Routledge
Taylor & Francis Group

Creativity Research Journal

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/hcrj20

The Receptive Brain: Up-Regulated Right Temporal Alpha Oscillation Boosting Aha!

Amna Ghani, Caroline Di Bernardi Luft, Smadar Ovadio-Caro, Klaus-Robert Müller & Joydeep Bhattacharya

To cite this article: Amna Ghani, Caroline Di Bernardi Luft, Smadar Ovadio-Caro, Klaus-Robert Müller & Joydeep Bhattacharya (06 Dec 2023): The Receptive Brain: Up-Regulated Right Temporal Alpha Oscillation Boosting Aha!, Creativity Research Journal, DOI: 10.1080/10400419.2023.2289757

To link to this article: https://doi.org/10.1080/10400419.2023.2289757

CREATIVITY RESEARCH JOURNAL
https://doi.org/10.1080/10400419.2023.2289757

The Receptive Brain: Up-Regulated Right Temporal Alpha Oscillation Boosting Aha!

Amna Ghani[a,b], Caroline Di Bernardi Luft[c], Smadar Ovadio-Caro[d], Klaus-Robert Müller[e,f,g,h,i,j], and Joydeep Bhattacharya[k]

[a]Charite Universitatsmedizin Berlin, Berlin, Germany; [b]Berlin School of Mind and Brain, Humboldt-Universität zu Berlin, Germany; [c]Brunel University, London; [d]University of Haifa; [e]Technische Universität Berlin, Berlin, Germany; [f]Berlin Institute for the Foundations of Learning and Data – BIFOLD, Berlin, Germany; [g]Korea University, Seoul, South Korea; [h]Max Planck Institute for Informatics, Saarbrücken, Germany; [i]Google DeepMind, Berlin, Germany; [j]Freie Universität Berlin, Berlin, Germany; [k]Goldsmiths University of London

ABSTRACT

Chance favors the prepared mind, said Louis Pasteur. Sometimes, significant breakthroughs occur when we creatively integrate new information, leading to a creative insight or an Aha! moment, while at other times when we fail to use a clue, we remain stuck in our habitual thinking patterns. In this study, we hypothesized that the brain's transient oscillatory states would characterize its receptivity or preparedness for such insights. We conducted a real-time brain-state-dependent cognitive stimulation experiment during insightful problem-solving. We showed that participants were more successful in utilizing clues and experienced more Aha responses when these clues were presented at the spontaneously up-regulated state of right temporal alpha oscillation, as opposed to the down-regulated state. Furthermore, we observed an inverse correlation between the coupling of alpha oscillation phase and gamma oscillation power and the frequency of insight. These results shed light on the neural mechanism underpinning the brain's receptivity to integrate upcoming semantic information, emphasizing the pivotal role of dynamical brain oscillations in the Aha! experience.

ARTICLE HISTORY

Received June 9, 2022

PLAIN LANGUAGE SUMMARY

In this study, we focused on finding the brain's receptive state during insightful problem solving – a state where new (semantic) information is successfully integrated to find creative solutions. We predicted that the brain's naturally fluctuating neuronal oscillations, specifically those occurring in the right temporal region, might indicate this receptivity. We recruited healthy volunteers and presented them with word association problems, and provided hints contingent on the brain's spontaneous up (or down) state of the right temporal alpha oscillation (8–12 Hz) on a trial-by-trial basis. We found that participants solved more problems and reported more insights or Aha! moments when hints were presented in the spontaneously up-regulated alpha states. In particular, this effect was specific to alpha and not beta oscillations (16–22 Hz). We also revealed that a phase-amplitude cross-frequency coupling between alpha phase and gamma (50–133 Hz) power was negatively correlated with the frequency of Aha!. This study has established a clear association between right temporal alpha oscillation and the brain's receptivity and Aha! experience through our innovative approach of real-time brain-state-dependent cognitive stimulation. Importantly, our approach is noninvasive, free from adverse side effects, and does not rely on performance feedback, making it convenient, affordable, and readily applicable beyond the laboratory setting.

