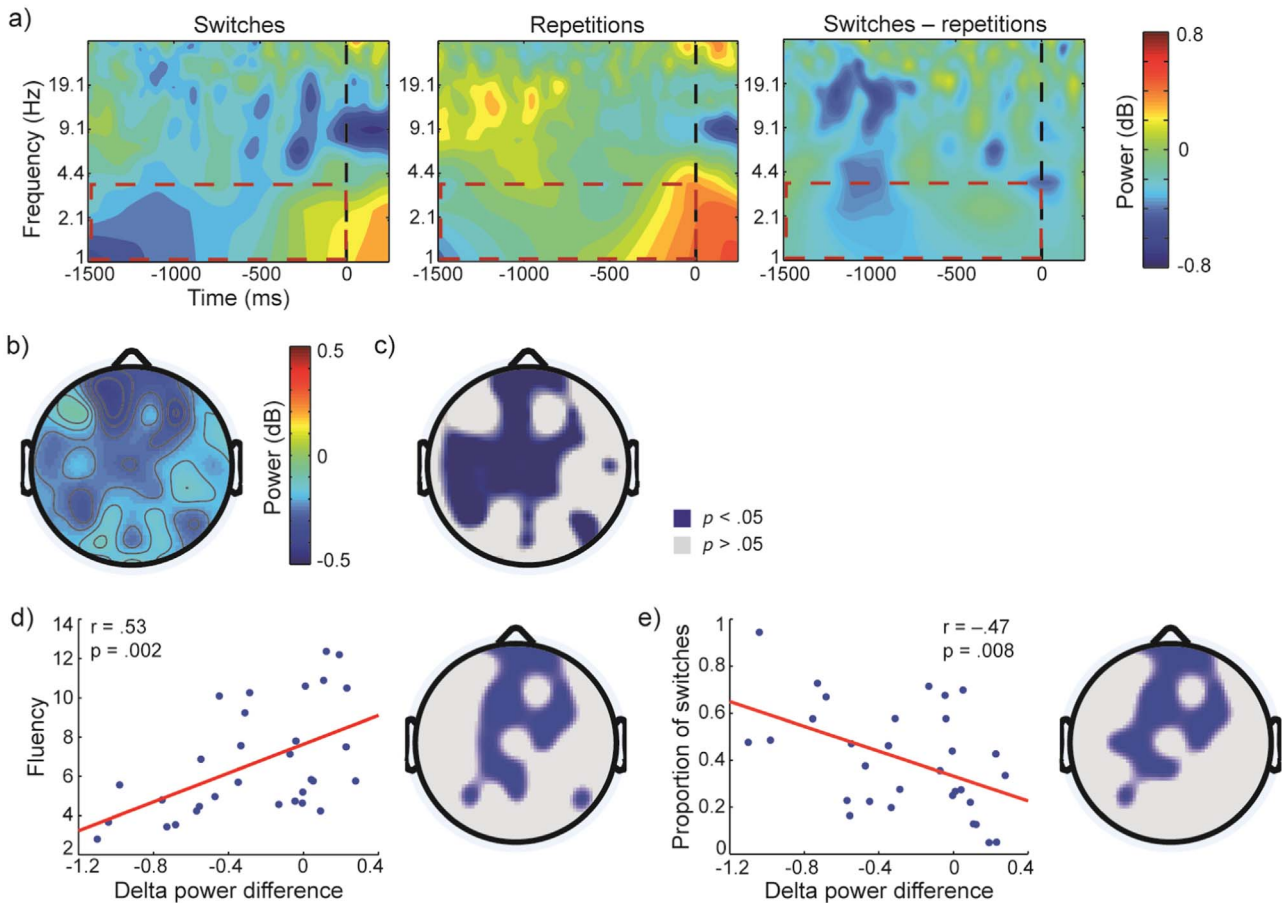


Fig. 3. Switching effect in the delta band and correlations with creative idea generation. (a) Time-frequency maps of the switching and repetition conditions, as well as their difference, averaged across all electrodes. (b) Topographical distribution of the switching effect in the delta band and (c) a thresholded headmap showing all individual electrodes with a $p < .05$ in blue. (d and e) Scatterplots of the association between the switching effect averaged over all significant electrodes (shown in 3c) and fluency (d) and the proportion of switches (e), across all participants. For display purposes, thresholded headmaps of the electrode sites where the correlation with these behavioral indices was significant, masked by the electrodes in which the rule divergence effect was significant (from c), are also shown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

