Clustering and switching in divergent thinking: Neurophysiological correlates underlying flexibility during idea generation

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ABSTRACT

EEG alpha synchronization, especially in posterior parietal cortical regions of the right hemisphere, is indicative of high internal processing demands that are typically involved in divergent thinking (DT). During the course of DT, as ideation proceeds, ideas tend to become more creative, being more likely to be drawn from new conceptual categories through the use of the cognitive mechanism of flexibility. The present study investigated whether EEG alpha synchronization can be modulated by flexibility in DT by comparing cortical activation patterns during the switch of category (switching) and the stay in the same category (clustering). Twenty participants were required to generate alternative uses of everyday objects during EEG recording. Differential results were specifically found in the lower alpha band (8–10 Hz): whereas clustering showed synchronization typically lateralized in the right posterior parietal areas, switching induced posterior parietal synchronization over both right and left hemispheres. These findings indicate that the two distinct cognitive mechanisms subsuming flexibility (switching and clustering) are associated with a different hemispheric modulation of lower alpha activity, as switching, in comparison to clustering, is related to higher power in the lower alpha band over the left hemisphere. Switching in comparison to clustering may thus require a larger investment of cognitive resources due to the exploratory process of moving from one semantic conceptual category to another in the course of creative ideation.

1. Introduction

'*He who is fixed to a star does not change his mind*', Leonardo da Vinci once said (Da Vinci, L., 2016, p. 205). The ability to avoid fixedness has been recognized by the scientific research as a main constituent of ideation in creative cognition. The creative cognition approach, which looks at creativity as the emergent process from the interaction of ordinary cognitive processes (e.g., Benedek and Fink, 2019; Finke et al., 1992; Mastria et al., 2018; Smith et al., 1995; Ward, 1994; Ward et al., 1999), has typically focused on specific constituents of creative thinking such as idea generation based on divergent thinking (DT). DT refers to the ability of finding potentially creative solutions to open-ended problems (Corazza, 2016; Guilford, 1950; Runco, 1999, 2013). One key mechanism of DT is specifically the cognitive ability to explore diverse conceptual categories during the course of ideation by moving from one semantic conceptual field to another, to possibly reach more creative solutions (Acar and Runco, 2017; Beaty and Silvia, 2012; Finke et al., 1992; Flach, 1990; Guilford, 1967; Runco, 1994). This subtle and effortful exploratory mechanism sustaining creative idea generation, also known as flexibility, drives individuals to follow diverse directions, dimensions, and pathways (Acar & Runco, 2015, 2017), and is generally associated to the general agility of thought, adaptability, and avoidance of rigidity or fixation (Acar et al., 2019a, 2019b; Landry, 1974; Runco and Okuda, 1991; Nijstad et al., 2010).

The current study focuses on the neural correlates of flexibility specifically associated to the divergent mode of creative thinking. In this context, flexibility can be operatively defined as the number of switches from one conceptual category to another, possibly facilitating the

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achievement of creative solutions (Runco, 1986). This definition of flexibility can be viewed in the light of the general idea that creative processes rely on the associative nature of long-term memory, which posits that related concepts in human semantic networks are in closer proximity than unrelated concepts (Collins and Loftus, 1975; Kenett et al., 2016). As a consequence, the activation of a specific concept instantaneously stimulates the activation of other related concepts with a consequent facilitation in their retrieval; this has been demonstrated with a shorter time period in the retrieval of semantically related concepts as compared to unrelated concepts (see Nijstad and Stroebe, 2006, for an overview).

While the current neuroscientific approach to the study of creative cognition has produced substantial evidences regarding potential brain correlates associated to the idea generation process as a function of the quality of its outcome (i.e., the originality of the ideas produced; e.g., Agnoli et al., 2020; Fink et al., 2006; Grabner et al., 2007; Rominger et al., 2019; Schwab et al., 2014; Wang et al., 2017; for an overview see Fink and Benedek, 2014), there is still a lack of direct investigations of the full spectrum of cognitive mechanisms implicated in the divergent thinking process. In particular, given that flexibility is a constitutional element defining DT (e.g., Acar et al., 2019a, 2019b), the present study focuses for the first time (to the best of our knowledge) on this specific cognitive mechanism by exploring the neurophysiological correlates associated to the ability of switching between conceptual categories during ideation. Data from the present dataset were analyzed in the context of a previous study (Agnoli et al., 2020), in which brain dynamics associated with the emergence of originality during the production of alternative ideas in DT were investigated. The present study was instead devoted to investigate the role of flexibility, rather than originality, in creative ideation, focusing on its neurophysiological correlates.

1.1. EEG research on divergent thinking

Studies focusing on the neurophysiological changes associated to the ideational process by means of electroencephalography (EEG) have showed that the oscillatory activity in the alpha frequency band (8–12 Hz), as compared with other frequency ranges, is particularly sensitive to diverse creative tasks involving DT (Benedek et al., 2011; Jauk et al., 2012; see also Fink et al., 2007 for an overview). Specifically, an increase in the alpha task related power (TRP), as compared to a pre-task reference interval, called alpha synchronization (ERS), was consistently observed during divergent modalities of thinking (Jauk et al., 2012; Martindale and Hasenfus, 1978; Mölle et al., 1999). Relevant EEG research has also demonstrated that the generation of highly original ideas, as compared to less original ideas in an Alternative Uses Task (AUT; Guilford, 1967) asking participants to generate alternative uses for common objects, was accompanied by stronger alpha ERS, especially over frontal and temporo-parietal cortical regions (e.g., Fink et al., 2006; Grabner et al., 2007; Benedek et al., 2014c). Alpha increases over frontal cortical areas seem to reflect the involvement of strategic or executive processes, such as the inhibition of both dominant common associations and prepotent response tendencies that would serve to facilitate the emergence of remoteness and cleverness in idea generation (e.g., Agnoli et al., 2020; Luft et al., 2018; Wang et al., 2017). Alpha ERS during creative idea production over temporo-parietal sensors sites, especially in the right hemisphere, has instead been interpreted to reflect more internally directed attention involving self-generated mental representations, imagination, and specific memory processes such as the efficient (re-)combination of remotely associated semantic concepts (Agnoli et al., 2020; Benedek et al., 2011; Camarda et al., 2018; see also Fink and Benedek, 2014 for a comprehensive literature survey). As a whole, the aforementioned EEG research on creative cognition has accumulated substantial evidence that alpha power in frontal and (right) temporo-parietal regions changes as a function of divergent-related task demands and the originality of ideas.

