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Predicting response originality through brain activity: An analysis of changes in EEG alpha power during the generation of alternative ideas

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ABSTRACT

Growing neurophysiological evidence points to a role of alpha oscillations in divergent thinking (DT). In particular, studies have shown a consistent EEG alpha synchronization during performance on the Alternative Uses Task (AUT), a well-established DT task. However, there is a need for investigating the brain dynamics underlying the production of a sequence of multiple, alternative ideas at the AUT and their relationship with idea originality. In twenty young adults, we investigated changes in alpha power during performance on a structured version of the AUT, requiring to ideate four alternative uses for conventional objects in distinct and sequentially balanced time periods. Data analysis followed a three-step approach, including behaviour aspects, physiology aspects, and their mutual relationship. At the behavioural level, we observed a typical serial order effect during DT production, with an increase of originality associated with an increase in ideational time and a decrease in response percentage over the four responses. This pattern was paralleled by a shift from alpha desynchronization to alpha synchronization across production of the four alternative ideas. Remarkably, alpha power changes were able to explain response originality, with a differential role of alpha power over different sensor sites. In particular, alpha synchronization over frontal, central, and temporal sites was able to predict the generation of original ideas in the first phases of the DT process, whereas alpha synchronization over centro-parietal sites persistently predicted response originality during the entire DT production. Moreover, a bilateral hemispheric effect in frontal sites and a left-lateralized effect in central, temporal, and parietal sensor sites emerged as predictors of the increase in response originality. These findings highlight the temporal dynamics of DT production across the generation of alternative ideas and support a partially distinct functional role of specific cortical areas during DT.

1. Introduction

The creative thinking process is a complex, multidimensional phenomenon, which develops across time requiring a number of thoughts and actions to find original and effective productions (e.g., Lubart, 2001; Mumford et al., 2012; Sternberg and Lubart, 1996). Drawing on Beethoven's life, he stated: *I change many things, discard others, and try again and again until I am satisfied …. I hear and see the image in front of me from every angle, as if it had been cast, and only the labour of writing it down remains* (Fisk and Nichols, 1997, p.56, p.56). This example highlights the complex process underlying the generation of a creative idea during the time course of creative thinking. Although several cognitive functions are required during the temporal evolution of creative thinking, research agrees in particular on the interdependence and joint influence of generative capacities and evaluative abilities in the emergence of creative ideas (Basadur et al., 2000; Beaty et al., 2016; Mumford et al., 2002). Accordingly, finding a creative idea necessarily needs time and effort first to generate alternative ideas and then to select the most creative ones while discarding obvious and ineffective alternatives (Kaufman et al., 2008).

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However, we still know little about how the brain supports creative cognition, even if a number of evidences is emerging on the central role of divergent thinking (DT) – a thought process used to generate creative ideas. DT has been described as an exploratory behavior used to generate multiple potential original solutions to an open-ended problem (Barbot and Lubart, 2012; Guilford, 1959). As mentioned before, in recent years cognitive neuroscience has started to shed light on the neural correlates of DT (e.g., Benedek et al., 2014; Wang et al., 2017; Dietrich and Kanso, 2010; Fink and Benedek, 2014). Most of these studies have used electroencephalography (EEG) and functional magnetic resonance imaging (fMRI) during performance on the Alternative Uses Task (AUT; Guilford, 1968; for a review see Vartanian et al., 2019). AUT requires participants to generate as many alternative uses as possible for everyday objects (e.g., "a bike as a lamp"). This task allows to quantify the participant's outcomes in terms of ideational fluency (i.e., the number of ideas an individual provides) and originality (judged on the basis of external consensus; Amabile, 1982; Baer and Kaufman, 2019; Benedek et al., 2013; Benedek et al., 2014; Wang et al., 2017) and provides a reliable psychometric assessment of the participant's creative potential (Guilford, 1950; Runco and Acar, 2012).

Interestingly, it has been shown that, as time passes by during performance on the AUT (or other DT tasks), the number of alternative ideas decreases while originality increases, a phenomenon called 'serial order effect' (Christensen et al., 1957; Johns et al., 2001; Milgram and Rabkin, 1980; Phillips and Torrance, 1977): in these conditions, people tend to progressively suppress interference from obvious ideas, which come to mind at first, and continue the exploration in order to generate more original ideas (Benedek et al., 2014; Wang et al., 2017). However, despite several neuroscientific studies have explored DT using AUT, little is known about the temporal brain dynamics underlying the serial order effect in DT tasks and their relation with the generation of original ideas.

1.1. Alpha activity and DT

During performance on the AUT, one of the most robust and replicable EEG finding is the increase of brain oscillations in the alpha band (8–12 Hz) over frontal and temporo-parietal sites (see Fink and Benedek, 2014 for a comprehensive review). Increase in alpha power during idea generation, compared to a reference interval (i.e., event-related synchronization; ERS), is commonly thought to reflect inhibitory functions involved in top-down control of non-task relevant processes and high-level semantic processes (Camarda et al., 2018; Klimesch et al., 2007, Klimesch, 2012; Jensen and Mazaheri, 2010) and has been frequently reported in association with internal mental processes, particularly with creative ideation. In fact, alpha ERS has been observed: 1) during divergent tasks compared to convergent tasks (Fink et al., 2007; Jauk et al., 2012; Jaušovec, 1997); 2) for more original ideas compared to less original ideas (Fink and Neubauer, 2006; Grabner et al., 2007), 3) to a greater extent in highly creative individuals relative to less creative individuals (e.g., Fink and Neubauer, 2008; Fink et al., 2009a, 2009b; Martindale and Hines, 1975; Martindale and Hasenfus, 1978).

Topographically, alpha ERS emerged in frontal and temporo-parietal sites (Benedek et al., 2014). Scholars have suggested partially distinct roles for alpha ERS over these sites, with frontal alpha ERS possibly reflecting executive functions such as the inhibition of interfering memories (e.g., obvious and common ideas; Fink et al., 2006; Hanslmayr et al., 2011; Jensen and Mazaheri, 2010; Klimesch et al., 2007; Wang et al., 2017), and parietal alpha ERS reflecting a shielding mechanism preventing interference from irrelevant external stimuli and supporting internally-directed attention, which in turn facilitates the (re)combination of remotely associated semantic information (Agnoli et al., 2018; Benedek et al., 2014; Benedek et al., 2011; Fink et al., 2007, Fink et al., 2009a, 2009b; Benedek et al., 2016). Furthermore, alpha oscillations in the right temporal region have been recently characterized to reflect inhibitory control, rather than semantic re-elaboration processes, involved in creative ideation. In particular, this region is actively involved in the inhibition of automatic retrieval of close semantic associations, to overcome a fixation effect and allow an effective recombination of information to produce semantically remote and original ideas (Camarda et al., 2018; Luft et al., 2018).

Only a few EEG studies instead have investigated the time-course of the changes in alpha activity during the idea generation interval in the AUT (e.g. Rominger et al., 2019; Schwab et al., 2014). This research has mostly asked participants to report a single highly original, alternative use for each object of the AUT. Results showed that alpha power during creative ideation varies as a function of time, with the highest level of alpha power after stimulus onset (possibly reflecting the inhibition of obvious ideas coming first to the mind, i.e., interfering memories) and at the end of the creative thinking process (possibly reflecting a genuine generation of novel ideas), particularly in participants with greater ideational originality. Notably, only two recent studies have investigated alpha activity in the generation of multiple, alternative ideas produced in distinct and sequential time periods, and thus more properly explore the neurophysiological correlates of the serial order effect (Wang et al., 2017; Kraus et al., 2019). Both studies used a purely linguistic version of the AUT and showed an increase in alpha power during idea generation. Additionally, Kraus et al. (2019) reported a linear increase in alpha power as a function of the serial order effect in AUT. It should be noted that in all these EEG studies a "be creative" instruction was used (Forthmann et al., 2016). This instruction is known to lead to more creative ideas but also to reduce fluency, as participants tend to select and report their best ideas only (Nusbaum et al., 2014). Thus, it remains unclear whether changes in alpha power as a function of the serial order are peculiarly related to the varying quality of the ideas produced during the task. Specifically, even if an alpha power increase has been associated with the serial production of responses during AUT, whether alpha power can be used to predict idea originality remains an unresolved question.

