Neural Oscillation Mechanisms in the Creative Process

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Abstract

The mechanisms underlying creativity generation remain without a unified consensus. Neuroelectrophysiological techniques, with their high temporal resolution, can accurately reveal the neural oscillation mechanisms underlying the creative generation process, thereby facilitating a deeper understanding of the nature of creativity. Recent research has demonstrated that single-rhythm alpha neural oscillations are enhanced with increased creativity, reflecting elevated internal information processing demands and strengthened top-down inhibitory control during the creative generation process. Concurrently, cross-frequency coupling of multi-band neural oscillations reflects the dynamic alterations in information exchange among multiple brain regions, including the frontal, temporal, and parietal lobes, during the creative generation process. Future research should be grounded in an integrated theoretical framework, employing multi-level and multi-methodological research tools, introducing more ecologically valid mathematical and computational approaches, and utilizing computational neuroscience modeling to predict individual creativity trajectories, thereby achieving a comprehensive and profound understanding of the essence of creativity.

Full Text

Neural Oscillation Mechanisms in the Creative Process

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Abstract: How creativity emerges remains a matter of debate. Electrophysiological techniques, with their high temporal resolution, can accurately reveal the neural oscillation mechanisms underlying the creative process, thereby facilitating a deeper understanding of the nature of creativity. Recent studies have found that single-rhythm alpha oscillations increase with creativity, reflecting heightened demands for internal information processing and enhanced top-down inhibitory control during creative generation. Meanwhile, cross-frequency coupling of neural oscillations demonstrates dynamic changes in information exchange among multiple brain regions—including the frontal, temporal, and parietal lobes—during creative production. Future research should be grounded in integrated theoretical frameworks, combine multi-level and multi-methodological tools, introduce more ecologically valid computational approaches, and employ computational neuroscience modeling to predict individual creativity trajectories, thereby achieving a comprehensive and profound understanding of creativity' s essence.

Keywords: creativity, neural oscillation, electroencephalography, alpha neural oscillation, cross-frequency coupling
Classification: B842; B845

1 Introduction

Creativity is typically defined as the ability to produce novel, unique, and socially valuable or applicable products or ideas within a given social context (Runco & Jaeger, 2012; Sternberg, 1996). It represents both a critical determinant of individual achievement and an inexhaustible driving force for human civilization and socioeconomic progress (Runco & Acar, 2012). Given its profound importance, research investigating the cognitive and neural mechanisms of creativity has surged in recent decades. Although exploring these mechanisms constitutes a primary pathway to understanding creativity' s essence, a consistent conclusion has yet to emerge.

Creative generation involves numerous cognitive processes—including attention, memory retrieval, and working memory—that play vital roles. The emergence of novel ideas depends on the capacity to break existing mental frameworks or conceptual connections and reestablish novel, meaningful frameworks or long-distance semantic associations (Benedek, Könen, & Neubauer, 2012; Mednick, 1962). To generate creative ideas, individuals must first perceive or become aware of a problem, analyze and redefine it; then produce alternative ideas or solutions through cognitive processes such as divergent thinking and remote association; and finally evaluate these ideas, selecting those that are original and applicable while discarding conventional or ineffective ones (Beaty, Benedek, Silvia, & Schacter, 2016; Luft, Zioga, Thompson, Banissy, & Bhattacharya, 2018). Moreover, extensive neuroimaging research demonstrates that creativity relies on multiple cognitive processes and the activation and coordination of numerous brain regions. For instance, functional magnetic resonance imaging (fMRI) evidence indicates that the neural architecture underlying creativity includes the medial and lateral temporal systems involved in episodic and semantic memory; the lateral parietal and dorsolateral prefrontal systems responsible for semantic retrieval and control; the executive control network encompassing working memory and inhibition; and the medial default network subserving emotion, personality, and motivation (陈群林, 2017). The critical question, however, concerns how these neural networks rapidly exchange information to ensure temporally precise coordination in generating creativity, and how multiple cognitive functions cooperate throughout the creative process.