1.2. The role of flexibility in divergent thinking

As stated above, the cerebral correlates associated to the outcomes of divergent thinking, such as the originality or the fluency of ideas, have been widely investigated to understand the functional significance of brain dynamics predicting the occurrence of creativity. However, neurophysiological research directly investigating the cognitive mechanisms characterizing the exploratory process at the basis of DT is still neglected. Flexibility in particular is strongly associated with the divergent capacity to think in multiple directions and semantic categories, exploring new associations among distant concepts and overcoming "functional fixedness" (e.g., Chrysikou et al., 2016; Smith and Blankenship, 1991). Whereas other indicators of divergent thinking process (e.g., originality or fluency) measure the outcome of the process, flexibility can be considered a cognitive mechanism underlying the process itself. Past psychological research has indeed consistently shown that during the course of divergent thinking, as ideation proceeds, ideas tend to be more likely drawn from remote conceptual categories and thus become more creative (e.g., Acar et al., 2019a, 2019b; Beaty and Silvia, 2012; Hass, 2017). It has been consistently proposed that individuals with high creative ability exhibits a semantic memory network characterized by lower distance (i.e., shorter path between any pair of nodes in the network), higher clustering coefficient (i.e., the degree to which a word's neighbors are neighbors of one another), and lower modularity (i.e., the extent to which the network breaks into smaller sub-network) than individuals with low creative ability (Kenett et al., 2014). These findings are further supported by the works demonstrating that the semantic network of high creative individuals is more flexible than that of low creative individuals (Kenett et al., 2018; see also Kenett and Faust, 2019).

From an operational point of view, the flexibility that plays a role in creativity has been classically studied through indirect behavioral measures (e.g., Benedek et al., 2014a; Chermahini and Hommel, 2010; Pan and Yu, 2018) and more recently through computational approaches (Kenett et al., 2018). A classical approach for scoring flexibility in an idea generation task involves counting the total number of different categories within an individual's ideation (Guilford, 1967). This method is based on the subjective classification of the ideas into different clusters (conceptual categories) followed by the count of the diverse clusters. A useful variant of this scoring methodology has been proposed, which focuses on category transitions from idea to idea instead of the classification of all ideas into different categories followed by the count of the total number of categories exploited (Runco, 1986; Acar and Runco, 2017; Acar et al., 2019b; Torrance, 2008; see also Reiter-Palmon et al., 2019). This is consistent with the distinction in terms of clustering and switching (Troyer et al., 1997). Indeed, individuals during ideation may focus on a category and generate ideas within this category by going deeper and deeper, or explore different categories, jumping from one category to another. In this perspective, as specified by Troyer et al. (1997), to capture all of the important aspects of any given participant performance, not only the number of clusters is valuable, but also the number of switches between categories, i.e., the number of transitions between clusters (see also Troyer, 2000). The present study embraced this approach, adopting a recent alternative scoring method for idea generation tasks based on counting the number of stays and switches between conceptual categories during DT (Acar and Runco, 2017; Acar et al., 2019b). Scoring methods based on category transitions are indeed considered particularly suitable for the study of the idea generation process (Acar and Runco, 2019; Reiter-Palmon et al., 2019; see also Silvia et al., 2008). Using a rater-based scoring, responses can thus be categorized in terms of *category switch* (i.e., *switching*), when idea moves from one conceptual category to another (e.g., from "food" to "tool") or *category stay* (i.e., *clustering*), when idea takes place within the same conceptual category (e.g., from "food" to "eating"). Psychological studies applying multi-level methods to DT tasks have suggested that the processes and mechanisms underlying

category switch and category stay are quite discernible. Whereas switching, which is an indicator of flexibility, requires more effort and time because it involves the activation of distant frameworks and strategic processes, clustering emerges as less effortful, more automated and taking less time, as it relies on the retrieval of related concepts (Acar and Runco, 2017; Bousfield and Sedgewick, 1944; Troyer et al., 1998). What is still unexplored, however, is whether category switch and category stay during creative ideation are also discernible at the neurophysiological level.

1.3. The research problem

What are the brain markers of flexibility during creative ideation? Is the EEG activity pattern different during a switch to a diverse conceptual category as compared to staying within the same category? This study examines the electrophysiological correlates of flexibility in DT, specifically addressing the research question whether the category switch as opposed to the category stay, is related to a specific pattern of cortical activation. To answer this question, the present study used a typical DT task, i.e., AUT, specifically structured to allow the tracing of flexibility, which was operationalized in terms of category switch and category stay. The ideation process requiring the production of different alternative uses for common objects was structured over sequential ideational periods, which allows identifying the EEG cortical activity associated to each idea generation phase. We exclusively focused on the signal in the alpha band because it is reliably associated with divergent thinking (e.g., Benedek et al., 2011; Jauk et al., 2012; Martindale and Hasenfus, 1978; Mölle et al., 1999; see also Dietrich and Kanso, 2010). Since alpha activity reflects a complex ensemble of cognitive mechanisms associated to divergent thinking (Fink and Benedek, 2014; Benedek and Fink, 2019), we expect to be able to isolate within this brain activity a specific modulation associated with switching, which is an indicator of flexibility. Moreover, considering the fact that alpha synchronization during creative ideation is usually more pronounced in right than in left posterior parietal sites (e.g., Benedek et al., 2014c; Fink et al., 2009a,b; see also Fink and Benedek, 2014), the role played by both hemispheres during ideation as a function of switching and clustering was taken into account.