Introduction

Creative thinking is an essential skill that enables individuals to generate novel and useful ideas in various contexts. To engage in creative thinking, it is crucial to integrate new concepts with old ones (Turner & Fauconnier, 1999). This may demand being open and receptive to new information and combining it with appropriate previous knowledge, leading to an Aha! moment, a hallmark of creative cognition. Conversely, sticking to habitual thinking patterns can lead to stagnation, and the creative solution remains elusive. We propose that this receptivity to new information during creative problem-solving would be associated with the spontaneous fluctuations of alpha oscillation, occurring just before the new information becomes available.

Alpha (8–12 Hz) oscillation represents a prominent feature of spontaneous brain activity and is often

CONTACT Joydeep Bhattacharya j.bhattacharya@gold.ac.uk Department of Psychology, Goldsmiths University of London, London, UK

Supplemental data for this article can be accessed online at https://doi.org/10.1080/10400419.2023.2289757

considered as an effective indicator of cortical excitability (Klimesch, Sauseng, & Hanslmayr, 2007). Alpha oscillation has been extensively studied in sensory attentional processing (Peylo, Hilla, & Sauseng, 2021). While the precise neurophysiological mechanisms governing alpha oscillation's role in attentional processing remain a subject of debate (Schneider, Herbst, Klatt, Wöstmann, & Keitel, 2022), it is widely recognized that alpha oscillation within the visual cortex (i.e., within the task-relevant brain regions) represents a transient modulation of local cortical excitability; this modulation, in turn, influences the processing of upcoming visual stimuli. A growing body of research has delved into the pivotal, and potentially causal, role of alpha oscillation in the prestimulus period in shaping poststimulus responses. For example, studies have shown that prestimulus alpha activity over visual areas can predict perceptual task performance (Michail, Toran Jenner, & Keil, 2021), impact the perception of phosphenes (Romei et al., 2008), influence perceptual dominance in multisensory illusion (Yun et al., 2020), and play a role in temporal binding across sensory modalities (Buergers & Noppeney, 2022).

Alpha oscillation has also been robustly linked to creativity. For example, alpha oscillation is consistently observed in several cortical regions during divergent thinking tasks (see, for a review, Fink & Benedek, 2014). Further, alpha oscillation is associated with creative insights, characterized by the sudden emergence of a solution into conscious awareness without any forewarning, often described subjectively as the "Aha!" moment. In a seminal study exploring insight (Jung-Beeman et al., 2004), participants solved remote associate tests (RAT), where they were asked to find a solution word that could make three compound words or familiar phrases with three cue words (e.g., walker/main/sweeper; solution: street). Solutions were obtained either by insight, where they appeared suddenly, or by analysis, involving a conscious, deliberate and incremental approach. The authors reported heightened alpha power specifically over the right posterior parietal region around 1 s before the moment of insight in insight trials compared to the analysis trials. In a follow-up study by the same group of authors (Kounios et al., 2006), they showed that alpha power during the 2 s prestimulus period preceding the RAT trials was higher for insight trials than for analysis trials; this effect was observed over a broad range of brain regions, including right temporal, right inferior frontal, mid frontal cortex and left temporal areas. The results suggest heightened preparatory processing in the semantic network, influenced by the top-down control of the cognitive control network (Kounios et al., 2006).