Neural oscillations play a crucial role in creative generation (Agnoli et al., 2020; Fink & Benedek, 2014; Friston, Bastos, Pinotsis, & Litvak, 2015). These oscillations represent rhythmic fluctuations in the relative depolarization levels of dendritic or somatic membrane potentials in neuronal populations, reflecting fundamental principles and intrinsic mechanisms of brain cognitive activity (Buzsaki & Draguhn, 2004; Tiesinga, Fellous, & Sejnowski, 2008; X. J. Wang, 2010) and enabling deeper understanding of dynamic information exchange processes.

Investigating neural oscillation mechanisms in creativity helps reveal how multiple cognitive functions cooperate and how information exchange dynamically changes among brain regions during creative generation, thereby illuminating the underlying neural mechanisms. In recent years, an increasing number of empirical studies have employed high-temporal-resolution electroencephalography (EEG) to explore these mechanisms (Agnoli et al., 2020; Arden, Chavez, Grazioplene, & Jung, 2010; Benedek, Beaty, et al., 2014; Benedek, Bergner, Konen, Fink, & Neubauer, 2011; Benedek, Jauk, et al., 2014; Brinkman, Stolk, Dijkerman, de Lange, & Toni, 2014; Dietrich & Kanso, 2010; Fink et al., 2017; Grabner, Krenn, Fink, Arendasy, & Benedek, 2018; Lechinger et al., 2016; Lustenberger, Boyle, Foulser, Mellin, & Froehlich, 2015; Rominger et al., 2019; Schwab, Benedek, Papousek, Weiss, & Fink, 2014; X. Wang et al., 2019; Zhou et al., 2019), gradually advancing our understanding. Based on research progress from the past decade, this review synthesizes findings on neural oscillation mechanisms in creativity from two perspectives—single-rhythm oscillations and cross-frequency coupling—and outlines future research directions concerning theoretical foundations, methodological tools, ecologically valid statistical approaches, and integration with related disciplines to better comprehend the neural oscillation mechanisms underlying creativity.

2 Single-Rhythm Neural Oscillations in Creative Generation

All human cognitive activities are regulated by the central nervous system, with the cerebral cortex composed of large neuronal populations as its core organization. Neurons within these populations connect via excitatory or inhibitory synapses to transmit electrophysiological information, becoming activated or inhibited according to specific electrophysiological rhythms. This rhythmic electrophysiological behavior of neuronal populations is termed neural oscillation. In practice, neural oscillations are commonly simplified into five frequency bands: delta (0.5-4 Hz), theta (4-8 Hz), alpha (8-12 Hz), beta (13-28 Hz), and gamma (28-100 Hz).

Early creativity research aimed to identify neural oscillation frequency bands associated with creative generation, with alpha-band oscillations being the most frequently reported.

2.1 Alpha Neural Oscillations and Their Cognitive Mechanisms

Alpha-band (8–12 Hz) neural oscillations are among the most well-known macroscopic neuronal population activities. Early EEG experiments found that alpha activity was exceptionally strong during quiet relaxation, rest, or sleep, but weakened during alert wakefulness. Consequently, when Martindale first applied EEG to creativity research and found that highly creative individuals exhibited stronger alpha oscillations compared to less creative individuals (Martindale & Hines, 1975), early researchers interpreted creativity-related alpha enhancement as reflecting cortical idling or reduced information processing intensity (Dietrich, 2003; Martindale, 1999; Mendelsohn, 1976; Pfurtscheller & Lopes da Silva, 1999). This led to the low arousal theory of creativity and associative processing theory, which posited that low cortical arousal, defocused attention, and reduced inhibitory control facilitate creative or original idea generation (Mednick, 1962).