that participants generated could also be classified as a repetition or a switch with respect to the ending of the generated name in the previous trial. Whereas the rule divergence effect reflects the overall breaking of the implicit rule towards a more creative, *out of the box* name, the switching effect reflects rule breaking on a much shorter time scale, compared to the previously generated name and independent of the rule presented in the examples. For switches vs. repetitions, we observed a power difference similar to the difference between rule divergent vs. rule convergent thinking. Fig. 3a displays the time-frequency maps of the switch and repetition conditions separately, as well as their difference, averaged across all electrodes. During the idea generation interval, the power in the delta ($t_{30} = -3.05, p = .005$), theta ($t_{30} = -3.74, p < .001$), alpha ($t_{30} = -2.82, p = .008$), and beta band ($t_{30} = -3.57, p = .001$) was weaker for switches compared to repetitions (Bonferroni-corrected for multiple comparisons). Although this switching effect was broad-band, only the difference in the delta band correlated positively with fluency ($r = .50, p = .004$), and negatively with the proportion of switches ($r = -.44, p = .01$) and the number of unique name endings ($r = -.47, p = .007$). This was not the case for all the other frequency bands (all r s $< .211$, all p s $> .254$), suggesting that it is mainly the modulation in the delta band that relates to creative idea generation. Fig. 3b shows the topographical distribution of the switching effect in the delta band, which was widely distributed. For display purposes, a thresholded headmap showing all individual electrodes with a $p < .05$ (in blue) is displayed in Fig. 3c. Fig. 3d shows the scatterplot of the correlation between the switching

effect (averaged across the cluster of electrodes in which the delta difference was significant, shown in Fig. 2c) and fluency. To visualize the topographical distribution of this correlation, Fig. 3d also displays a thresholded headmap of the individual electrodes in which this correlation was significant, masked by the electrodes in which the delta-band switching effect was significant (all r s $> .359$, all p s $< .05$). The scatterplots of the correlation between the switching effect and the proportion of switches is shown in Fig. 3e, together with a thresholded map of the individual electrodes in which this correlation was significant (all r s $> -.367$, all p s $< .05$), masked by the electrodes in which the switching effect was significant.

Although the switching effect correlated with the proportion of switches, it is unlikely that this effect was driven by an insufficient number of switching epochs compared to repetition epochs. In that case, this correlation would have been positive rather than negative (i.e., a smaller proportion of switches would be associated with a smaller delta effect).

3.2.3. Effects of motivation manipulation

We manipulated participants' motivation towards attaining a positive outcome vs. preventing a negative outcome across blocks of the ANT. Participants did not generate significantly more names while trying to attain a positive outcome ($M = 86.23$) or when trying to prevent to a negative outcome ($M = 84.13; t_{30} = 1.41, p = .168$). Also, this manipulation did not affect the proportion of divergent names that participants generated ($t_{30} = -1.71, p = .099; M_{\text{gain}} = .38, M_{\text{loss}} =$

.41). However, contrary to our expectations, the proportion of switches relative to repetitions was higher when participants were trying to prevent a negative outcome ($M_{\text{loss}} = .45$) than when they were trying to attain a positive outcome ($M_{\text{gain}} = .38$; $t_{30} = -3.66$, $p = .001$). Motivation ratings did not differ between gain and loss blocks ($t_{30} = -.06$, $p = .953$), and motivation ratings in general did not correlate with any of the creativity indicators (all $r_s < .18$, all $p_s > .343$). Also, this manipulation of motivation did not influence the EEG patterns in our study.

3.2.4. Eye blink rate

On average, participants blinked 15.3 times per minute (range: 4.6–30.2 times). Spontaneous eye blink rate was not correlated with any of the behavioral outcomes of the creativity task (all $r_s < .165$, $p_s > .352$).

4. Discussion

In this study, we explored the neural dynamics of rule convergent and rule divergent processes in creativity by comparing EEG power across different frequency bands while participants generated new names under mild cognitive load. We measured these dynamics using a newly developed event-related paradigm that allowed us to measure rule convergent and rule divergent ideation simultaneously, while keeping context and instructions constant. Moreover, our paradigm allowed us to assess relatively rapid, spontaneous switching between rule divergent and rule convergent thinking modes on a trial-to-trial basis. We found that power differences in the delta band in a widespread network differentiated rule divergent vs. rule convergent thinking, as well as switching vs. repeating a name ending from one idea generation interval to another, just before subjects indicated their creative outcome. These oscillatory dynamics were clearly related to behavioral indices of creativity. In both cases, the delta-band power difference was smaller for people who generated more new names during the task (a measure of overall fluency). In addition, the rule divergence and switching effects in the delta band were larger for those subjects who generated new names with more unique name endings and who switched between name endings more often.