First, based on previous studies in this field (e.g., Agnoli et al., 2020; Benedek et al., 2014c; Fink et al., 2006), we generally expected that alpha power would increase over (bilateral) frontal and (right) temporo-parietal cortical regions as being particularly sensitive to the divergent ideational process. Second, we expect to find that brain oscillations in this specific frequency band, and its scalp topography, when switching to a diverse category would be discernible to brain oscillations observed when staying into the same category. This hypothesis is based on the view that switching and clustering reflect different functional mechanisms in divergent thinking and that this difference should emerge in the brain activity associated with the two mechanisms. Specifically, category switch during creative ideation has been described as a more demanding exploratory mechanism involving the activation of distant semantic concepts as compared to clustering (Acar and Runco, 2017; Bousfield and Sedgewick, 1944; Troyer et al., 1998). Therefore, a larger and more extended modulation in alpha power in association with the category switch in comparison to the category stay could be hypothesized, especially over posterior parietal cortical areas, where alpha activity has been particularly associated to the re-combinatorial and imaginative processes of DT (e.g., Agnoli, Zanon et al., 2010; Benedek et al., 2014b,c).

2. Method

2.1. Participants

All participants were recruited from the University of Bologna and signed written consent prior to participation. This study conformed to the Declaration of Helsinki and was approved by the Ethical Committee of the Department of Psychology at the University of Bologna. We calculated *a-priori* sample size required to achieve 80% statistical power to detect an adequate effect by G*power 3.1 (Faul et al., 2007) software. Effects of TRP changes in the EEG alpha frequency band during AUT tasks are typically medium to large in terms of effect size (e.g., Wang et al., 2017). Using an f = 0.4 (Cohen, 1988), the power calculation yielded a recommended sample size of 19 participants. Thus, a total of 20 students between 20 and 25 years (M_{age} = 22, *SD* = 1.8; all females) 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. All participants received 20 euros as compensation for their participation.

2.2. Experimental task and procedure

A structured version of the Alternative Uses Task (AUT; Guilford, 1967) was used as experimental task in the present study, as it is a well-established DT task typically used to measure creative potential (e.g., Runco and Mraz, 1992; Runco and Acar, 2012). Participants were instructed to sequentially produce in four ordered time periods four different alternative uses for 30 randomly arranged everyday objects, which were divided in 6 blocks of 5 trials each. This experimental procedure emerged to be particularly suited to control the sequential generation of different alternative ideas during the time-course of the divergent thinking process (Agnoli et al., 2020), which is essential for the detection of clustering or switching between ideational categories (see Acar et al., 2019b). The procedure for the AUT trial is depicted in Fig. 1. After a 5-s fixation cross on the screen (i.e., reference period), a picture of an everyday object (e.g., a pen) was presented for 3 s. The timing of stimulus presentation was comparable to that employed in previous studies (see Fink et al., 2011; Schwab et al., 2014). Afterwards, in the idea generation period participants had to think of their first alternative use for the given object within maximum 15 s (fixation cross on the screen). During this time period the stimulus was not visible on the screen, avoiding continuous bottom-up processing, thus ensuring that the task had to be processed internally (Benedek et al., 2011; see also Fink and Benedek, 2014). When participants were ready to report their first idea, they pressed a response button to vocalize the idea within a time period of maximum 6 s (speech balloon on the screen). In the case participants did not verbalize an idea, the response was considered null. Following the idea generation progression, participants pressed the response button to start the next alternative use generation interval and vocalize the second idea that had come to the mind, and so on. Thus, participants in each trial provided four alternative responses for the same object before moving to the next trial. Before moving to the next trial, after a short filler task (i.e., an easy mathematical operation), participants were asked to explicitly evaluate the originality of their ideas using a 5-points scale (from 1 = not at all original to 5 = highly original). This procedure was used to keep separated the generative and the evaluative periods, but the data referring to the idea evaluation were not considered in the present study because outside of our purposes. This allowed that the production of the four responses was consecutive and sequential. The next trial began after a variable inter-trial-interval (ITI) between 1.5 and 3 s. EEG activity was recorded during the whole experimental procedure.

2.3. EEG recording and pre-processing

The EEG was measured 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

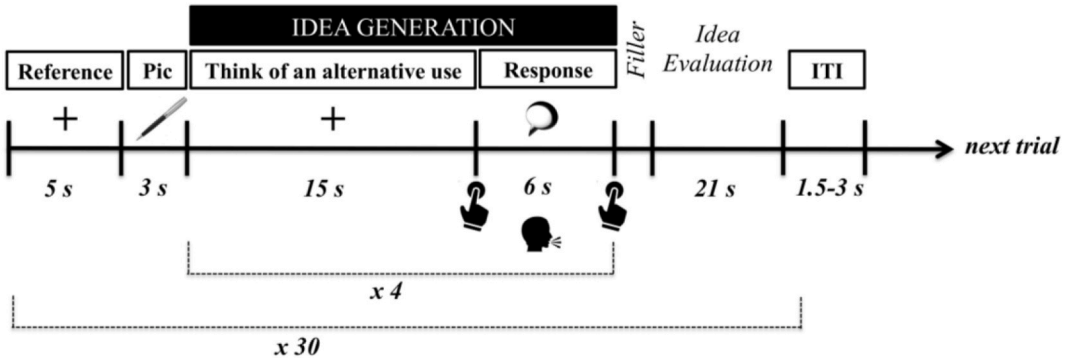

Fig. 1. Overview of the trial procedure for solving an AUT problem. A 3 s time interval during the presentation of the fixation cross (reference period) before the onset of stimulus presentation as well as a 3 s time interval before pressing the response button (idea generation period) were used for EEG analyses.

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 analyzed offline 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. 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 artefacts, were excluded from further analysis by visual inspection (4.9%). Epochs in which participants pressed the response button in less than 3 s after the beginning of the idea generation interval were excluded (24.91%). Eye movements and blinks correction was performed by independent component analysis (ICA) with the FastICA algorithm (Hyvärinen, 1999; Hyvärinen and Oja, 2000; see Chaumon et al., 2015; Jung et al., 2000). We re-referenced the EEG signal to the average of all sensors (Hao et al., 2016; Wang, 2017).