However, accumulating evidence suggests this interpretation is overly simplistic (Dietrich & Kanso, 2010; Fink & Benedek, 2014; Palva, 2007). Over the past decade, numerous EEG studies on creativity have demonstrated that individuals exhibit stronger alpha-band oscillations when completing creative tasks (such as the widely used Alternate Uses Task) compared to conventional tasks involving reasoning, calculation, or memory retrieval (Fink & Benedek, 2014). For example, Fink et al. (2007, 2009) found that individuals showed enhanced frontal alpha oscillations when completing the AUT compared to conventional verbal intelligence tasks (Fink, Benedek, Grabner, Staudt, & Neubauer, 2007; Fink, Grabner, et al., 2009). Fink, Graif, and Neubauer (2009) observed stronger frontal and parietal alpha oscillations during improvisational dance creation compared to standard waltz performance. During creative generation, frontoparietal alpha oscillations increase with the production of novel ideas (Fink & Neubauer, 2006; Grabner, Fink, & Neubauer, 2007). Research on the cognitive mechanisms of alpha 1 and alpha 2 sub-bands has not yielded consistent conclusions (Fink et al., 2006; Fink et al., 2011). Most creativity studies find that distinguishing between alpha 1 and alpha 2 sub-bands does not significantly affect creativity (Agnoli et al., 2020; Fink & Neubauer, 2008; Jauk et al., 2012; Rominger et al., 2019), further reflecting the close relationship between creativity and alpha oscillations. These findings indicate a positive correlation between alpha oscillations and task demands during creative generation (Fink et al., 2007; Jauk et al., 2012; Martindale & Hasenfus, 1978), with highly creative individuals maintaining enhanced frontal and parietal alpha oscillations for significantly longer durations than less creative individuals (Camarda et al., 2018). A transcranial alternating current stimulation (tACS) study demonstrated that applying 10 Hz tACS to the frontal cortex to enhance alpha oscillations significantly improved creativity task performance (Lustenberger et al., 2015), directly confirming alpha oscillations' crucial role in creative generation. Fink et al. (2009) combined EEG and fMRI to further investigate the neural mechanisms underlying alpha enhancement during creativity, finding that increased frontal alpha oscillations during creative tasks were accompanied by elevated blood oxygen levels in frontal brain regions, indicating that alpha enhancement reflects active cognitive processing rather than cortical idling.

Furthermore, researchers have examined temporal dynamics of alpha oscillations during creative generation. Studies reveal an inverted U-shaped serial order effect (Kraus, Cadle, & Simon-Dack, 2019; Rominger et al., 2019; Schwab et al., 2014; M. Wang, Hao, Ku, Grabner, & Fink, 2017), though alpha oscillations increase overall. This reflects different strategies and cognitive functions engaged at various stages: initial broad divergent thinking relying on knowledge and long-term memory retrieval; second-stage filtering that compares and selects more creative ideas while discarding conventional ones; and final reflection and reconsideration. Inhibitory control plays a key role throughout this process (Benedek & Neubauer, 2013; Fink & Benedek, 2014). To confirm this, researchers combined tACS with EEG, finding that 10 Hz tACS applied to the right temporal lobe enhanced performance on the Remote Associates Task (RAT), directly demonstrating inhibitory control' s importance and its neural mechanism (Luft et al., 2018). fMRI studies with superior spatial resolution have also confirmed inhibitory control' s role, showing that activation of the inferior frontal gyrus (IFG)—a region associated with inhibitory control—correlates positively with idea originality (Benedek, Jauk, et al., 2014). Research at the local field potential (LFP) level (Bonnefond & Jensen, 2012; de Pesters et al., 2016; Dougherty, Cox, Ninomiya, Leopold, & Maier, 2017; Haegens, Nacher, Luna, Romo, & Jensen, 2011; Samaha & Postle, 2015) and neuronal level (Watson, Ding, & Buzsaki, 2018) also links alpha oscillations to inhibitory function, suggesting alpha originates from inhibitory neuronal populations firing at approximately 10 Hz. Direct evidence from Haegens et al. (2011) shows that LFP alpha oscillations reduce neuronal firing rates, leading researchers to propose that alpha strength correlates with inhibitory function: stronger alpha oscillations indicate greater synchrony in inhibitory populations and stronger inhibition. This aligns with the relationship between alpha oscillations and cognitive control in creative generation.