The first preliminary evidence suggesting alpha oscillation as a marker of the brain's receptivity was provided by our previous study (Sandkühler, Bhattacharya, & Zak, 2008). In this study, we recorded the EEG of participants while they solved RAT trials. When a RAT problem could not be solved within 45 s, we presented a hint or a clue (e.g., s _ _ _ _ t) with hints revealing the solution word partially but always including the first letter. We found higher alpha power in the right temporal region from −0.2 to 0.3 s after the onset of hint presentation for trials that resulted in a correct solution, compared to trials that led to a timeout (when no solution was found within the allotted time of 7 s after the hint). To solve RAT problems, individuals need to suppress the most obvious associations of at least one of the three given words and instead find a fourth word associated with all three words. This alpha-band activity before the hint might reflect the inhibition of ongoing, habitual semantic processing, allowing a competitive but weaker, unconscious semantic processing to integrate with the hint. This integration eventually leads to the production of the solution or target word, reaching the level of conscious awareness (Bowden & Jung-Beeman, 2003a; Bowers, Regehr, Balthazard, & Parker, 1990; Sandkühler, Bhattacharya, & Zak, 2008).

While this early finding of right temporal alpha oscillation in the brain's receptivity was promising, the evidence remains purely correlational. To establish any form of causality, it is essential to regulate alpha oscillation in a controlled manner and then subsequently investigate its impact on creative insights. The two most widely used techniques for modulating brain oscillations to demonstrate causal links between specific brain oscillation and cognitive processes are transcranial alternating current stimulation (tACS) and neurofeedback (Herrmann, Strüber, Helfrich, & Engel, 2016). The first technique, tACS, involves applying current at specific frequencies to boost neural oscillation at the same frequency (Wischnewski, Alekseichuk, & Opitz, 2023). Regarding creative cognition, boosting alpha power by 10 Hz tACS, but not by 40 Hz, in the frontal region has been shown to improve divergent thinking task performance (Lustenberger, Boyle, Foulser, Mellin, & Fröhlich, 2015). More relevant to our current study, we found earlier that under 10 Hz tACS to the right temporal region, participants solved more RAT problems with words that shared misleading associations (Luft, Zioga, Thompson, Banissy, & Bhattacharya, 2018), corroborating the critical role of right temporal alpha activity in suppressing obvious but misleading associations. Notably, another brain stimulation study has established a causal link between the right temporal brain region and insight problem-solving (Salvi, Beeman, Bikson, McKinley, & Grafman, 2020); however, because the stimulation method used was tDCS in which a direct current with specific polarity was applied to a target brain region, no specific inferences about the involved oscillations could be made out of this study. The second technique, neurofeedback, measures brain activity in real-time and provides participants with feedback to help them self-regulate specific brain activity (Sitaram et al., 2017). Feedback can be overt, where participants are explicitly aware of the nature of the feedback, or covert, where targeted brain activity is reinforced implicitly (Ramot & Martin, 2022). Past research has demonstrated the usefulness of neurofeedback in boosting creativity (see for a review, Gruzelier, 2014). However, the causal links between specific brain activity patterns and constituent cognitive processes during creative problem-solving remain elusive. OIt is noteworthy that the effects of both tACS and neurofeedback are longer lasting, ranging from minutes to hours, limiting their value in investigating the brain's receptivity during creative problem-solving.

An appropriate method in this context is brain-state-dependent cognitive stimulation (Jensen et al., 2011), which allows for the manipulation of cognitive processing, such as the brain's receptivity, by considering real-time brain activity, specifically the right temporal alpha oscillation. This manipulation could be achieved by adjusting the stimuli presented to the participant based on the real-time evaluation of their brain activity (Hartmann, Schulz, & Weisz, 2011). The efficacy of this method has been demonstrated in research studies using single-neuron recording (Cerf et al., 2010) and EEG (Vigué-Guix, Morís Fernández, Torralba Cuello, Ruzzoli, & Soto-Faraco, 2022). In our current study, we monitored the ongoing right temporal alpha oscillation in real-time while participants were solving RAT problems. If a participant was unable to solve a problem within an allotted time, we presented a hint; the timing of the hint was contingent on the state, up or down, of the right temporal alpha oscillation. Our primary hypothesis was that hints followed by an elevated right temporal alpha state would result in more correct responses and frequent insights, implying the importance of right temporal alpha oscillation in the brain's receptivity. More particularly, we sought to examine whether hints provided contingent on an increase in the right temporal alpha power would improve participants' overall accuracy and lead to more frequent insights compared to hints provided contingent on a decrease in the right temporal alpha power.