Indeed, originality is the main requirement, along with effectiveness, for an idea to be defined as creative (Runco and Jaeger, 2012). Originality in particular refers to the novel, authentic, and surprising properties of a new idea (Corazza, 2016) and its research during idea generation activates a DT process that has been defined as exploratory (Barbot and Lubart, 2012; Guilford, 1959). Studies have reported a relationship between AUT response originality and changes in alpha power during a single creative ideation (e.g. Rominger et al., 2019). However, whether changes in alpha oscillations predict AUT response originality as a function of the serial order effect is a relevant and largely unexplored issue.

1.2. The current study: aims and hypotheses

In the present study, participants were required to perform a structured version of the AUT. Crucially, to focus on the temporal dynamics associated with the generative phase of DT, we presented pictures of conventional objects and asked participants to sequentially generate and verbalize in four ordered and distinct time periods four *alternative* uses of these objects. In contrast to previous studies, we set no constraints on the requested originality of the response such that, according to the standard instructions for AUT (see Runco and Acar, 2010), any alternative use could be produced. The aim was to allow the generation of both common/old ideas (which are usually inhibited or discarded with the "be creative" instructions; Forthmann et al., 2016) and genuinely novel ideas, in order to explore the functional significance of alpha activity underlying the sequential generation of different alternative ideas. Specifically, we were interested in revealing whether changes in alpha activity over different cortical areas and over the two hemispheres during the generation of alternative ideas could significantly explain the occurrence of originality. In contrast with previous studies that have mainly focused on quantifying changes in the alpha activity as a function of idea originality, in this study we specifically addressed the issue whether changes in idea originality as a function of the response order can be predicted by changes over idea generation intervals and over different scalp sites in alpha activity. We were therefore not only interested in the association between alpha power and response originality, but rather in the direction of this association, explicitly analyzing the explanatory power of alpha power over participants' behavior in terms of response originality.

We hypothesized that: (1) given that the ideas originality increases as a function of time when solving AUT, as a consequence of the serial order effect (e.g., Wang et al., 2017), alpha power over the scalp areas typically associated to creative ideation, especially of the right hemisphere, should progressively increase from the first (typically obvious) alternative use to the fourth (typically original) response (Kraus et al., 2019); accordingly, (2) alpha power would predict ideational originality as a function of the temporal order of the generated alternative response, and this effect could even change as a function of the considered scalp area and hemisphere, as the generation of original ideas and the mere retrieval of obvious ideas during DT subtend different anatomical correlates with consequent separated functional mechanisms (Benedek et al., 2014, 2016; Jensen and Mazaheri, 2010; Kraus et al., 2019; Rominger et al., 2019; Wang et al., 2017); finally and consequently, (3) alpha activity should be differently modulated by the externally assessed individuals' creative achievement in the AUT task as a function of time, and in the same way, this effect could change as a function of the involved scalp area and hemisphere.

2. Method

2.1. Participants

Twenty participants between 20 and 25 years ($M_{age} = 22.0$, $SD = 1.8$; all females) recruited at the University of Bologna took part in the study. All participants had normal or corrected to normal vision, and none of them reported current or past neurological or psychopathological problems. Participants gave written informed consent prior to the EEG recording session and received 20 Euros as compensation for their participation. The experimental protocol conformed to the Declaration of Helsinki and was approved by the Bioethical Committee at the University of Bologna.

We calculated the sample size required to achieve the 80% power to detect a significant 4 RESPONSE (R1, R2, R3, R4), × 2 HEMISPHERE (left, right) × 5 POSITION interaction effect using G*power 3.1 (Faul et al., 2007) software. Effects of ERD/ERS values in the alpha band during AUT tasks are typically medium to large in terms of effect size (Wang et al., 2017). Using an $f = 0.4$ (Cohen, 1988), the power calculation yielded a recommended sample size of 19 participants.

2.2. Task and procedure

We used a structured version of the AUT, a classic DT task and well-established test of creative potential (Guilford, 1968; Runco, 1999; Runco and Mraz, 1992). In the standard version of this task participants are asked to generate as many alternative uses as they can for a series of everyday objects in the search of original and remote uses (e.g., pencil, clock, table, button; Fink et al., 2007; Fink et al., 2011; Runco and Acar, 2012; Schwab et al., 2014; Wang et al., 2017; Wilson et al., 1953). In the present study, participants were instructed to first sequentially produce four different alternative uses for everyday objects in four distinct, time balanced generation periods, and then in a later phase, to evaluate the originality of the produced alternative uses. This experimental design was proposed in order to control the time-course of the generation of alternative responses during the divergent thinking process and to keep it separated from the evaluative phase of the process. We avoided the use of the "be creative!" instruction which induces the production of only the most original ideas participants could think of, which implies a selective internal bias and a reduction of fluency. We use instead the standard instructions for AUT tasks (see Runco and Acar, 2010) which allow participants to produce also common alternatives, in order to leave unconstrained the unfolding of originality during the course of the task.

As shown in Fig. 1, the experimental trial started with a 5-s fixation cross on the screen (pre-stimulus reference interval), then the visual object (e.g., a tire) appeared for 3 s. A subsequent fixation cross indicated that participants had to think about a first alternative use for the given stimulus for a time period of maximum 15 s (first idea generation interval, IG1). During this time period, which was totally comparable in duration with ideation intervals derived from past literature (e.g., Benedek et al., 2014; Fink et al., 2011), no response was required from participants. As soon as they wanted to report their idea, participants pressed a response button. The appearance of a speech balloon informed participants to verbalize the first alternative use (e.g., swing) within a time period of maximum 6 s (first response, R1). Participants pressed the response button to start the next alternative use generation interval. Participants were required to provide four different alternative responses (i.e., R1; R2; R3; R4) for the same object in four distinct idea generation intervals (i.e., IG1; IG2; IG3; IG4). In the case participants did not verbalize an idea in the maximum amount of time, a null response was considered.

In order to minimize the influence of early evaluation processes, possibly leading to the selection of alternative ideas, after each generation phase we included in the experimental design a subsequent separate time interval during which participants were asked to evaluate the originality of their ideas. Participants were indeed explicitly required to first generate and then evaluate their alternative ideas. Specifically, a short interval in which participants were required to solve a simple mathematical operation separated the generative and the evaluative phases; after this short filler task, the four alternative responses were presented simultaneously on the screen and participants were required to evaluate the originality of each of them. Similarly to the idea generation phase, participants had a maximum of 30 s (idea evaluation interval, IE) to think about the originality of their responses using a 5-points scale (i.e., from 1 = not at all original to 5 = highly original) and to press the response button to verbalize their ratings (R). Since the purpose of the study was to analyze the time course of idea production during DT, our design was expressly meant to keep idea generation and idea evaluation ratings separated.

The next trial started after a variable inter-trial-interval (ITI) between 1.5 and 3 s. Each participant saw a total of 30 objects. They produced four alternative uses to each object. Objects were presented in 6 blocks of 5 objects each. The sequence of objects presentation was pseudo-randomly arranged for every participant. Participants had to rest with open eyes for 3 min at the beginning and at the end of the experimental session. EEG activity was recorded during the whole experimental procedure.