2.2 Other Frequency Bands and Their Cognitive Mechanisms

Besides alpha-band increases, other frequency bands also change during creative tasks. Boot, Baas, Muhlfeld, Dreu, and Gaal (2017) developed a novel paradigm to examine neural oscillation changes during shifts in creative thinking, finding reduced delta oscillations during divergent versus convergent thinking. Another study found that midfrontal theta oscillations decreased as creativity scores increased when participants generated novel titles for unusual scenes, though importantly, fronto-occipital theta connectivity strength increased with creativity (Wokke, Padding, & Ridderinkhof, 2019). Generally, different rhythmic oscillations provide information about neuronal population communication across different temporal and spatial scales. Low-frequency oscillations, with longer cycles, can modulate information exchange across larger temporal windows and spatial ranges, whereas high-frequency oscillations, with shorter cycles, regulate smaller temporal windows and local regions (Buzsaki & Draguhn, 2004; Csicsvari, Jamieson, Wise, & Buzsaki, 2003; Jensen & Colgin, 2007). Thus, low-frequency theta activity enables large-scale neural communication, facilitating top-down cognitive control from higher to lower brain regions and coordinating multi-regional cooperation to construct the neural foundation of creativity. Creative generation therefore results from prolonged information exchange and integration across extensive brain networks. Additionally, theta activity originating in the frontal lobe is considered the neural basis of cognitive control, reflecting neural computations underlying cognitive regulation (Cavanagh & Frank, 2014), further highlighting inhibitory control’ s importance. Zabelina and Ganis (2018) also demonstrated that creativity correlates positively with attentional flexibility. Beta oscillations are closely related to divergent thinking, with studies showing enhanced frontal and parietal beta activity during divergent thinking tasks (Razumnikova, 2007). Gamma oscillation research in creativity has focused primarily on artistic domains, with one study finding that 40 Hz tACS applied to the occipital lobe significantly improved creative performance in free drawing (Luft, Zioga, Banissy, & Bhattacharya, 2019), possibly related to occipital gamma’ s involvement in multi-object perceptual processing (Tallon & Bertrand, 1999).

These findings illustrate the difficulty of deriving a consistent cognitive-neural mechanism for creativity from current research. However, the sensitivity of alpha oscillations to creative generation and the consistent finding that alpha strength increases with creativity represent the most robustly supported conclusion in the field. Enhanced frontal alpha oscillations during creative generation are thought to reflect top-down cognitive control that actively suppresses task-irrelevant activity, eliminating interference from irrelevant actions or mental processes, or inhibiting distracting stimuli to focus attention on the current task (Klimesch, Sauseng, & Hanslmayr, 2007; Sauseng et al., 2005). Enhanced temporal alpha oscillations reflect top-down control that breaks rigid mental frameworks or strengthens long-distance semantic connections by inhibiting dominant “common” semantic concepts and enhancing the probability of remote semantic associations (Beaty & Silvia, 2012; Benedek, Franz, Heene, & Neubauer, 2012; Gilhooly, Fioratou, Anthony, & Wynn, 2007), thereby facilitating novel and original ideas (Benedek & Neubauer, 2013; Fink & Benedek, 2014). However, internal processing and top-down inhibitory control are not specific to creative generation but also relate to other cognitive tasks. These may be necessary but not sufficient features of creativity. Meanwhile, the important roles of other frequency bands—such as theta’ s significance for large-scale connectivity and the contributions of gamma and beta bands—represent crucial and non-negligible aspects for future research.

3 Cross-Frequency Coupling in Creative Generation

Phase synchronization between identical rhythmic oscillations across different brain regions modulates information exchange (Fries, 2005; Gregoriou, Gotts, Zhou, & Desimone, 2009), whereas interactions between different rhythmic oscillations within or across brain regions manifest as cross-frequency coupling (CFC). Since different frequency oscillations have distinct physiological meanings, they play different roles in neural information transmission, processing, and storage. CFC may integrate more distinctive oscillatory information, facilitating deeper understanding of the special mechanisms underlying cognitive function information transfer, processing, and storage during creative generation.