Oscillations have been hypothesized to support the integration of large-scale networks (Buzsáki and Draguhn, 2004; Fries, 2005; Hipp et al., 2011) and the control of top-down information flow (Engel et al., 2001). For example, alpha-band activity may selectively route the flow of information according to task goals by selectively inhibiting brain areas representing task-irrelevant or distracting information (Haegens et al., 2011; Jensen and Mazaheri, 2010). This may be the physiological mechanism by which task-relevant areas become functionally coupled and decoupled according to task demands (Chadick and Gazzaley, 2011; Egnér and Hirsch, 2005). Less is known about the role of delta-band activity in coordinating large-scale networks (Nácher et al., 2013) and how delta activity may relate to creative idea generation is unclear. This notwithstanding, the present findings do not stand in isolation. For example, Bhattacharya and Petsche (2005) found stronger delta synchronization in artists compared to non-artists during mental composition of drawings. In another study, participants who were able to generate many unique figural patterns showed weaker delta activity compared to participants who generated fewer unique patterns (Foster et al., 2005).

Using an event-related design, the present study did not replicate the findings from a number of previous EEG studies that observed divergent vs. convergent thinking to be associated with differences in alpha-band activity (Fink and Benedek, 2014; Jauk et al., 2012; Krug et al., 2003). For example, Jauk et al. (2012) found that divergent thinking, measured as the generation of uncommon responses during the Alternate Uses Task, was associated with stronger alpha-band activity than convergent thinking, measured as the generation of common ideas during the same task. Potentially, the alpha-band effects found in

previous studies may reflect differences in the demands that the different tasks place on cognitive resources, rather than the fast-acting processes underlying the creative processes studied here (Fink and Benedek, 2014; Klimesch et al., 2007). Findings by Benedek et al. (2011) suggest that alpha power during creativity tasks may indeed reflect the level of internal processing required for task performance, but does not distinguish divergent from convergent thinking. In their study, an increase in alpha power was observed for both divergent and convergent thinking when the demands placed on cognitive resources were high, but not when these demands were low. In our study, we tried to keep external processing demands during rule divergent and rule convergent ideation constant by measuring both in the same event-related design rather than across different tasks or blocks of trials. Also, task-related effects found in block designs may be confounded by other relatively unspecific factors that differ across blocks, such as motivation and attentional processes. This may explain why we did not replicate the findings of previous studies.

Alternatively, differences between previous and present findings may result from the different approach to convergent and divergent thinking that we took in the present study. While previous studies have defined convergent thinking as a series of cognitive operations that converges on the correct or best possible answer (Krug et al., 2003) or have equated convergent thinking with intelligence-related, as opposed to creativity-related, divergent processes (Benedek et al., 2011), we focus on a more narrow subset of convergent and divergent processes, involving the convergence on, or divergence from, implicit rules during creative idea generation. Therefore, the findings of the present study are hard to directly compare to those of previous studies. Although alpha oscillations may well play a role in the broader constructs of convergent and divergent thinking, as suggested by a number of studies (see Fink and Benedek, 2014, for a review), our results indicate that they may not underlie relatively fast, spontaneous alternations between rule divergent and rule convergent ideation on a trial-to-trial basis. Also, the fact that we manipulated motivation during the ideation task in the present study may explain why we did not observe differences in alpha power between rule divergent and rule convergent thinking. Because being creative did not improve the chances of winning or preventing a loss of the bonus, it is possible that (some) participants prioritized memorization of the numbers over the generation of new names, although the proportions of convergent vs. divergent names, and repetitions vs. switches that participants generated were highly consistent with those observed in previous studies by our group (Boot et al., 2017b; De Dreu et al., 2014). Finally, previous studies have shown that the generation of more original ideas during a divergent thinking task was associated with more alpha-band activity compared to the generation of less original ideas (Fink and Neubauer, 2006; Grabner et al., 2007). The task that we used in the present study does not allow for an assessment of the originality of ideas, because the names that participants generated during this task were too variable to classify some new names as more uncommon than others. It would be interesting to assess the oscillatory dynamics that underlie the originality of both rule convergent and rule divergent idea generation and whether or not these involve alpha-band activity in future studies.