As in previous studies (e.g., Fink et al., 2011; Wang et al., 2017; Rominger et al., 2019), we quantified task-related power (TRP) changes in different EEG alpha frequency bands, i.e., in the lower alpha (8–10 Hz) and in the upper alpha band (10–12 Hz). Since some previous studies reported higher sensitivity during creative ideation in the lower alpha band (e.g., Fink et al., 2006; Grabner et al., 2007; Razumnikova, 2007), and some others reported higher sensitivity in the upper alpha band (e.g., Fink et al., 2009a,b; 2011; Shemyakina et al., 2007), we decided to differentiate between these two frequency bands for the purpose of clarity. We used a band-pass filter (band cut-offs for lower alpha: 8–10 Hz; band cut-offs for upper alpha: 10–12 Hz, Hamming windowed sinc FIR filter, filter order automatically defined by the pop_eegfiltnew function for each sub-band) to isolate the rhythmic activity in the two alpha sub-bands and squared samples to estimate power (Pow, in μV2). Lower and upper alpha power was computed in the interval between −2.5 and −0.5 s for each epoch. Then a measure of TRP changes in each channel (i) for each epoch was computed according to the formula: TRPi = Log(Powi, idea generation) - Log(Powi, reference). This means that the log-power calculated during the reference intervals was subtracted from the log-power calculated for each idea generation interval. Thus, positive TRP values reflect increases in alpha power from the reference to the activation interval, called alpha synchronization (ERS), whereas negative values reflect decreases in alpha power, named alpha desynchronization (Pfurtscheller, 1999; Klimesch, 1999; Klimesch et al., 2007; see also Neuper and Klimesch, 2006).

For statistical analyses, electrode positions were topographically aggregated as follows: 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 analogously for the right hemisphere. The midline electrodes (Fpz, AFz, Fz, FCz, Cz, CPz, Pz, POz, Oz) were not included in the analyses because we were interested in hemispheric differences. We selected five sets of electrodes for each hemisphere in order to cover the entire scalp following the cranio–cerebral correlations with the 10–10 system of electrode placement (see Koessler et al., 2009). All analysis settings were similar to those of our previous study (Agnoli et al., 2020) to ensure comparability.

2.4. Assessment of flexibility in DT

Participants' AUT responses were scored in terms of flexibility (Runco, 1986; Acar and Runco, 2017; Acar et al., 2019b). Participants generated a total of 2400 uses for objects across the six blocks of the AUT. According to the assessment procedure adopted in previous studies (see Acar and Runco, 2017; Acar et al., 2019b), the responses produced by each participant were scored independently by two expert judges for category switch (i.e., switching) and category stay (i.e., clustering) as compared to the previously generated response. Each idea was scored as 1 for switching and 0 for clustering. In particular, after a short training on the distinction between the two (including examples of each), two judges (i.e., colleagues with an expertise in creativity) evaluated the ideas produced in terms of switching and clustering independently. Instructions pursued by the two raters were as follows: A response was coded for category switch when the participant moved to a different conceptual category as compared to the previous alternative use in the sequential production of responses, whereas it was coded for category stay when the participant remained in the same conceptual category as compared to the previous response. To give an example, alternative uses for a common object such as a "box" may be listed as "1. eating spaghetti", "2. drinking milk", "3. eating soup", and "4. house for birds", respectively. Transition from idea 1 to 2 and 2 to 3 was coded as "category stay" because ideation takes place within the same conceptual category, namely "food", whereas transition from idea 3 to idea 4 means the instance of "category switch" because ideation moves from "food" to another category. Since category stay and switch were scored referring to the previous response, the first uses associated with each idea production were taken as reference responses and not included in the analysis (see Acar and Runco, 2017). A total of 1342 responses were hence scored as category switch and 379 responses were coded as category stay. This fits well with previous findings reporting that the number of shifts from the conceptual category of the previously generated idea is typically higher as compared to stays into the same conceptual category during DT tasks (Acar, 2013; Acar and Runco, 2017). The interrater reliability was high with a Cohen's kappa of .93. The flexibility ratings of the first rater was used for analysis.

Besides expert external raters' flexibility scores, latencies were

calculated as the time elapsed between the beginning of ideation period (i.e., fixation cross on the screen) and the moment participants pressed the button to vocalize an idea during the ideation period.

2.4.1. Data analysis

In order to take into account the unequal number of events of switching and clustering, the effect of flexibility on dependent variables was analyzed by means of a Generalized Linear Mixed Model (GLMM), as it is asymptotically efficient (minimum variance) regardless of whether the data are balanced or not (Field, 2013; Hayes, 2006; West et al., 2014). Using a multilevel approach, through mixed-effects analysis we were able to control for the random effect of subjects as well as of stimuli, and to use a robust error estimation to control for the possible effect of outliers (Wu, 2009). Therefore, for behavioral data, a GLMM (First-order autoregressive - AR1 - covariance structure) on participants' latencies was performed in order to check the effect of FLEXIBILITY (Category Switch, Category Stay). Similarly, for physiological data, POSITION (Frontal, Central, Temporal, Parietal, and Occipital), HEMISPHERE (Left, Right), and BAND (lower and upper alpha) were entered in the models as within-subjects factors, whereas FLEXIBILITY (Category Switch, Category Stay) was entered as a between-subject factor. In the case of a significant four-way interaction between these variables, with the purpose of facilitating the interpretation of the findings, we decided, consistently with the literature (e.g., Rominger et al., 2019; Wang et al., 2017), to split the analyses running separate models for the lower and for the upper alpha TRP values. The main effects, two- and three-way interactions between the variables were added to the models. Bonferroni corrections were used to take account of *post-hoc* comparisons.

3. Results

3.1. Behavioral results

3.1.1. Latencies

Consistent with previous findings (see e.g., Acar et al., 2019b), analysis of participants' latencies showed a significant main effect of FLEXIBILITY ($F_{1,1.715} = 8.739$, $p = .003$, $b = 0.758$, $t_{1.715} = 2.956$, $p = .003$, 95% CI = [0.255, 1.261]) indicating that the mean latency was longer when ideational category switched between sequential alternative ideas than when the next idea stayed within the same category. The mean category switch and stay latencies were, respectively (numbers in parentheses are standard deviations), 8.2 (4.29) and 6.5 (4.51) seconds.

3.2. EEG results

As a main finding of the GLMM on the TRP values, the analysis revealed an interaction between POSITION, HEMISPHERE, FLEXIBILITY, and BAND, $F_{20,28.220} = 3.058$, $p < .001$. As previously stated, in order to disentangle this complex 4-way interaction, and to further understand the effect of the flexibility in the different positions over the two hemispheres as a function of the frequency band, two separate analyses for the lower and for the upper alpha band were performed.