Bhattacharya and Petsche (2005) used EEG to examine differences between professional artists and non-artists during artistic conception versus non-conception, finding that artists showed enhanced short- and long-term synchronization in the delta (<4 Hz) band, while non-artists exhibited enhanced short-term synchronization in beta (13-28 Hz) and gamma (30-70 Hz) bands in frontal regions. Further analysis revealed that artists showed increased delta oscillations in posterior occipitotemporal regions and increased beta and gamma oscillations in the right temporal lobe during artistic creativity tasks, whereas non-artists showed these high-frequency synchronizations in frontal regions. These results indicate amplitude-amplitude coupling (AAC) between delta-beta and delta-gamma bands, where higher-frequency oscillation amplitude changes are modulated by lower-frequency amplitude. A recent study found similar phenomena: Rosen et al. (2020) used SPM-EEG to examine dual-process contributions to jazz improvisation, finding that high-quality improvisations correlated with high-frequency oscillations (beta and gamma) in left hemisphere regions, while low-quality performances correlated with greater beta and gamma activity in right temporoparietal junction and right frontal pole. This low-frequency modulation of high-frequency AAC across brain regions suggests that artistic creativity is closely related to prefrontal, temporal, and occipital/occipitotemporal cortices, and that experienced artists and novices differ in their patterns of intra- and inter-hemispheric functional coupling during creative tasks (Bhattacharya & Petsche, 2005). A combined EEG-fMRI study examining differences between insight and analytical trial-and-error thinking in solving RAT tasks revealed neural specificity for insight: fMRI showed activation of right anterior superior temporal gyrus (aSTG), while EEG showed decreased alpha and sudden high-frequency gamma oscillations 0.3 seconds before insight (Jung-Beeman et al., 2004). This suggests gamma may bind object features during conscious perception and relates to sensory and memory processes, including top-down and bottom-up information matching (Herrmann, Munk, & Engel, 2004), indicating that alpha-gamma coupling may reflect subconscious information association and subsequent binding to perception during insight. Additionally, a study predicting individual differences in insight versus trial-and-error approaches to solving anagrams and CRA tasks from resting-state EEG found that individuals using insight showed enhanced alpha-theta coupling in left temporal pole regions (Erickson et al., 2018), suggesting that low-frequency theta modulates alpha to enhance remote associative inhibition and facilitate long-distance semantic connections, consistent with theta’ s role in large-scale network connectivity (Solomon et al., 2017).

In summary, although research on multi-band cross-frequency coupling during creative generation remains limited, this phenomenon cannot be ignored. CFC likely reflects dynamic information exchange and cooperative mechanisms among frontal, temporal, and parietal regions, though precise neural mechanisms require further investigation. Notably, CFC across different brain regions, within single regions, and between different oscillations represents a valuable future research direction that may reveal more complex cognitive-neural mechanisms and enhance our understanding of creativity’ s essence.

4 Summary and Outlook

The reviewed research demonstrates that creativity, as a high-level cognitive function, does not rely on a single brain region but involves dynamic cooperation among multiple regions and networks (Beaty et al., 2016; Sun et al., 2019), closely related to frontal, temporal, and parietal (and some occipitoparietal) cortices. High-temporal-resolution electrophysiological techniques effectively examine information exchange and dynamic cooperation among brain regions during creative generation. However, inconsistencies in findings may arise from: (1) different creative tasks used across studies, which emphasize different aspects —AUT tasks assess divergent thinking, RAT tasks assess remote semantic connections and insight, while artistic creativity tasks measure domain-specific creativity (刘春雷, 王敏, 张庆林, 2009); (2) variations in experimental parameters and analytical techniques, such as event-related synchronization/desynchronization, functional connectivity, and oscillation coupling methods (Dietrich & Kanso, 2010; Fink & Benedek, 2014); and (3) differences in stimuli, control conditions, timing, and response modes. Some researchers explain these differences from a neural efficiency perspective, suggesting that the brain allocates cognitive resources during creative idea generation through top-down control of information processing, leading to variations in activated brain regions and oscillations across tasks and conditions (Fink & Neubauer, 2006; 沈汪兵, 刘昌, 陈晶晶, 2010). This variability also underscores alpha band’ s sensitivity to creative generation.