Creativity results from the interplay between a range of different cognitive processes and likely involves a large-scale neural network. Functional magnetic resonance imaging (fMRI) studies have associated creativity with a large number of brain areas, particularly areas in the prefrontal and parietal cortex (Dietrich and Kanso, 2010; Gonen-Yaacovi et al., 2013). Flexible, associative processes that characterize divergent thinking benefit from a relatively relaxed cognitive control state (Hommel, 2012) and enhanced processing of task-irrelevant information (Carson et al., 2003). Further, divergent thinking seems to be modulated by the (striatal) dopaminergic system (e.g., Boot et al., 2017a; Chermahini and Hommel, 2012, 2010; Zhang et al., 2014) and is associated with increased structural connectivity between frontal and posterior brain areas (Takeuchi et al., 2010). Convergent thinking

involves more top-down controlled processing (Hommel, 2012), strongly depends on working memory capacity (De Dreu et al., 2012), and can be enhanced by stimulation of the dorsolateral prefrontal cortex (Cerruti and Schlaug, 2009). Thus, it seems clear that creativity results from dynamic interactions between a large number of brain areas (Dietrich, 2004).

Oscillations in the delta band may relate to these functional interactions between areas in the large-scale neural network involved in creative processes, although evidence is rather indirect. Decreases in delta-band activity over fronto-central areas have been associated with increased activity in the default mode network (Jann et al., 2010). The default mode network is implicated in mind wandering (Buckner et al., 2008; Christoff et al., 2009), which has been shown to benefit the generation of original ideas in divergent thinking tasks (Baird et al., 2012). Further, recent studies have associated gray matter volume in areas of the default mode network, such as the ventromedial prefrontal cortex and the precuneus (Jauk et al., 2015; Kühn et al., 2014) and functional connectivity between these areas (Takeuchi et al., 2012) with enhanced divergent thinking. In line with the idea that convergent thinking requires relatively strong top-down cognitive control (Hommel, 2012), delta activity seems to be associated with inhibition of potentially interfering processes during cognitive tasks (Harmony, 2013; Prada et al., 2014). Divergent thinking, on the other hand, benefits from attentional flexibility (Zabelina et al., 2016) and enhanced processing of task-irrelevant information (Carson et al., 2003). Therefore, although speculative, differences in delta-band oscillations between rule convergent and rule divergent ideation may reflect differences in the relative flexibility and inhibition of task-unrelated processes that these two processes require.

In addition to the rule divergence effect in the delta band, we found that switching from generating a name with a certain ending to another ending involves broadband EEG activity, as reflected in decreased delta, theta, alpha, and beta power. To our knowledge, no other creativity study has investigated the electrophysiological correlates of spontaneous switching between thinking modes on a trial-to-trial basis. Switching between tasks or response rules requires people to retrieve goal representations into working memory, to inhibit dominant responses, and to shift attention to an alternative response set (Monsell, 2003). In the task-switching literature, such switch-related processes have been associated with activity in various frequency bands. Previous studies have reported power changes in delta (Prada et al., 2014), theta (Cunillera et al., 2012; Gladwin and De Jong, 2005), alpha (Cunillera et al., 2012; Gladwin and De Jong, 2005; Mansfield et al., 2012; Verstraeten and Cluydts, 2002), and beta activity (Cunillera et al., 2012). For example, Cunillera et al. (2012) found that switching between response rules according to auditory cues during a version of the Wisconsin Card Sorting Task was associated with increases in theta power over frontal areas following switch cues, while power in the alpha and beta bands decreased. However, most of these studies investigated task-switching in response to explicit instructions (e.g., Gladwin and De Jong, 2005) or external switch cues (e.g., Cunillera et al., 2012), whereas the switches in our study occurred spontaneously. As cued and voluntary task switches involve distinct preparatory processes and neural networks (Forstmann et al., 2006; Kang et al., 2014), it is unclear to what extent these findings are directly comparable. In our study, only differences in delta-band activity correlated with indices of creative idea generation, suggesting that activity in this frequency band was particularly relevant for idea generation processes.

It is important to note that the delta-band effects associated with the rule divergence and switching contrasts seemed very similar in our study. Although rule divergence and switching between different lines of thought are theoretically independent processes, in practice, the two were strongly correlated. Rule divergent names were more often switches away from the previous name ending than repetitions of the

previous name ending, whereas rule convergent names were more often repetitions than switches. Therefore, it is difficult to dissociate the rule divergence from the switching effect in the present design. By manipulating switching to and away from more rule divergent or rule convergent thinking modes during idea generation in future studies, it would be possible to assess whether activity in the delta band characterizes the rule breaking during idea generation, switching between different lines of thought, or both.