3.2.1. Task-related power (TRP) changes in the lower alpha band (8–10 Hz)

For the lower alpha band, as depicted in Fig. 2A, a significant FLEXIBILITY X POSITION X HEMISPHERE ($F_{4,14.110} = 2.694$, $p = .029$) interaction emerged from the analysis. In order to disentangle this complex three-way interaction, and to explore in greater depth any hemispheric difference as a function of flexibility, as emerged in a significant FLEXIBILITY × HEMISPHERE interaction ($F_{4,14.110} = 9.155$, $p = .002$, $b = -0.070$, $t_{14.110} = -3.164$, $p = .002$, 95% CI = [-0.114,

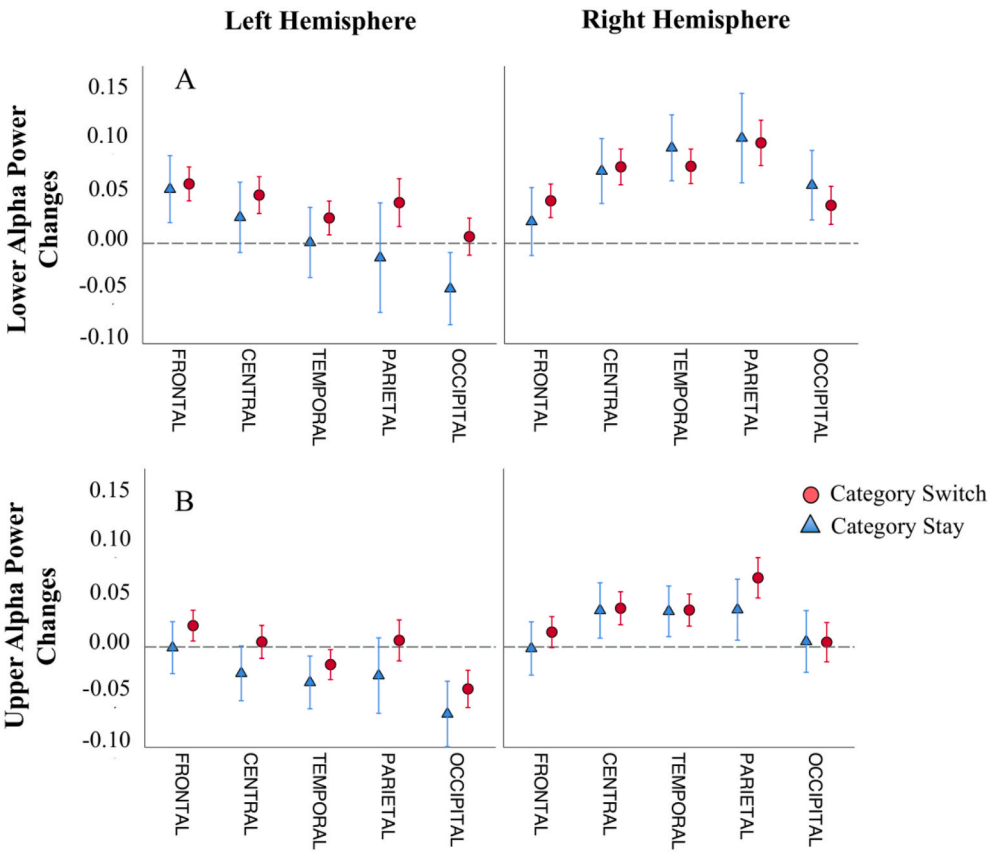

Fig. 2. Task-related changes in EEG alpha power during category switch and category stay. (A) Mean TRP values in the lower (8–10 Hz; top panel) alpha band during category stay (blue triangles) and category switch (red circles) as a function of the five scalp positions (frontal, central, temporal, parietal, occipital) over the left and right hemisphere. (B) Mean TRP values in the upper (10–12 Hz; bottom panel) alpha band during category stay (blue triangles) and category switch (red circles) as a function of the five scalp positions (frontal, central, temporal, parietal, occipital) over the left and right hemisphere. Error bars indicate 95% CI. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

−0.027]), five separate generalized linear mixed models, one for each position (i.e., frontal, central, temporal, parietal, and occipital sets of sensors), were performed. Note that the number of trials for each separate model was sufficient to guarantee the robustness of the estimates of effects, which were again calculated using robust error estimation and controlled for the random effects of subjects and stimuli.

Effects of HEMISPHERE, FLEXIBILITY, and its interaction (HEMISPHERE X FLEXIBILITY) on lower alpha activity were therefore explored over the five sets of sensors. A main effect of HEMISPHERE emerged consistently across all models, showing that lower alpha power was overall higher in the right as compared to the left hemisphere over central ($F_{1,2.822} = 12.554$, $p < .001$, $b = 0.037$, $t_{2.822} = 3.543$, p < .001, 95% CI = [0.017, 0.058]), temporal ($F_{1,2.822} = 33.107$, $p < .001$, $b = 0.072$, $t_{2.822} = 5.754$, p < .001, 95% CI = [0.048, 0.097]), parietal ($F_{1,2.822} = 30.320$, $p < .001$, $b = 0.089$, $t_{2.822} = 5.506$, p < .001, 95% CI = [0.058, 0.121]), and occipital ($F_{1,2.822} = 26.167$, $p < .001$, $b = 0.067$, $t_{2.822} = 5.115$, p < .001, 95% CI = [0.041, 0.093]) cortical areas, while an opposite hemispheric dominance was observed over frontal cortical areas ($F_{1,2.822} = 7.914$, $p = .005$, $b = -0.025$, $t_{2.822} = -2.813$, p = .005, 95% CI = [-0.042, −0.007]). Interestingly, an interaction FLEXIBILITY X HEMISPHERE was specifically observed over temporal (marginally significant: $F_{1,2.822} = 3.069$, $p = .080$, $b = -0.038$, $t_{2.822} = -1.752$, p = .080, 95% CI = [-0.081, 0.005]), parietal ($F_{1,2.822} = 4.552$, $p = .033$, $b = -0.059$, $t_{2.822} = -2.134$, p = .033, 95% CI = [-0.113, −0.005]) and occipital ($F_{1,2.822} = 9.675$, $p = .002$, $b = -0.069$, $t_{2.822} = -3.110$, p = .002, 95% CI = [-0.112, −0.025]) sets of sensors. As depicted in the bar chart of Fig. 3 (which shows the average across parietal and occipital sets of sensors), and as emphasized in the scalp maps (bottom panel), this result clearly indicated a marked reduction of hemispheric asymmetry in category switch with respect to category stay over posterior positions, demonstrating different EEG lower alpha dynamics during ideation over these positions in association with diverse flexibility mechanisms. For each position, no other main effects or interactions were significant (*ps* > .296). Further main effects and interactions emerging in the lower alpha band analysis are described in the Supplementary Material.