As cognitive neuroscience technologies and experimental paradigms continue to develop, creativity’ s cognitive-neural mechanisms will become increasingly clear. Nevertheless, numerous issues and controversies remain to be resolved. Future research should pursue the following directions:

First, regarding theoretical foundations, creativity research requires theoretical integration to construct a unified framework. Many problems in current cognitive-neuroscientific creativity research stem from the lack of an integrated theoretical framework to explain heterogeneity. Although most researchers define creativity as "the ability to produce novel, unique, and socially valuable ideas or products," different theories—such as Guilford' s divergent thinking theory (Guilford, 1950), Mednick' s remote association theory (Mednick, 1962), and Martindale' s low cortical arousal theory (Martindale, 1999)—hinder integration and create confusion. Therefore, promoting close integration between empirical research and theoretical foundations is essential, with mutual verification between theory and data. Additionally, drawing from other disciplines, such as social cognitive neuroscience, which reveals how different social cultures influence creativity and their neural mechanisms (Ivancovsky, Kleinmintz, Lee, Kurman, & Shamay-Tsoory, 2018), will enable more comprehensive understanding.

Second, at the methodological level, multi-level and multi-methodological approaches should be emphasized. Beyond examining differences between task and resting states, research should focus on the dynamic temporal evolution of neural oscillations during creative generation, such as the serial order effect in divergent thinking. EEG studies should combine dynamic and static strategies—while oscillations reflect dynamic information transmission characteristics in neural networks, anatomical connectivity represents static features (Smith, Yu, Smulders, Hartemink, & Jarvis, 2006). Integrating both will better explain directional changes in neural information flow. Furthermore, combining electrophysiological techniques with neuromodulation, such as EEG with tACS, enables causal rather than correlational investigations (Herrmann, Struber, Helfrich, & Engel, 2016), providing more direct scientific evidence for creativity training.

Third, EEG data analysis algorithms should be selected appropriately based on experimental conditions and research questions. Given the highly nonlinear nature of neuronal activity, power spectrum analysis alone may be insufficient to reveal nonlinear dynamical features. More complex algorithms such as sample entropy (SampEn), which measures nonlinear characteristics of neuronal activity, should be employed. Higher SampEn values indicate greater complexity and nonlinearity, while lower values indicate greater self-similarity and simplicity. For example, Qiu Jiang' s team used the large-sample Gene-Brain-Behavior (GBB) dataset to measure resting-state brain entropy, finding positive correlations between divergent thinking and SampEn in left dorsal anterior cingulate cortex (dACC) and left dorsolateral prefrontal cortex (DLPFC), regions associated with cognitive flexibility and inhibitory control. Creative dimensions (fluency, flexibility, originality) also correlated positively with entropy in semantic networks (MTG, IFG). These results were validated in Chinese and American samples (Shi et al., 2019). Using resting-state EEG SampEn across the whole brain or in creativity-related regions like frontal and parietal cortices will yield more ecologically valid results.

Fourth, resting-state EEG research is becoming increasingly important in creativity studies. Unlike task-related EEG, resting-state EEG is a completely random signal with random frequency, amplitude, and phase, theoretically unsuitable for direct Fourier transform or time-frequency and phase spectrum analysis. Instead, higher-order signal processing methods such as multiscale entropy (MSE), power spectrum density (PSD), and surface Laplacian transformation should be used. MSE, similar to SampEn, measures complexity across multiple time series scales. Ueno et al. (2015) first used MSE to examine resting-state EEG complexity differences between high- and low-creativity elderly individuals, clarifying the neurophysiological basis of creativity in healthy aging. Erickson et al. (2018) used Laplacian transformation of resting-state EEG to predict, weeks in advance, whether individuals would use insight or trial-and-error approaches to solving anagrams and CRA tasks. Prent and Smit (2020) used PSD analysis of resting-state EEG, successfully predicting individual creativity differences through the power-law exponent (β) of alpha band power spectra ($( )\quad -\beta$). These advanced algorithms for complex resting-state EEG data provide effective approaches for predictive creativity research and broaden future research perspectives.

Fifth, computational neuroscience and big data analytics should be strengthened to advance creativity research. Quantitative analysis of coupling strength and direction changes in multi-band cross-frequency coupling during creative generation can reveal deeper relationships between creativity and CFC indices. Combining neurophysiological data with behavioral data and employing computational modeling alongside machine learning methods such as Decision Trees, Random Forests, and Support Vector Machines (SVM) can enable effective prediction of individual creativity development, offering a more rigorous perspective for explaining neural oscillation mechanisms in creativity.

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