2.3. EEG recording and pre-processing

Participants sat in a comfortable chair in a quiet room, in front of an LCD screen at eye level. The EEG was recorded with a BrainAmp DC amplifier (BrainProducts GmbH, Germany) from 61 electrodes mounted on an elastic cap (EASYCAP GmbH, Germany), according to the 10/10 system (Jurcak et al., 2007; Oostenveld and Praamstra, 2001). The ground electrode was located on the right cheek; the reference electrode was placed on the right mastoid. Two additional sensors were placed on the outer canthus and beneath the participant's left eye to record respectively horizontal (hEOG) and vertical (vEOG) Electrooculography eye movements and blinks. The EEG and EOG signals were amplified, on-line filtered (0.1–500 Hz band-pass filter) and digitalized (1000 Hz sampling rate). Electrode impedances were kept below 5 kΩ for the EEG and for the EOG.

EEG data were processed off-line using EEGlab v13.4.4b (Delorme and Makeig, 2004) and custom functions developed in MATLAB. Continuous signals were segmented in 3-s epochs considering the reference and the idea generation intervals. Specifically, reference epochs ranged from 3 s before the onset of stimulus presentation, whereas idea generation epochs ranged from 3 s before pressing the response button.

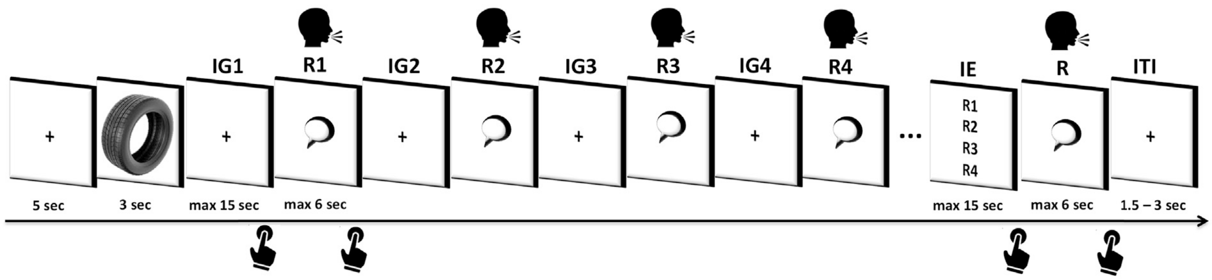

Fig. 1. Schematic structure of the experimental procedure. Each trial started with a fixation cross for 5s, followed by the presentation of the object for 3s. A subsequent fixation cross indicated participants to start thinking about an alternative use for the object, for a maximum of 15s. Participants were instructed to press a button as soon as they were ready to verbally report the prodiced alternative use. A speech balloon signaled participants to articulate the response within 6s. A total of four distinct Idea Generation periods (i.e., IG1; IG2; IG3; IG4) followed by four distinct Response periods (i.e., R1; R2; R3; R4) for each object were required. The four IG periods were then followed by an evaluation phase. Participants were presented with their responses and asked to start assessing the originality of each response (using a rating scale from 1 – not original at all – to 5 – extremely original), for a maximum of 15s (IE). Participants were instructed to press a button as soon as they were ready to verbalize the evaluation of their responses. A speech balloon signaled participants to articulate their evaluation within 6s (R).

Epochs were low-pass filtered (Hamming windowed sinc FIR filter, cutoff frequency = 80 Hz) and down-sampled to 500 Hz. Epochs contaminated by non-stereotyped or paroxysmal noise, such as muscle artifacts, were excluded from further analysis by visual inspection (4.9%). Additionally, epochs from idea generation intervals that lasted less than 3 s (i.e., participants thought and pressed the response button in less than 3 s after the beginning of the idea generation interval) were excluded (24.6%). Thus, a percentage of 57.8 (R1), 79.8 (R2), 81.8 (R3), and 82.2 (R4) trials across participants were used for the analysis. This allowed a sufficient amount of EEG signal free from visual- or motor-related events. Eye movements and blinks were corrected by performing an independent component analysis (ICA) with the FastICA algorithm (Hyvarinen, 1999; Hyvarinen and Oja, 2000; see Chaumon et al., 2015; Jung et al., 2000).

Cleaned EEG signals were re-referenced to common average reference (Hao et al., 2016; Wang et al., 2017), to reduce reference-dependent effects on EEG potentials (Dien, 1998; Kayser and Tenke, 2010), band-pass filtered (band cut-offs: 8–12 Hz, Hamming windowed sinc FIR filter) to isolate the rhythmic activity in the alpha band and squared to estimate alpha power (Pow, in μV^2). Mean alpha power was first computed in the interval between −2.5 and −0.5 s and then averaged across epochs to measure task-related power (TRP) change in each channel (i) according to the formula: $TRP_i = Log(Pow_{i,\ idea\ generation})$ - $Log(Pow_{i,\ reference})$. That means that the mean log-power calculated during the reference intervals was subtracted from the mean log-power calculated for each idea generation interval (Pfurtscheller, 1999). Therefore, positive TRP values reflect increases in alpha power from the reference to the activation interval (i.e., alpha synchronization), whereas negative values reflect decreases in alpha power (i.e., alpha desynchronization) (Klimesch, 1999; Klimesch et al., 2007; Neuper and Klimesch, 2006).

Since idea generation intervals that lasted less than 3 s were excluded, differences in TRP changes among responses (i.e., R1, R2, R3, and R4) could be biased by the different number of epochs considered to compute mean log-power values in each corresponding idea generation interval. A trial resample bootstrapping approach was used before TRP changes computation to control for this potential bias, in order to ensure the same amount of epochs among the four responses. Starting from the response with the smallest number of valid epochs in each participant, the same number of epochs was randomly sampled among the valid epochs for the other three responses. Trial re-sampling was repeated 1000 times and TRP changes was computed as the mean across all resamples (Cohen, 2014).

Statistical analyses were performed considering eight sets of electrodes, five in each hemisphere, suitably selected in order to cover the entire scalp (see Koessler et al., 2009 for the 10-10 system of electrode placement): frontal left (Fp1, AF3, AF7, F1, F3, F5, F7, FC1, FC3), central left (FC5, C1, C3, C5), temporal left (FT7, T7, TP7, CP5, P5) parietal left (CP1, CP3, P1, P3), and occipital left (PO3, PO7, P7, O1), and the corresponding electrodes in the right hemisphere. The midline electrodes (Fpz, AFz, Fz, FCz, Cz, CPz, Pz, POz, Oz) were not included in the analysis since we were interested in potential hemispheric differences. All analysis settings are similar to that of previous studies (e.g., Benedek et al., 2011; Benedek et al., 2014; Fink et al., 2006, 2011; Schwab et al., 2014; Wang et al., 2017) to ensure comparability.

2.4. *Assessment of DT performance*

Consistently with past EEG studies investigating the modulation of the alpha band during divergent thinking (e.g., Kraus et al., 2019; Schwab et al., 2014; Wang et al., 2017), participants' performance on AUT was assessed by considering the ratings of originality performed by expert external raters (Guilford, 1967; Runco, 1991). In particular, two raters evaluated independently the originality of each response to each target object. Responses were previously transcribed into a spreadsheet and then sorted alphabetically within each target object. In this way, the raters were blind to the response serial position in the set, the total number of responses in the set, the participant who produced the response, and the preceding and following responses. The raters first read all responses, then scored each response individually. Similarly to previous studies (Wilson et al., 1953; Silvia et al., 2008), each response received a rating on a 1 (not at all original) to 5 (highly original) scale. The inter-rater reliability calculated on the total number of alternative uses was acceptable (Cohen's $\kappa = 0.60$). In case of important discrepancies in ratings, raters reviewed and assigned scores by consensus (e.g., Agnoli et al., 2018). Finally, the two ratings were averaged into one originality score for each idea.