Although our unique real-time experimental design was exclusively centered around monitoring alpha oscillation in real-time, other brain oscillations are also involved in creative problem-solving (Jung-Beeman et al., 2004; Oh, Chesebrough, Erickson, Zhang, & Kounios, 2020; Sandkühler, Bhattacharya, & Zak, 2008; Sheth, Sandkühler, & Bhattacharya, 2009). Gamma oscillation (30–50 Hz) is particularly relevant for creative insights due to its involvement in multiple cognitive processes, including selective attention (Fries, Reynolds, Rorie, & Desimone, 2001), retrieval (Sederberg et al., 2007), semantic integration (Jung-Beeman et al., 2004), and conscious awareness (Summerfield, Jack, & Burgess, 2002) – all of which are essential for insights or Aha! moments (Stevens & Zabelina, 2019). A previous study showed that applying 40 Hz tACS over the right temporal region resulted in a substantial (20%) increase in insights during the solving of RAT problems (Santarnecchi et al., 2019); this finding suggests a causal role of gamma oscillation in the right temporal brain region in facilitating creative insight. Although alpha and gamma activity have typically been studied independently in the context of creative cognition, some key findings have underscored the coupling between slow (theta and alpha) and fast (gamma) oscillations as a characteristic of enhanced communication between neuronal assemblies during cognitive processing (Canolty & Knight, 2010; Canolty et al., 2006; Esghaei, Treue, & Vidyasagar, 2022). In particular, gamma power coupled with the alpha phase acts as a filter for incoming information (Bonnefond, Jensen, & Tort, 2015) so that gamma oscillation retains the information while alpha oscillation protects that information from distractors (Park et al., 2016; Roux & Uhlhaas, 2014). This alpha-gamma phase-amplitude coupling provides a mechanism for organizing and controlling the flow of information (Jensen, Gips, Bergmann, & Bonnefond, 2014). Therefore, we had a secondary hypothesis that posited that the nature of alpha-gamma phase-amplitude coupling at the hint presentation could be a determining feature of solutions reported as Aha! effect – insight responses. More specifically, we aimed to observe whether alpha – coupled gamma power suppression would be related to the frequency of insights.

Materials and methods

Participants

Two independent groups of healthy human adults participated in two separate conditions, alpha and beta (as control). Each condition had two separate sessions – up and down – held a week apart. Each participant attended two separate sessions on two separate days with an intersession interval of about seven days. The sessions were named alpha-up and alpha-down for the alpha condition (beta-up and beta-down for the beta condition). There were two sets of 100 remote association problem sets (RAT-A and RAT-B). These two problem sets and two sessions (up or down) were counterbalanced across participants. The alpha condition had seventeen participants, and the beta condition had nineteen participants (10 females, 24.11 ± 2.73 years). All participants were healthy human adults and right-handed university students, and they gave informed consent before participating in the experiments. The study protocol was approved by the Local Ethics Committee.

Task and procedure

In each session, participants were tasked with solving 100 compound versions of the remote associate test, RAT (Bowden & Jung-Beeman, 2003b; Sandkühler, Bhattacharya, & Zak, 2008). In each RAT trial, three cue words (e.g., river, note, account) were presented on a computer screen; the task was to find a solution word that would make three compound words with the presented cue words (e.g., the solution word is "bank" in this case: riverbank, banknote, bankaccount). As mentioned earlier, previous research suggests that a RAT problem can be solved via insight (i.e., the solution appearing suddenly in awareness without any prior conscious forewarning) or analysis (i.e., the solution appearing gradually after working out in a deliberate, conscious manner) (Jung-Beeman et al., 2004; Rothmaler, Nigbur, & Ivanova, 2017). Furthermore, an extensive body of research demonstrates the suitability of RAT problems for studying the neural markers of insight in neuroimaging studies (for reviews, see Bowden, Jung-Beeman, Fleck, & Kounios, 2005; Kounios & Beeman, 2009).