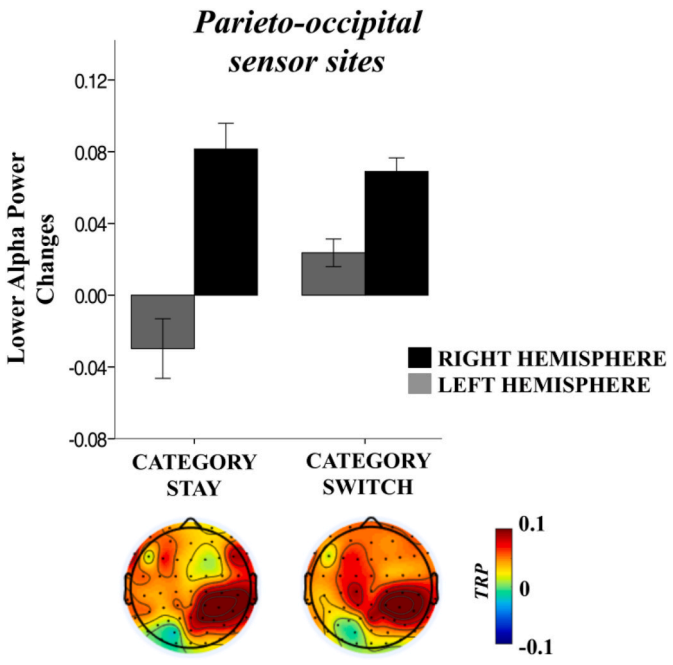

Fig. 3. Task-related changes in the lower alpha band (8–10 Hz) over posterior cortical areas during category switch and category stay. Lower alpha mean TRP values for the right (black bars) hemisphere and the left (grey bars) hemisphere over posterior sensor sites (averaged across parietal and occipital groups of sensors) as a function of category stay and category switch. The error bars indicate 1 SEM. Scalp topographies represent lower alpha TRP values during category stay and category switch.

3.2.2. Task-related power (TRP) changes in the upper alpha band (10–12 Hz)

The same statistical approach used for lower alpha activity was used in order to explore upper alpha activity. For the TRP upper alpha values, no significant main effect of FLEXIBILITY or its interaction with other factors emerged from the model (*ps* > .147). Interestingly, as depicted in Fig. 2B, a significant interaction POSITION X HEMISPHERE ($F_{4,14.110} = 9.345$, $p < .001$) indicated that whereas the left upper alpha power decreased from anterior to posterior cortical areas (frontal *vs.* temporal: $b = -0.037$, $t_{14.110} = -3.981$, $p = .001$, 95% CI = [-0.064, −0.011]; frontal *vs.* occipital: $b = -0.063$, $t_{14.110} = -6.313$, $p < .001$, 95% CI = [-0.091, −0.035]; central *vs.* occipital: $b = -0.042$, $t_{14.110} = -3.620$, $p = .002$, 95% CI = [-0.074, −0.010]), and parietal *vs.* occipital ($b = -0.043$, $t_{14.110} = -3.598$, $p = .002$, 95% CI = [-0.076, −0.011]), the right upper alpha power increased from anterior to posterior positions (frontal *vs.* central: $b = 0.031$, $t_{14.110} = 3.695$, $p = .002$, 95% CI = [0.008, 0.054]; frontal *vs.* temporal: $b = 0.028$, $t_{14.110} = 3.168$, $p = .009$, 95% CI = [0.005, 0.052]; and frontal *vs.* parietal ($b = 0.047$, $t_{14.110} = 4.566$, $p < .001$, 95% CI = [0.018, 0.075]), which in turn were greater as compared to the occipital position (temporal *vs.* occipital: $b = 0.030$, $t_{14.110} = 3.460$, $p = .004$, 95% CI = [0.007, 0.053]; and parietal *vs.* occipital: $b = 0.048$, $t_{14.110} = 4.226$, $p < .001$, 95% CI = [0.017, 0.080]). No other comparisons were significantly different in the two hemispheres (all *ps* > .060). Moreover, Bonferroni-corrected pairwise comparisons revealed that upper alpha power was higher in the right hemisphere in comparison to the left one over central ($b = 0.048$, $t_{14.110} = 4.875$, $p < .001$, 95% CI = [0.029, 0.068]), temporal ($b = 0.062$, $t_{14.110} = 5.779$, $p < .001$, 95% CI = [0.041, 0.084]), parietal ($b = 0.063$, $t_{14.110} = 4.707$, $p < .001$, 95% CI = [0.037, 0.089]), and occipital ($b = 0.058$, $t_{14.110} = 4.970$, $p < .001$, 95% CI = [0.035, 0.081]) groups of sensors. No significant hemispheric difference was observed over the frontal cortical area (p = .655). Further main effects emerging in the upper alpha band analysis are described in the Supplementary Material.