Besides expert external raters' originality scores (OS), the number of responses (NRs, percentage of non-null responses) and the time of response (idea generation time, IGT, in seconds) for each idea generation interval were calculated. Specifically, IGT time was computed as the interval between the beginning of the ideation interval (i.e., the presentation of the fixation cross) and the pressure of the response button. In the case participants did not press the button, but took the entire ideation interval to think on the alternative idea, the entire 15-s interval was considered.

2.5. *Data analysis*

Mean IGTs, Originality Scores (OS), and NRs were separately analyzed by means of repeated-measures one-way ANOVAs. Idea generation intervals in which participants did not produce any response were excluded from IGTs and Originality Scores analyses. In the same vein, the alpha TRP values were analyzed by means of repeated measurement ANOVAs. In each ANOVA, to deal with sphericity violations that increase the probability of type I error, a Huynh–Feldt correction was applied to the degrees of freedom. Where appropriate, significant effects were further evaluated using Bonferroni-corrected pairwise comparisons.

To explore the relation between EEG alpha and creative behavior, testing our hypotheses, we used a two-steps statistical approach: 1) To understand whether TRP changes in alpha power during idea generation intervals could predict originality as a function of the response order, of the hemisphere, and/or the position, a generalized linear mixed model (GLMM) was performed. Through this analysis we intended to explore whether alpha power changes could explain variations in response originality taking into account the time (response order), the cortical site, and the cortical hemisphere. The advantages offered by mixed-effects analysis are the possibility to control for the random effect of subjects and to easily use a robust error estimation. 3) In the second step, a confirmatory analysis was tested applying separate GLMM models on each position emerged as significant in the previous analysis. Our rational was the following: If alpha activity could predict response originality as a function of response order, hemisphere, and/or position, then individuals characterized by a different ability to produce original responses (high versus low-originality achievers) should show a different alpha activity as a function of the same variables (response, hemisphere, and/or position).

3. Results

3.1. Creative behavior

Mean (±*SE*) OS, IGT, and NR, are reported in Table 1, separately for each response (i.e., R1, R2, R3, R4) provided during the four IG intervals. Three one-way ANOVAs were computed with RESPONSE (R1, R2, R3, R4) as a within-subject factor, separately for OS, IGT, and NR. As expected, IGT and OS tended to increase, whereas NR tended to decrease across IG intervals, confirming the serial-order effect. The ANOVA on IGT was significant, F(3,57) = 54.528, $p < 0.001$, $\eta^2_p = 0.742$. Bonferroni-corrected pairwise comparisons showed that IGTs for R2–4 were significantly longer than IGT for R1 (R1 vs. R2 $p < 0.001$; R1 vs. R3 $p < 0.001$; R1 vs. R4 $p < 0.001$), and, in turn, IGTs for R3-4 were higher than IGT for R2 (R2 vs. R3 $p < 0.001$; R2 vs. R4 $p < 0.001$). IGTs for R3 and R4 did not differ between each other (R3 vs. R4 $p = 0.060$). The ANOVA on NRs was significant, F(3,57) = 9.325, $p < 0.001$, $\eta^2_p = 0.329$, and was explained by a larger number of ideas produced in the first IG interval compared the other three IG intervals (IG1 vs. IG2 $p = 0.039$; IG1 vs. IG3 $p = 0.035$; IG1 vs. IG4 $p = 0.003$). No other significant comparisons were observed (all *ps* > 0.11). Lastly, the ANOVA on OS was also significant, F(3,57) = 3.799, $p = 0.016$, $\eta^2_p = 0.167$, indicating that R1 was less original than later ideas (see Fig. 2) and qualified by a significant difference between R1 and R2 ($p = 0.02$). No other significant comparisons were observed (all *ps* > 0.14).

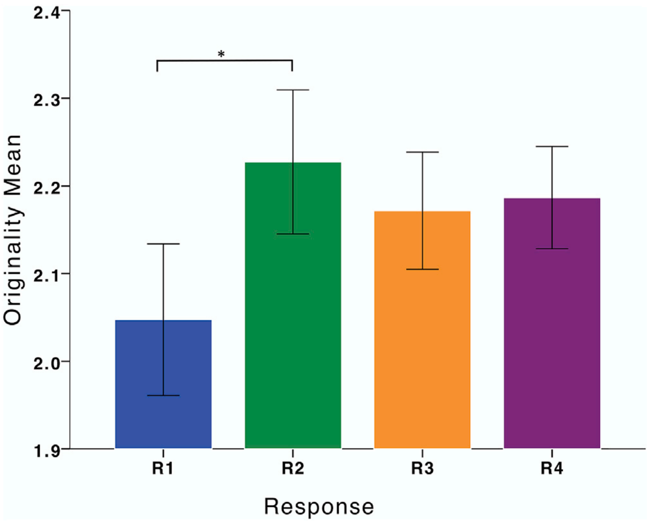

Fig. 2. Originality Scores (OS) as judged by external independent raters. The bar plot depicts mean OS for each response, error bars represent standard error (SE). Asterisks indicate significant differences ($p < 0.05$).

3.2. EEG alpha activity

The ANOVAs with RESPONSE (R1, R2, R3, R4), HEMISPHERE (left vs. right), and POSITION (five positions in each hemisphere) as within-subjects variables on alpha TRP values revealed the main significant effects of RESPONSE (F(3,57) = 10.410, $p < 0.001$, $\eta^2_p = 0.354$), and HEMISPHERE (F(1,19) = 10.371, $p = 0.005$, $\eta^2_p = 0.353$). These effects were further qualified by a significant RESPONSE × POSITION interaction (F(12,228) = 3.202, $p < 0.001$, $\eta^2_p = 0.144$), and HEMISPHERE × POSITION interaction (F(4,76) = 4.242, $p = 0.001$, $\eta^2_p = 0.214$). No other significant main effects or interactions were observed (all Fs < 2.514, $\eta^2_p < 0.117$).

The main effect of RESPONSE revealed that later ideas (i.e., R2, R3, R4) elicited an overall alpha synchronization compared to the first idea (i.e., R1). Specifically, Bonferroni-corrected pairwise comparisons revealed significant differences between the first response and all later responses (R1 vs. R2, R3, R4 *ps* < 0.009). The main effect of HEMISPHERE showed an overall higher power increases (relative to pre-stimulus reference) in the right than in the left hemisphere ($p = 0.005$).

As shown in Fig. 3(A), the significant RESPONSE × POSITION interaction revealed that all sets of sensors showed alpha desynchronization for R1, while later responses (i.e., R2, R3, and R4) exhibited significant alpha synchronization increases in central, temporal, parietal, and partially in frontal positions. Bonferroni-corrected pairwise comparisons showed that TRP change for R1 significantly differed from later responses (R1 vs. R2, R3, R4) in frontal (*ps* < 0.17), central (*ps* < 0.004), temporal (*ps* < 0.03), and parietal (*ps* < 0.20) sensors, whereas in occipital sensors alpha TRP changes for R1 were significantly different only from alpha TRP changes for R2 ($p = 0.030$). As shown in the insert of Fig. 3(B), the interaction HEMISPHERE × POSITION was mainly due to the difference in TRP changes between the left and right hemisphere over the different positions. More specifically, the frontal position emerged to be characterized by a left lateralized activity (higher alpha power in the left hemisphere than in the right hemisphere; $p = 0.055$) in comparison to the right-lateralized activity (higher alpha power in the right hemisphere than in the left hemisphere) in the central ($p = 0.021$), temporal ($p = 0.005$), parietal ($p = 0.009$), and occipital ($p = 0.028$) position. Moreover, whereas the alpha power in the left hemisphere showed a linear decrease (relative to pre-stimulus reference) from frontal to occipital sensors (linear, F(1,19) = 6.048, $p = 0.024$, $\eta^2_p = 0.241$), the right alpha power showed an increase (as compared to pre-stimulus reference) as a function of position (F(4,76) = 5.893, $p < 0.001$, $\eta^2_p = 0.237$). Specifically, the right alpha activity gradually synchronized over central ($p = 0.029$), temporal ($p = 0.015$), and parietal ($p = 0.010$) sensors, as compared to frontal sensors, which did not differ from the alpha activity over occipital sensors ($p > 0.05$).