In this study, on each trial (as shown in Figure 1), participants were initially given 20 s to solve a RAT problem. They were asked to press a button as soon as they found the solution word without engaging in detailed mental checks. Subsequently, participants verbalized the solution and reported whether they obtained it with insight or non-insight, as explained to them beforehand, after previous research (Jung-Beeman et al., 2004). Afterward, they proceeded to the next trial. If a solution was not found within the initial 20 s period, we provided a hint showing the number of letters in the solution word but revealing only the first letter (e.g., "b _ _ _"). However, the timing of hint presentation depended on the fluctuations (either up or down) of ongoing alpha oscillation over the right temporal brain regions. For the alpha condition, we computed the average alpha power (8–12 Hz) across the three right temporal electrodes (FT8, T8, and TP8) in real-time, with power computed with a 1 s window and a 50% overlap on each trial. We obtained the mean

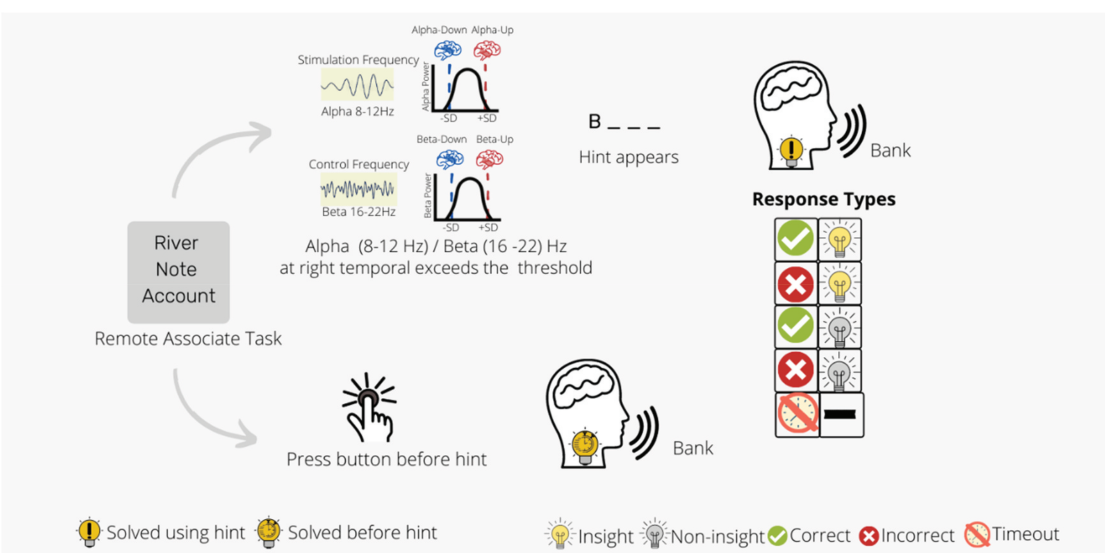

Figure 1. Brain-state-dependent cognitive stimulation paradigm. participants solved RAT problems. Three cue words were presented on each trial, and participants had to find a fourth word, which makes a compound word with each of these three words. We calculated alpha power over the right temporal brain region (FT8, T8, TP8) in real-time during the problem presentation to estimate a trial-specific threshold. If a solution was not found within the first 20 s, a hint (revealing the first letter of the solution) was provided at a time when the transient right temporal alpha power was higher (shown in red for alpha up) or lower (blue for alpha-down) than the trial-specific threshold.