Contrary to findings in previous studies (Roskes et al., 2012), we found that participants were not more flexible in idea generation when focusing on possible gains compared to possible losses. Although the manipulation of motivation across blocks did not affect fluency or the proportion of divergent names that participants generated, participants switched to different name endings relatively more often during loss blocks compared to gain blocks of the ANT. Although speculative, the fact that participants were facing a potential loss during loss blocks may have made them pay less attention to the examples that were presented prior to each name generation interval, resulting in more switching between different name endings. Again, participants may have prioritized memorization of the numbers over the generation of new names, because being creative did not improve the chances of winning or preventing a loss of the bonus in our study. This may explain why we did not replicate previous findings. In addition, we did not replicate previous findings showing that spontaneous eye blink rate was associated with more flexible divergent thinking, but with reduced convergent thinking (Chermahini and Hommel, 2010, 2012). In our study, eye blink rate was not related to any of the behavioral indices of creativity, suggesting that the more specific rule convergent and rule divergent processes that we focused on here are not differentially modulated by dopamine.

In the present study, we have taken a rather exploratory approach. We used a novel task that targets more specific aspects of divergent and convergent thinking compared to previously used tasks, which may circumvent some methodological issues of block designs. Therefore, we did not have a priori hypotheses about the specific frequency band, the timing, or localization of possible effects. Overall, the delta-band difference between rule divergent and rule convergent ideation, and similarly between switches and repetition of name endings, seemed widespread, but the correlations with behavioral indices of creative ideation were limited to clusters of mainly frontal and parietal electrodes. It is tempting to conclude that these delta-band modulations have their neural origin in a large fronto-parietal network, as previous fMRI studies have also shown that frontal and parietal regions play a role in creative processes (Dietrich and Kanso, 2010; Gonen-Yaacovi et al., 2013). However, as the spatial resolution to determine the neural origin of oscillatory activity is quite poor in EEG studies, future fMRI studies may provide more precise information on the neural origin of the mechanisms that dissociate rule divergent from rule convergent thinking in this task.

Although it is difficult to interpret the reported rule divergence and switching effects in terms of specific underlying neural mechanisms, the present study contributes to advancing our understanding of the neural underpinnings of creativity also by resolving the methodological challenges that neuroscientific creativity research faces. By increasing the comparability between different creative processes (rule divergent vs. rule convergent ideation) in a new paradigm, we showed that relatively flexible, divergent processes in creative idea generation are associated with decreases in delta-band activity compared to more systematic, convergent processes. To further explore the neural mechanisms underlying different aspects of creativity, including flexibility and originality, we believe that future studies should focus on developing similar event-related paradigms in which creative sub-processes can be tracked on a trial-to-trial basis and can therefore be directly linked to (different) neural recordings and creative output.

Appendix A. Alternate names task: categories and examples

	Category		Examples	
1.	Planets	verunus	arctanus	tronus
2.	Brazilian music styles	rumzao	dorvao	obrinao
3.	Flowers	lunia	fridia	ezilia
4.	Airlines	Jimair	Greenair	Scanair
5.	IKEA products	Leksvik	Nudik	Rostik
6.	Belgian villages	Luizigem	Wierdegem	Sellegem
7.	Rocks	geradiet	boniet	terradiet
8.	Arab oils states	Raman	Jibulan	Urdan
9.	Pain killers	paradon	maladon	haptadon
10.	STDs	dafilus	polipilus	agridius
11.	Indonesian dishes	sendang	warundang	kresang
12.	Dances	salimba	mueva	dolsa
13.	Bacteria	robella	kradella	tremella
14.	Balkan countries	Girolië	Tazinië	Onardië
15.	French cheeses	mibrulain	provurain	chauvitain
16.	Pasta	fussilini	krapi	falucci
17.	Cocktails	domicita	hawaiana	passilada
18.	Software companies	Triddle	Wubble	Kimple
19.	Surinam dishes	ramoti	baraseti	misoti
20.	Scandinavian lakes	Holmö	Arviksjö	Kongebro
21.	Statistical tests	denta	chynia	fishca
22.	Pizza's	sanadina	aruviala	buenarita
23.	Spanish dishes	comida	rosilla	ajola
24.	Martial arts	nikato	kaido	sadamo
25.	Cleaning products	Clearex	Swipex	Glamix
26.	Wine grapes	romignon	armagnon	blabignon
27.	Polish delicacies	poshniak	balovniak	zorniak
28.	Fashion brands	Tressordini	Malucci	Sardi
29.	Japanese car manufacturers	Daisuki	Takeshi	Mizatsi
30.	Drugs	polytomine	sedoline	fadoine
31.*	Radioactive elements	tortium	ronium	catalonium
32.*	Greek islands	Mianos	Nikonos	Presos

*Practice trials.

Appendix B. Supporting information

Supplementary data associated with this article can be found in the online version at <http://dx.doi.org/10.1016/j.neuropsychologia.2017.07.033>.

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