Table 1
Means (and Standard Errors) of Originality scores, Idea Generation Times (IGTs, sec), and Number of responses (NR, %) for each response (R1, R2, R3, R4) during AUT.

		Originality	IGT (sec)	NR (%)
Response	R1	2.04 (0.08)	5.45 (0.69)	91.31 (3.14)
	R2	2.22 (0.08)	7.06 (0.62)	86.68 (3.68)
	R3	2.17 (0.06)	8.20 (0.67)	83.78 (4.09)
	R4	2.18 (0.05)	8.68 (0.65)	80.88 (4.63)

3.3. Relationship between creative behavior and EEG alpha activity

In order to test if TRP changes in alpha power during ideation could

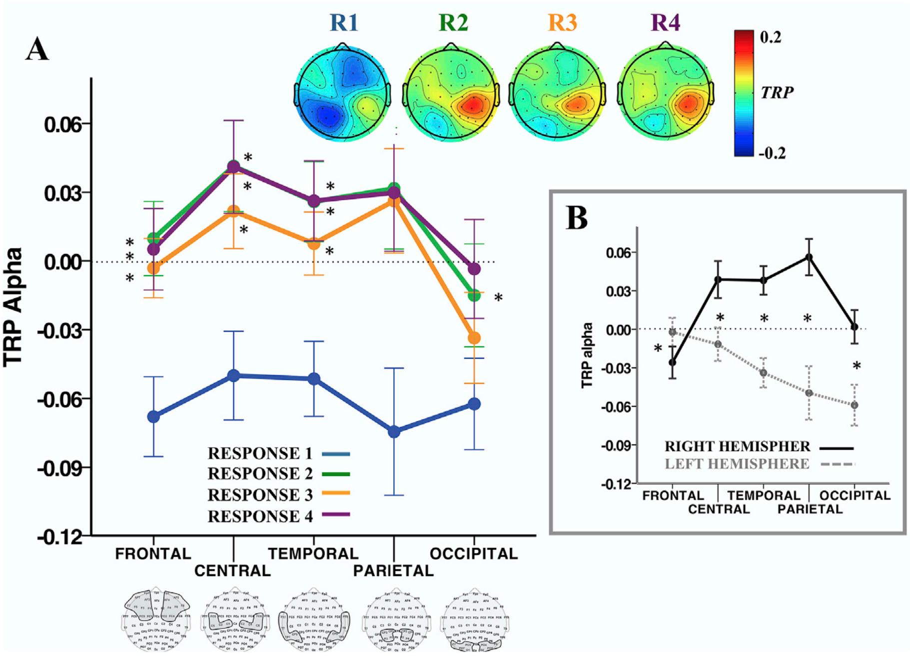

Fig. 3. Alpha TRP changes over the entire scalp. The line plot on the left side (A) shows mean alpha TRP changes in the five cortical areas (frontal, central, temporal, parietal, and occipital) as a function of the four alternative uses generation (R1, R2, R3, and R4). Scalp maps depict the topographical distribution of mean alpha TRP changes for each response. The line plot on the right side (B) depicts alpha TRP changes in the five cortical areas divided by the right and left hemispheres (solid and dotted line, respectively). Positive and negative values represent respectively an increase and a decrease in alpha power compared to the reference period and indicate task-related alpha synchronization and desynchronization, respectively. Error bars represent standard error (SE). Asterisks indicate significant differences ($p < 0.05$).

predict originality as a function of the response order, of the hemisphere, and/or the position, originality was entered in a GLMM as repeated dependent variable. RESPONSE (R1, R2, R3, R4), HEMISPHERE (left vs. right) and POSITION (frontal, central, temporal, parietal, occipital) were entered as categorical within-subject effects, whereas alpha TRP values were treated as a continuous covariate effect. Interactions between alpha TRP values and the within-subjects factors as well as any interaction effect emerged as significant in the previous analysis were explored in the model. Robust error estimation was applied in order to control for the effect of possible outliers (Wu, 2009). The model showed significant interactions, and in particular RESPONSE × TRP changes ($F(3,759) = 5.391$, $p = 0.001$), and HEMISPHERE × TRP changes ($F(1,759) = 5.057$, $p = 0.025$), which were further specified by a significant three-way interaction RESPONSE × TRP changes × POSITION ($F(12,759) = 2.265$, $p = 0.008$), and a significant four-way interaction RESPONSE × TRP changes × POSITION × HEMISPHERE ($F(12,759) = 2.468$, $p = 0.004$). No other significant interactions were observed (all Fs < 1.450, $ps > 0.216$).

In order to disentangle the complex effect emerging from the latter four-way interaction, five separate generalized linear mixed models, one for each position (i.e., frontal, central, temporal, parietal, occipital sets of sensors) over the two hemisphere (left and right) were performed controlling for the random effects of subjects to explore the influence of TRP changes as a function of RESPONSE on originality. The predictive model performed on the frontal sites showed a significant interaction between TRP change and RESPONSE both in the left ($F(4,75) = 3.353$, $p = 0.014$) and in right hemisphere ($F(4,75) = 2.611$, $p = 0.042$). This result (see Fig. 4) revealed that alpha synchronization in bilateral frontal sensors predicted originality specifically for the first response (R1 in left hemisphere: $b = 1.608$, $t(75) = 3.499$, $p = 0.001$, 95% C = [0.692,2.523] and R1 in right hemisphere: $b = 1.196$, $t(75) = 3.066$, $p = 0.003$, 95% C = [0.419,1.973]. No other significant effects were observed (all $ps > 0.903$). The TRP change × RESPONSE interaction was also significant over central ($F(4,75) = 3.001$, $p = 0.024$) and temporal ($F(4,75) = 6.706$, $p = 0.001$) sets of sensors of the left hemisphere, but not of the right hemisphere (central: $F(4,75) = 1.973$, $p = 0.107$; temporal: $F(4,75) = 1.070$, $p = 0.378$). These results (see Fig. 4) indicated that the increase of alpha power over the left hemisphere predicted the originality of the first response over central (R1 in left hemisphere: $b = 0.848$, $t(75) = 2.308$, $p = 0.024$, 95% C = [0.116,1.581] and temporal (R1 in left hemisphere: $b = 1.358$, $t(75) = 3.260$, $p = 0.002$, 95% C = [0.528,2.187] sites. No other significant effects were observed over central (all $ps > 0.903$) and temporal (all $ps > 0.257$) sets of sensors. Interestingly, a significant interaction between TRP change and RESPONSE over parietal sensors of the left hemisphere ($F(4,75) = 5.579$, $p = 0.001$), but not of the right hemisphere ($F(4,75) = 0.829$, $p = 0.511$), revealed that the left alpha synchronization in this site predicted originality for the first ($b = 1.052$, $t(75) = 4.282$, $p = 0.000$, 95% C = [0.563,1.542]), second ($b = 0.612$, $t(75) = 2.355$, $p = 0.021$, 95% C = [0.094,1.129]), and forth ($b = 0.427$, $t(75) = 2.527$, $p = 0.014$, 95% C = [0.090,0.763]) response, but not for the third response ($b = 0.268$, $t(75) = 0.946$, $p = 0.347$, 95% C = [-0.296,0.832]). Finally, no significant interaction effect emerged on the occipital set of sensors of the left ($F(4,75) = 1.863$, $p = 0.126$) and the right ($F(4,75) = 0.529$, $p = 0.715$) hemisphere, suggesting that alpha power increases in this scalp region did not predict originality scores. See Fig. 4 for an overview of the above-described significant effects.