(μ) and standard deviation (σ) of the right temporal alpha power for the first 20 s of the problem presentation. For the alpha-up condition, we set a trial-specific threshold (T) as follows: $T = \mu + 1.5\sigma$; a hint was presented in the alpha-up condition if the transient right temporal power on a given trial surpassed this trial-specific threshold. The alpha-down was the opposite: the trial-specific threshold was $T = \mu - 1.5\sigma$, and a hint was presented if the transient alpha power dropped below this threshold of that specific trial. Following the hint presentation, the participants were given a further 15 s to solve the problem. Like earlier, they verbalized the solution and reported whether it was obtained via insight or analysis. The trial was terminated if no solution was found within 15 s following the hint presentation.

The experimental task, including instructions and stimuli, was presented on a PC using the MATLAB Toolbox Cogent 2000 (http://www.vislab.ucl.ac.uk/cogent_2000.php). Real-time processing of the EEG signals was performed using ActiView®, the acquisition software of the BiosSemi ActiveTwo EEG system. ActiView, developed within the LabVIEW® programming environment, was modified to enable real-time processing of the EEG signals. This modified ActiView program communicated with the MATLAB-based stimulus-presentation program through a parallel port (DB-25). At the start of a RAT trial, a trigger was sent from the MATLAB Cogent software to the ActiView program to initiate real-time signal processing and calculate the trial-specific threshold. When the ActiView program detected an increase or decrease in alpha power over three right temporal electrodes, exceeding or falling below the trial-specific threshold for the alpha up or down condition, it sent a trigger back to the MATLAB program. This trigger prompted the presentation of a hint on the screen. Participants responded by pressing a button, and all their responses were recorded through the MATLAB Cogent program.

The entire protocol remained similar for the beta-up and beta-down conditions, with the exception that we monitored the right temporal beta power (16–24 Hz) in real-time. Hints were presented if the transient beta power exceeded or fell below the trial-specific threshold, which was calculated within the beta frequency band, as described above.

EEG recordings

We recorded EEG signals with sixty-four Ag-AgCl electrodes placed according to the extended 10–20 electrode placement system and amplified by a BioSemi ActiveTwo® amplifier. Vertical and horizontal electro-occulograms were recorded by placing electrodes above and below the left eye and at the outer canthus of each eye, respectively. The sampling frequency was 512 Hz. We used the MATLAB Toolbox EEGLAB (Delorme & Makeig, 2004) and custom MATLAB scripts for EEG preprocessing. EEG data were high-pass filtered at 1 Hz and algebraically re-referenced to the average of the two earlobes. The line-noise interference at 50 Hz was removed by the EEGLAB *CleanLine* function. Artifact rejection was done in a semiautomatic fashion. First, we removed sections with large artifacts by visual inspection and replaced bad channels by spline interpolation. Second, we applied independent component analysis (ICA) to correct eye-blink-related artifacts. Finally, the ICA-cleaned sections were visually inspected to remove any remaining large artifacts with amplitudes over ±120 μV.

Behavioral analysis

We calculated the accuracy for each participant as the number of correct solutions obtained in each session (up, down) for each condition (alpha, beta). Further, we categorized the accuracy based on whether solutions were obtained with or without a hint. Further, we calculated the percentage of correct insights with hints out of the total problems solved with a hint. The data were normalized using the square-root transformation and analyzed using mixed ANOVA; normality was validated by the Shapiro-Wilk normality test. Finally, we used Wilcoxon and paired-sample tests to compare the reported insight obtained with hints in alpha-up and alpha-down sessions. The statistical analysis was performed in R and SPSS software packages.