4. Discussion

The present study explored the neurophysiological correlates associated to flexibility during the production of alternative responses in a divergent thinking task. In the current study, flexibility was operationalized as transition across conceptual categories (Runco, 1986; Acar and Runco, 2017; Acar et al., 2019b; see also Reiter-Palmon et al., 2019). Specifically, the current work focused on switching and clustering during creative ideation, respectively referring to jumping to a new category after the exploration of a given category, and to the progressive deeper exploration within the same conceptual category (Acar and Runco, 2017; Acar et al., 2019a, 2019b). It is worth highlighting that cognitive processes related to cognitive flexibility, which is a dynamic property of the cognitive system (Ionescu, 2012) and that allows adapting behaviour in response to changing environmental situations (Badre and Wagner, 2006; Miyake et al., 2000; Wolff et al., 2016), have been widely investigated (e.g., Allport et al., 1994; Rogers and Monsell, 1995). In the context of creativity research, cognitive flexibility was referred to as one of the key executive functions of the creative thinking process (Boot et al., 2017; Chermahini and Hommel, 2010; Dietrich, 2004; Nijstad et al., 2010; Kenett et al., 2018; Ward, 2007). The present study draws from this literature and focuses on the neural correlates of the flexible processing mode during creative ideation. Since cognitive flexibility shows different characterizations in relation to various cognitive processes (Ionescu, 2012), with the present study we tried to clarify the possible neurophysiological correlates of flexibility involved in divergent thinking. We specifically aimed at a better understanding of the strategies and processes employed by participants when clustering and switching during creative ideation (Volle, 2018).

Overall, it appears that behavioural and physiological results perfectly complement each other in supporting the view that switching and clustering may reflect different mechanisms in divergent thinking. At the behavioural level, in line with previous findings, results showed longer latencies during switching in comparison to the clustering condition, confirming that category switching during creative ideation is associated with a higher investment of cognitive resources due to the use of loosely related semantic concepts in comparison to clustering (e.g., Acar et al., 2019a, 2019b; Acar and Runco, 2017; Bousfield and Sedgewick, 1944; Troyer et al., 1998). This result is nicely in accordance with several models on creative ideation process stating that semantically related ideas are produced more rapidly than semantically unrelated ideas (Beaty and Silvia, 2012; Hass, 2017). Indeed, as ideation continues in divergent thinking, latency of the responses seems to be a reliable predictor of originality in DT (Acar et al., 2019a, 2019b), in the sense that ideas tend to get more original as time passes. Our behavioral results seem to go in the same direction, as the switch trials appear to be more original (measured with a rater-based method; see Agnoli et al., 2020) than the stay trials ($F(1,39) = 8.33$, $p < .01$, $\eta^2_p = .18$). The physiological data support this view, demonstrating that the two cognitive mechanisms subsuming flexibility (switching and clustering) during creative ideation may represent different processes also at the cortical level.

According to the neurophysiological literature on creative cognition, the present work focused on the cortical alpha rhythm in the range between 8 and 12 Hz. Brain oscillations in this specific band have been indeed widely referred to as being indicative of specific cognitive processes involved in divergent thinking (e.g., Benedek et al., 2011; Fink et al., 2006; Jauk et al., 2012). Moreover, because different patterns in alpha power have been observed in association with several creative behaviors when the wide alpha frequency range was subdivided into different alpha sub-bands (see Fink and Benedek, 2014 for an overview), a differentiation between lower (8–10 Hz) and upper (10–12 Hz) alpha frequency bands has been introduced. As for what concerns the role of alpha, the results from the present work confirmed previous literature on creative cognition (see e.g., Fink and Benedek, 2014), showing the typical modulation patterns of alpha activity in both lower and upper frequency bands during creative ideation. We specifically found that the generation of alternative uses during DT elicited increases in power of the wide alpha frequency range (both lower and upper alpha) over frontal and temporo-parietal cortical regions, especially over the right hemisphere. Past research has stressed the functional role of alpha oscillations at frontal brain regions as supporting executive functions to suppress dominant but uncreative responses during idea production (e.g., Agnoli et al., 2020; Luft et al., 2018; Lustenberger et al., 2015). Conversely, task-related synchronization of alpha activity over temporo-parietal sites during creative ideation (see e.g., Benedek et al., 2014c; Fink et al., 2009a,b; see also Fink and Benedek, 2014) has been interpreted as reflective of a state of absence of stimulus-driven or external bottom-up stimulation and, consequently, as a state of top-down controlled internal attention that may favour the retrieval of stored knowledge and the access to remote associations, which can be recombined into new creative solutions (Agnoli et al., 2018; Benedek et al., 2011; Benedek et al., 2014c; see also Fink and Benedek, 2014).

Crucially, the cognitive mechanism of flexibility sustaining ideation seems to rely on the modulation of alpha activity exclusively in lower frequencies, which exhibited specific and different patterns of activation as a function of switching and clustering. Specifically, when creative task performance was quantified in terms of switching or clustering, a higher sensitivity of the alpha activity in the lower frequency in comparison to the upper frequency band was observed. The main result emerging from the present study was that category switch during ideation evoked a strong ERS of the lower alpha activity over temporo-parietal and occipital sites not only in the right, but also in the left hemisphere. Clustering was instead associated to an activation pattern that is typical for creative ideation, i.e., alpha ERS specifically lateralized to the right hemisphere over posterior sites. Put differently, switching categories in comparison to clustering during the generation of alternative uses induced a reduced hemispheric asymmetry in the lower alpha frequency band over those cortical areas that are commonly associated with imagination and with the creation of novel combinations between remotely associated semantic concepts (e.g., Agnoli et al., 2018; Benedek et al., 2011, 2014c). This result might be considered consistent with the general view that lower alpha band is commonly known to reflect general, unspecific, attentional task demands, in contrast to the upper alpha band, which is supposed to selectively respond to more specific task demands such as intelligence-related requests (Doppelmayr et al., 2002, 2005, 2005; Klimesch et al., 2005; Neubauer et al., 2006). The potential specificity of lower alpha band for flexibility could possibly help to explain the sometimes fuzzy picture of the role of different EEG alpha frequency bands, viz. lower alpha and upper alpha, in creativity-related tasks (see Fink and Benedek, 2014).