3.4. *Individual differences in originality scores and EEG alpha activity*

In order to further understand the effects emerged in the previous analyses, differences in the alpha activity were explored in relation with individual performance in the four responses. Specifically, we analyzed whether participants who produced highly original responses (high-originality achievers) vs. poorly original responses (low-originality achievers) showed differences in TRP changes during the generation of the four ideas in the four sets of sensors that the previous analyses showed to be predictive of Originality. Thus, four separate generalized linear mixed models for frontal, central, temporal, and parietal sets of sensors explored differences in TRP changes as a function of the response in high vs. low originality achievers (median split in high and low originality level over the four responses). In a GLMM, we used alpha TRP changes as dependent variable, and ORIGINALITY LEVEL (high vs. low), RESPONSE (R1, R2, R3, R4) and HEMISPHERE (left vs. right) as categorical fixed effects controlling for the random effect of subjects. The main effect of ORIGINALITY LEVEL as well as the interactions between ORIGINALITY LEVEL × HEMISPHERE, and ORIGINALITY LEVEL × RESPONSE were entered in the model. Robust error estimation was applied in order to control for the effect of possible outliers (Wu, 2009). As shown in Fig. 5, a significant main effect of the ORIGINALITY LEVEL emerged in each set of sensors (frontal: $F(1,150) = 6.972$, $p = 0.009$;

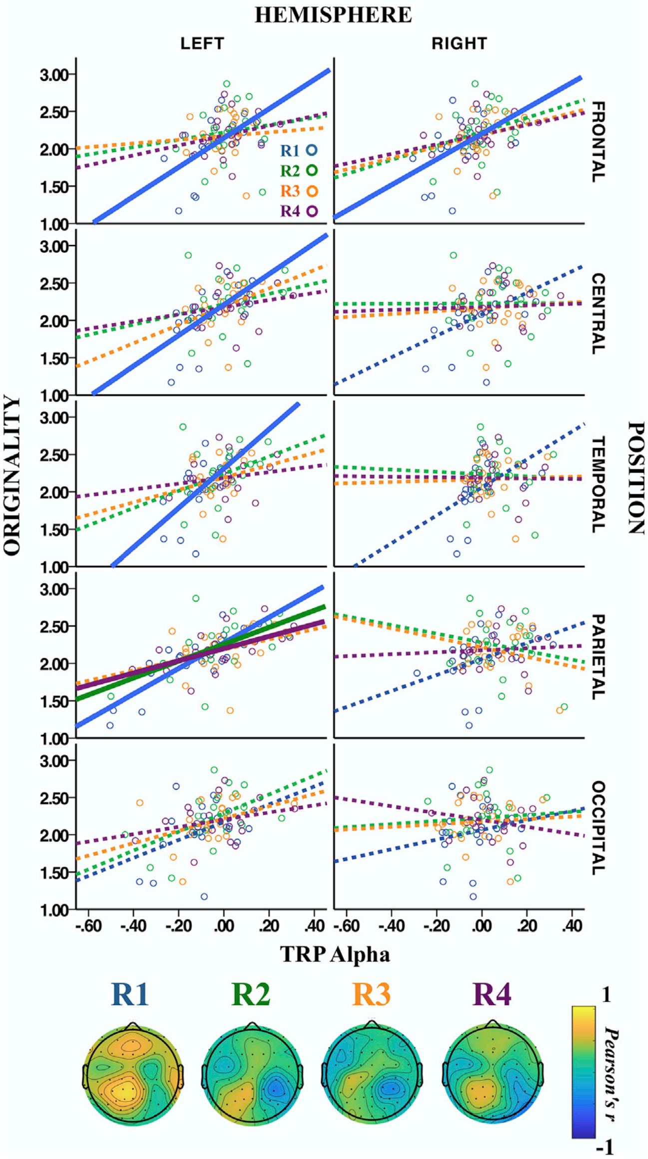

Fig. 4. Changes in the Originality Scores (OS) as a function of the Alpha TRP changes in the five scalp sensor sites of interest divided by hemisphere. Scatter plots depict the relation between TRP changes and OS in frontal, central, temporal, parietal, and occipital sensor sites over the left and the right hemisphere. Each response is represented by a different color (blue, green, orange, and purple for R1, R2, R3, and R4, respectively). Significant regression lines are depicted as solid lines; dotted lines represent non-significant regression lines. Scalp maps depict the topographical distribution of the Pearson Correlation between the alpha TRP and OS for each response.

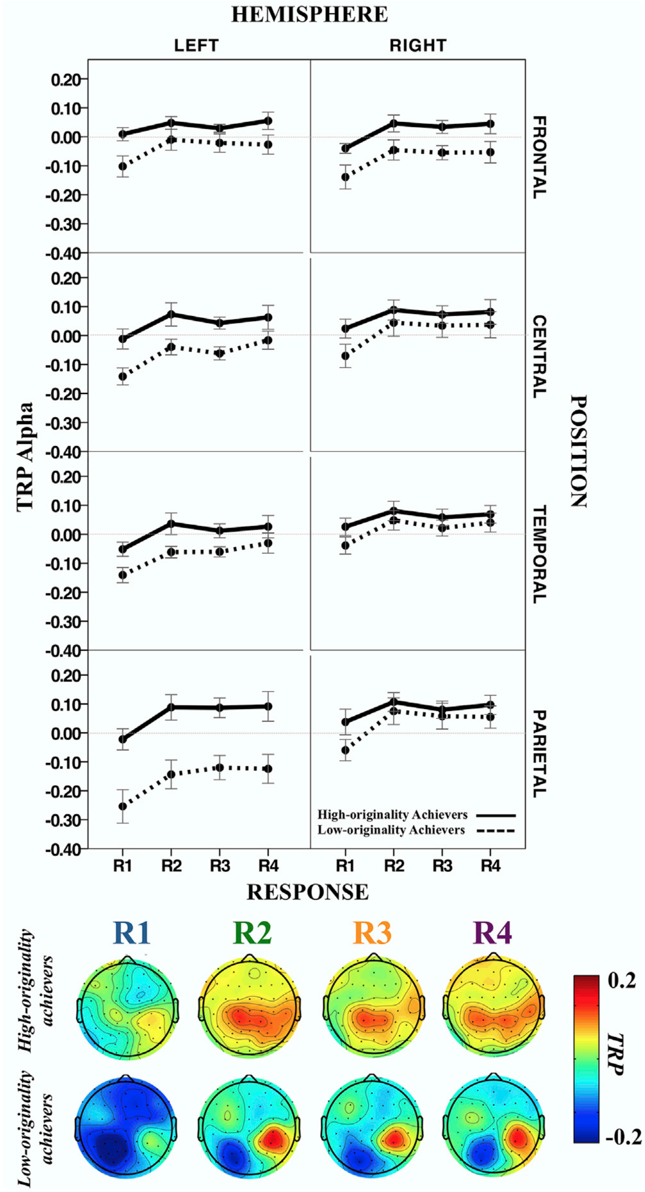

Fig. 5. Alpha TRP changes in high and low originality achievers. Line plots depict mean TRP changes in high (solid lines) and low (dotted lines) originality achievers for each response and for the frontal, central, temporal, and parietal scalp sensor sites divided by left and the right hemisphere. Error bars represent standard error (SE). Asterisks indicate significant differences ($p < 0.05$). Scalp maps depict the topographical distribution of mean alpha TRP changes in each response for high and low-originality achievers.

central: F(1,150) = 4.502, $p = 0.036$; temporal: F(1,150) = 4.872, $p = 0.029$; parietal: F(1,150) = 13.036, $p = 0.000$), indicating that generally low-originality achievers were associated with alpha power decreases, as compared to high-originality achievers (low vs. high in frontal sites: b = −0.085, $t(150) = -2.640$, $p = 0.009$, 95% CI = [-0.149, -0.021]; central sites: b = −0.081, $t(150) = -2.122$, $p = 0.036$, 95% CI = [-0.157, -0.006]; temporal sites: b = −0.060, $t(150) = -2.207$, $p = 0.029$, 95% CI = [-0.114, -0.006]; parietal sites: b = −0.035, $t(150) = -3.611$, $p = 0.000$, 95% CI = [-0.209, -0.061]). This main effect was further qualified by a significant interaction ORIGINALITY LEVEL × HEMISPHERE over central (F(2,150) = 3.958, $p = 0.021$), temporal (F(2,150) = 12.314, $p = 0.000$), and parietal (F(2,150) = 8.771, $p = 0.000$) sites, but not over the frontal sites (F(2,150) = 2.645, $p = 0.074$). Specifically, low-originality achievers showed an overall decrease in alpha power that was left lateralized over central (b = −0.079, $t(150) = -2.516$, $p = 0.013$, 95% CI = [-0.141, -0.017]), temporal (b = −0.091, $t(150) = -4.772$, $p = 0.000$, 95% CI = [-0.129, -0.054]), and parietal (b = −0.191, $t(150) = -4.164$, $p = 0.000$, 95% CI = [-0.282, -0.101]) sensors, and bilaterally distributed over frontal sites. Interestingly, the interaction ORIGINALITY LEVEL × RESPONSE in each sets of sensors (frontal: F(6,150) = 5.401, $p = 0.000$; central: F(6,150) = 8.840, $p = 0.000$; temporal: F(6,150) = 8.389, $p = 0.000$; parietal: F(6,150) = 5.028, $p = 0.000$) confirmed that the decrease in alpha power for low-originality achievers, with respect to high-originality achievers, was specifically observed during the ideation of the first response, as respect to the fourth response, over frontal (b = −0.080, $t(150) = -4.162$, $p = 0.000$, 95% CI = [-0.118, -0.042]), central (b = −0.118, $t(150) = -5.164$, $p = 0.000$, 95% CI = [-0.163, -0.073]), temporal (b = −0.094, $t(150) = -4.634$, $p = 0.000$, 95% CI = [-0.134,

-0.054]), and parietal (b = −0.120, $t(150) = -4.660$, $p = 0.000$, 95% CI = [-0.171, -0.069]) sets of sensors. Lastly, the alpha desynchronization for the first response, as respect to the forth response, was also observed for high-originality achievers over central (b = −0.067, $t(150) = -1.978$, $p = 0.050$, 95% CI = [-0.134, -0.000]), and temporal (b = −0.062, $t(150) = -2.071$, $p = 0.040$, 95% CI = [-0.120, -0.003]) scalp areas. No significant effects for high-originality achievers as a function of response order over frontal and parietal scalp areas (all $ps > 0.081$) emerged.

4. Discussion

The main aim of the present study was to explore the time-dependent variations in topography for alpha power during the time-course of DT in order to increase our understanding of the brain dynamics associated with the emergence of originality during idea generation. To this purpose, we used a structured version of the AUT, and asked participants to generate four alternative uses for common objects in sequential and distinct time periods (Runco and Acar, 2010; Runco et al., 2005). Building on previous EEG literature on DT, we focused on task-related changes in alpha oscillations during creative ideation as a function of the response order, and tested whether response originality on the AUT can be explained by changes in alpha power.

The first objective of the current study was to investigate whether the serial order of alternative responses generated during DT could differently modulate idea generation at both the behavioral and the neuronal level. The behavioral results confirmed past findings on the typical serial order effect in DT (Beaty and Silvia, 2012; Johns et al., 2001; Milgram and Rabkin, 1980; Nusbaum et al., 2014; Runco, 1986). Indeed, our findings showed that response rate decreased and ideational time increase, while idea originality ratings (as judged by external independent raters) increased over the four responses at the AUT. Specifically, there was a clear distinction between the first and the following three ideas (Fig. 2), suggesting that producing the first alternative use was less cognitive demanding than the production of the following uses, which thereby require higher cognitive resources (e.g., Gilhooly et al., 2007; Wang et al., 2017). These results support the hypothesis that the search for originality is a natural exploratory behavior, which follows a progressive search pattern starting from the generation of the most common response up to the most remote ideas (Acar and Runco, 2014; Gilhooly et al., 2007; Mednick, 1962), and requires time and effort, as participants need to generate and discard the initial obvious ideas in order to reach more original solutions. Accordingly, our behavioral data showed that both ideational time (i.e., IGT) and frequency of null-responses (i.e., NR) increased over responses (see Table 1).

Consistently, the EEG results revealed that this behavioral pattern was paralleled by an increase in alpha power over the course of DT. In particular, the pattern of changes in alpha oscillations during the production of the four sequential alternative responses resembled the behavioral pattern of response originality (Fig. 3(A)). Specifically, as for response originality, a net distinction in alpha power changes was observed between the first and the subsequent three responses. Indeed, the generation of the first alternative use was characterized by alpha desynchronization, over frontal and left temporal and parietal sensor sites, whereas the generation of the following responses was related to alpha synchronization specifically over the right central, temporal, and parietal sensor sites. Interestingly, these results are in line with the results of two prior EEG studies addressing the neural correlates of the serial order effect (Wang et al., 2017; Kraus et al., 2019) and with the hypothesis of different processes underpinned respectively by alpha desynchronization and synchronization during idea generation (Rominger et al., 2019; Schwab et al., 2014), but extend previous literature by tracking at the neurophysiological level changes in the processes involved in the creative behavior (Gilhooly et al., 2007). Typically, the course of originality production is initially characterized by the recall of more traditional uses from long-term memory, whereas recombination of store knowledge and the production of new ideas occurs later, resulting in the serial order effect (Gilhooly et al., 2007). In this light, the decrease in alpha power during the generation of the first response might be associated with the prevailing retrieval of information from long-term memory (Klimesch et al., 2007; Hanslmayr et al., 2011). Also, the lack of alpha synchronization, especially in the right parietal and temporal areas, might be related to the ineffective inhibition of close semantic associations, that lead to the production of common, not original ideas (Camarda et al., 2018; Luft et al., 2018). From the second response on, the subsequent alpha power increase, especially in the right temporo-parietal scalp region, might be related to the effective engagement of top-down executive processes such as the active inhibition of close semantic association (Luft et al., 2018) to allow the recombination of remotely associated information (Benedek et al., 2011; Fink et al., 2007, Fink et al., 2009a, 2009b; Rominger et al., 2019). These results thus provide further support to past literature suggesting that the initial productions in AUT are driven by an experiential strategy, where past experiences are retrieved from memory, while the production of the following alternatives is based on a semantic strategy, where conceptual combinations are used to generate responses (Gilhooly et al., 2007). Furthermore, we provided evidence that during the exploratory behavior characterizing the generation of alternative uses for common objects, a modification of the ideational strategy, as proposed by Gilhooly et al. (2007), can be traced at the very beginning of the process, i.e., after the production of the first less original alternative idea, both at the behavioral and at the neurophysiological level. In line with previous EEG findings (e.g., Benedek et al., 2014), we also found an overall greater increase in alpha power over the right hemisphere, confirming that alpha synchronization can be considered as a valid indicator of an ongoing process of mental imagination during the cognitive process of creative ideation, but with differential involvement of frontal and temporo-parietal alpha oscillations (see Fig. 3(B)).

Our results confirmed findings from past literature on the relationship between oscillations in the alpha band and originality (Fink and Neubauer, 2006; Grabner et al., 2007), but, importantly, added new evidence on the explanatory role of alpha activity over original idea generation and on the different contribution of frontal and temporo-parietal areas. The second objective of this study was indeed to clarify whether these changes in alpha oscillations were specifically associated and could significantly predict the variability in response originality during the course of idea generation. We confirmed our second hypothesis, showing that TRP changes in alpha oscillations were able to predict the change in originality over the course of DT, such that the increase in alpha power could predict more novel productions as a function of the considered scalp areas and hemisphere. Precisely, whereas alpha activity over frontal, central, and temporal cortical areas predicted the originality of the first (less original) response, alpha activity over parietal cortical area emerged to be also associated with the production of originality in the following more original ideas (see Fig. 4). Interestingly, a bilateral hemispheric effect in frontal sites and a left-lateralized effect in central, temporal, and parietal sensor sites emerged.