We may interpret the observed findings in a manner that, since switching would result in the generation of associations that are more remotely related to accessible ideas, a higher investment of cognitive resources is needed in comparison to clustering, possibly requiring ERS lower alpha over posterior cortical regions in both hemispheres. In search for potential explanations, switching seems to involve not only a free-associative or global semantic processing mode, which is typically executed in the right hemisphere, but also, albeit to a lesser extent, a more analytical or local semantic processing mode of the left hemisphere (e.g., Bowden and Jung-Beeman, 2003; Bowden, 2005; Martindale, 1999; see also Arieti, 1976), which may be crucial to adequately recombine unrelated semantic concepts to generate creative solutions during ideation (Kenett and Faust, 2019). It has been indeed shown that divergent thinking with high creative task demands involved increased activation in the angular gyrus (AG) of the left hemisphere along with the right inferior parietal cortex, as compared with a divergent thinking task involving low creative demands (Fink et al., 2009a; see also Fink et al., 2010, 2012 and Abraham et al., 2012 for similar findings). Similarly, even when participants were required to generate new ideas (i.e., responses that come from a genuinely creative act in which previously unrelated concepts become associated in a new way) as compared to old ideas (i.e., responses that come from long-term memory or experiences), a higher activation in the anterior part of the left inferior parietal cortex including parts of the left supramarginal gyrus (SMG) was observed (Benedek et al., 2014b). A brain bilateral distributed system was indeed found to be involved in highly creative performance, with greater activation in left and right fronto-temporal and parietal functioning for highly creative individuals in comparison to low creative individuals (e.g., Bekhtereva et al., 2004; Chávez-Eakle et al., 2007).

Past neuroscientific research is consistently supportive of a strong activation of the frontal-posterior network performance involving cognitive flexibility (e.g., Badre and Wagner, 2006), which is also evidenced by the robust coherence in reporting the involvement of these regions during diverse creative tasks presented to participants in various modalities (e.g., Beaty et al., 2018; De Pisapia et al., 2016; Petsche, 1996; Zhu et al., 2017). Moreover, studies with functional Magnetic Resonance Imaging (fMRI) demonstrated that when comparing conditions in which participants switch between simple tasks to conditions in which they repeat the same task, switch conditions engaged brain regions associated to the fronto-parietal network, including ventrolateral prefrontal cortex (VLPFC), supplementary motor area (SMA), and bilateral inferior/superior parietal cortices, as respect to repeat conditions (e.g., Brade and Wagner, 2006; Braas and von Cramon, 2002, 2004; Crone et al., 2006; Dove et al., 2000). Switching is crucial for creative ideation because it allows making remote associations and thus producing possibly more original ideas. Highly-creative individuals in comparison to less-creative individuals, showed stronger associations between remote concepts (e.g., Eysenck, 1993, 1995; Guilford, 1967; Mednick, 1962; Simonton, 1997, 2003b; see Nijstad et al., 2010 for an overview), due to a more flexible semantic memory network structure

that permits more efficient retrieval strategies when producing unrelated conceptual associations (Beaty and Silvia, 2012; Gruszka and Necka, 2002; Kenett et al., 2014; Kenett et al., 2018; see also Kenett and Faust, 2019).

4.1. Limitations and future directions

Taken together, our results showed that the mechanism of flexibility during divergent thinking is characterized by specific patterns of alpha activity that change as a function of switching and clustering processing modes. Since to the best to our knowledge this is the first study addressing this specific research question, further studies are needed to replicate these findings. From a methodological point of view, although the effect on flexibility seems to have emerged in the lower alpha frequency band, we cannot rule out that different findings could have emerged if we had compared the conditions using the relative alpha power on the individual alpha frequency band of each subject. Therefore, we call for future studies exploring the potential impact of individualized alpha frequency on the findings emerging in our creative-divergent task. Related to this, although we specifically focused on alpha oscillations, others frequency bands could be associated to flexibility in creative ideation, as demonstrated in a study in which spontaneous switching between thinking modes (divergent vs convergent) on a trial-to-trial basis engaged a widespread delta band modulation (Boot et al., 2017). Moreover, we adopted a proven qualitative scoring approach to flexibility based on subjective ratings by judges (Acar and Runco, 2017; Acar et al., 2019b; see also Guilford, 1967; Nusbaum and Silvia, 2011). However, some researchers have raised the criticism that categorization of responses that relies on subjective judgment could generate potential issues regarding reliability and validity (Taler et al., 2013). Future studies could therefore investigate the (brain) mechanisms associated to flexibility by adopting objective (automated) methods for scoring based for instance on semantic network analysis (Acar and Runco, 2019; Beketayev and Runco, 2016; Kenett et al., 2018), or specific computational network tools (e.g., Borodkin et al., 2016), and by comparing these results to those obtained through judges. Moreover, despite the experimental paradigm used in the current study was expressly designed to associate each idea generation period with its cerebral correlates, this design could have influenced the normal distribution of switching and clustering in an ideational task. We indeed asked to participants to generate a total of four responses, which might have reduced the number of used clusters. Future studies should compare the data emerging from the current study with a more classical "be fluent" condition, which could allow both a deeper exploration within a cluster and a higher number of transitions between clusters. In addition, since in the present study we used a visual AU task, one could presume that these findings are specifically associated with the employment of the visual stimulus material. Future studies should compare behavioral and neurophysiological patterns of results to flexibility as a function of different stimulus presentation modalities in AU tasks, e.g., comparing visual vs. verbal stimulus material.

5. Conclusions

In summary, this study primarily provided further support to the critical role of EEG alpha activity in the context of creative cognition, confirming that alpha power increases over frontal and right temporo-parietal cortical areas during creative ideation. More importantly, when focusing on the cognitive mechanism of flexibility sustaining creative ideation, this work showed that it is possible to dissociate the cortical activity related to switching, i.e., when ideas move from one conceptual category to another, from the cortical activity associated with clustering, i.e., when ideas are generated within the same category. Precisely, bilateral lower alpha synchronization over posterior cortical areas was specifically observed during switching in comparison to the clustering condition, possibly reflecting a higher investment of cognitive resources during the exploratory process of moving from one semantic conceptual category to another in the course of creative ideation. The results from this study also emphasize the importance of using narrower frequency bands than the wide 8–12 Hz alpha band when observing creative performance, especially when focusing on the cerebral correlates associated with specific cognitive functions defining creative ideation. Taken together, these findings can be considered a first attempt to characterize the functional meaning of alpha synchronization in the particular context of flexibility, which is considered one of the main cognitive functions sustaining creative ideation.

Credit author statement

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