Together with our previous neurophysiological findings, these results firstly suggest that the involvement of the bilateral frontal region is especially important in the production of the first response. Whereas the first idea generation interval, characterized by the production of the less original responses, is dominated by frontal desynchronization (see R1 topography in Fig. 3), our prediction model significantly suggests that a bilateral reduction of this frontal desynchronization is related to more original ideas at the beginning of the DT process. Further evidence emerged from the confirmatory analysis aimed at answering whether participants' creative achievement level in the task could impact on changes in alpha power patterns. Alpha desynchronization over the left and right frontal sites during the first ideation period emerged indeed to be stronger in low originality achievers, thus in those individuals who probably failed to efficiently re-elaborate object-related information and are fixed to the retrieval of past information from long-term memory (Camarda et al., 2018; Hanslmayr et al., 2011).

We also found that the production of the first response was characterized by the desynchronization of the left central, temporal, and parietal sites (see R1 topography in Fig. 3) and that an increase of alpha power, especially in the left hemisphere over these sites, was significantly able to predict higher originality scores of the first response. Although the left-lateralized effect of alpha is not commonly reported in EEG study of creativity (but see Camarda et al., 2018 and Kraus et al., 2019), alpha desynchronization and its inverse relation with idea originality suggest that the production of the first, rather than the following ideas, is sensitive to bottom-up processes underpinned by the temporo-parietal region (Benedek et al., 2011; Camarda et al., 2018; Klimesch et al., 2007). The predictive model has been then confirmed in our following analyses, showing that only low-originality achievers were characterized by a strong left alpha desynchronization during the ideation of the first response over the left central, temporal and parietal sensor sites. In other words, whereas high originality achievers were characterized by a strong top-down activity (Payne and Sekuler, 2014; von Stein and Sarnthein, 2000; Jensen and Mazaheri, 2010; Klimesch et al., 2007) starting from the beginning of the generative process that resulted in a reduced desynchronization over both hemispheres, low originality achievers failed to reach high level of originality possibly due to the lack of inhibition of interfering past memories reflected in the strong alpha desynchronization (Hanslmayr et al., 2011). Similarly to the differences between high and low creative people emerged in the recent work by Rominger et al. (2019), these results showed that low-originality individuals differed from high-originality individuals in terms of EEG alpha desynchronization specifically observed during the first phase of the idea generation process.

Interestingly, whereas the following idea generation intervals, characterized by the production of more original responses, are dominated by a typical right parietal synchronization (see R1 topography in Fig. 3), our prediction model showed that an increase of alpha power over the left parietal scalp region was significantly able to predict a further increase of originality scores especially in the second and the fourth responses. This result was further confirmed by the finding revealing that low originality achievers showed strong alpha desynchronization in this scalp region in all the four responses in comparison to high originality achievers, who were not instead characterized by a difference in alpha power over this position between the two hemispheres. Considering previous literature, the persistent desynchronization in low originality achievers might be related to an ineffective shielding mechanism sustaining internally-directed attention, not favoring the combination of remotely associated semantic information (Agnoli et al., 2018; Benedek et al., 2011, 2014; Fink et al., 2007, Fink et al., 2009a, 2009b, 2016) and the prevention of fixedness during creative ideation (Camarda et al., 2018). At the same time, we did not find a significant relation between increased alpha power in the right parietal and temporal regions and originality scores, although our neurophysiological results showed right-lateralized alpha synchronization from the second idea generation interval and the confirmatory analysis showed widespread alpha synchronization in the right central and posterior scalp regions for high, but not for low, originality achievers. Tentatively, the findings suggest that the later involvement of the right temporo-parietal areas might reflect the achievement of a stable state of higher creative production and we could have not be able to reveal, with our experimental design and our task instructions, the production of strong changes in top-down activity (as reflected by the generalized alpha synchronization; Payne and Sekuler, 2014; von Stein and Sarnthein, 2000; Jensen and Mazaheri, 2010; Klimesch et al., 2007) that might be related to originality increase.

4.1. *Limitations and future directions*

Taken together our results showed that the emergence of originality during the course of divergent thinking is characterized by specific patterns of alpha activity that change as a function of time, and considered topography in terms of sensor sites and hemispheres. Further studies are however needed to confirm and extend these results. In the present study, using the standard instructions for an AUT task, we focused on the brain dynamics associated with the sequential production of four alternative uses for common objects, whereas in previous research participants were usually encouraged to try their best to generate creative ideas, i.e., ideas that should not be retrieved from memories (i.e., "be creative!" see Forthmann et al., 2016; Harrington, 1975). Future research should explore whether the behavioral and neurophysiological patterns described in this study might emerge when creativity is stressed in the task instructions. Moreover, it is worth noticing that our results should not be interpreted through a cause-effect logic. Our analyses showed that an increase of alpha power over different cortical sites and in function of the response order could be predictive of an increase of response originality. However, we should wait for specific experimental studies showing, e.g. through brain stimulation, that an increase of alpha power following the temporal and spatial indications provided by the present work is able to induce an increase of response originality during an AUT task.

In addition, even if the experimental setting described in this study was purposely designed to separate the generative phase from the evaluative phase during the production of alternative ideas, we cannot exclude that participants made a selection of their responses on the basis of the originality or appropriateness of various alternatives. A more specific analysis and *ad hoc* experimental settings should be designed in order to unravel the mechanisms underlying the relationship between the generative and evaluative cognitive processes in terms of temporal dynamics characterizing the production of original responses. We should also highlight that in the present study we asked participants to produce four alternative uses for common objects within a restricted time period of maximum 15s in each time-balanced ideational interval. This experimental design was in line with previous studies demonstrating that the request for four responses during AUT (Wang et al., 2017) for a maximum of 15s (Benedek et al., 2014) could ensure numerical equivalence across ideas and across participants. However, two consequences on participants' creative performance could derive from the adoption of our experimental design: 1) the fluency of ideas might have been constrained, since the number of responses requested to participants has been experimentally manipulated, and 2) the limitation set in the response time could have inhibited the search for originality. We therefore suggest to confirm and extent our results using a less constrained experimental setting, by using for example longer response times and giving to the participants the possibility to produce a higher number of responses. Finally, it should be noted that this study included only female participants, possibly limiting the generalization of the results to a general population. However, our recruitment strategy was consistent with recent neurophysiological studies on DT (e.g., Wang et al., 2017), as no differences in creativity among males and females emerged in seminal studies (e.g., Kogan, 1974) as well as in more recent literature reviews (e.g., Baer and Kaufman, 2008).

5. Conclusions

Our findings provided further evidence in support of a functional role of alpha activity during the time development of the DT process, highlighting the key role of alpha power increase over frontal, central, temporal, and parietal cortex for the production of original alternative responses in AUT. Extending previous findings, our study demonstrated the existence of specific patterns of EEG alpha activity during the sequential production of alternative responses in DT, which were superimposable to and predictive of the behavioral production of originality. Moreover, we add to the literature an analysis of the explanatory role of alpha activity for the emergence of originality during the course of DT, showing that a significant increase in alpha power over the frontal, central, temporal, and parietal sites especially in the left hemisphere would be able to predict higher original responses since the beginning of the DT process. Notably, our results have enabled us to clarify the involvement of different scalp regions in the emergence of originality during the time course of DT, showing a differential contribution of alpha synchronization over diverse scalp regions during distinctive time periods for the production of original responses.

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