EEG analysis

We obtained EEG sources using the Brainstorm toolbox (Tadel, Baillet, Mosher, Pantazis, & Leahy, 2011) for the epoch spanning 4 s before and 3 s after the hint presentation (−4 s to + 3 s). First, we calculated the standard head model using the openMEG toolbox, and then, we obtained cortical sources using sLORETA without selecting any noise covariance option. Once the sources were obtained, we extracted the scout time series for these sources using the Desikan-Killiany atlas (Desikan et al., 2006), which comprises 68 regions of the brain. Our primary focus was the right superior temporal gyrus. However, we also explored the inferior frontal gyrus (IFG) due to its known involvement in semantic and cognitive control (Becker, Sommer, & Kühn, 2020; Salvi, Beeman, Bikson, McKinley, & Grafman, 2020;

Stramaccia, Penolazzi, Altoè, & Galfano, 2017). Previous research has suggested that a balance between the right and left IFG is crucial for achieving better performance in creative tasks (Mayseless & Shamay-Tsoory, 2015); nonetheless, for this study, we limited our investigation to the right hemispheric region.

In this study, our primary hypothesis revolved around the right temporal alpha oscillation. Our secondary hypothesis was related to alpha-gamma phase-amplitude coupling, which was studied using cross-frequency coupling (CFC) maps (Canolty & Knight, 2010). The analysis focused on a specific time window, covering 4 s before and 3 s after the presentation of a hint. The CFC maps were obtained using the Brainstorm toolbox for 68 brain regions. CFC maps are essentially time-frequency decompositions that evaluate the relationship between low-frequency and high-frequency oscillations. These CFCs were quantified using phase-amplitude coupling (PAC) or nesting, which means that the amplitude of high-frequency oscillation is modulated by the phase of low-frequency oscillation. We specifically focused on the upper alpha oscillation at 12 Hz alpha as the average gamma power (60–100 Hz) was largest at the 12 Hz alpha phase (Figure S1 in the *Supplementary Materials*).

Results

Table 1 shows the average percentages of problems solved with and without a hint for alpha-up, alpha-down, beta-up and beta-down conditions, individually. Participants in the alpha-up and alpha-down conditions solved an average of 20.8% and 16.9% of the problems without a hint, respectively. For the beta-up and beta-down conditions, the values for the same are 20.9% and 20.8%, respectively. With hints, the solution rates for alpha-up and alpha-down were 37.0% and 34.5%, respectively; for the beta-up and beta-down conditions, the values for the same are 39.6% and 40.3%.

We analyzed these solution rates without a hint by a 2 (frequency: alpha, beta) x 2 (session: up, down) mixed ANOVA. There was no main effect of session ($F(1,32 = 3.38$, $p=.08$, partial-$\eta^2=.09$) or frequency ($F(1,32)=.62$, $p=.44$, partial-$\eta^2=.02$); the interaction between frequency and session was also not significant ($F(1,32) = 2.50$, $p=.12$, partial-$\eta^2=.07$).

Table 1. Averages of percent of problems solved without a hint, with a hint across alpha-up, alpha-down, beta-up, and beta-down.

	Solved without hint		Solved with hint	
	Average percent	SD	Average percent	SD
Alpha-up	20.8	9.53	37.0	10.3
Alpha-down	16.9	6.34	34.5	5.39
Beta-up	20.9	7.10	39.6	9.66
Beta-down	20.6	7.66	40.3	7.37

A similar analysis for overall reported insights revealed a main effect of frequency, $F(1,32) = 8.99$, $p = .005$, partial-$\eta^2 = 0.22$ and session, $F(1,32) = 4.34$, $p = .045$, $\eta^2 = 0.12$ and a significant interaction between frequency and session, $F(1,32) = 4.87$, $p = .035$, $\eta^2 = 0.013$. Planned contrasts revealed Figure 2(A) that the alpha-up session ($M = 27.11$) elicited significantly higher ($p = .017$) reported insights than the alpha-down session ($M = 20.8$); no such difference ($p=.091$) was observed between the beta-up ($M = 35.94$) and beta-down ($M = 35.53$) sessions. Another 2×2 mixed ANOVA for overall correct solutions revealed a marginal main effect of frequency, $F(1, 32) = 4.03$, $p = .053$, $\eta^2 = 0.11$, and a significant interaction between frequency and session, $F(1,32) = 5.38$, $p = .027$, $\eta^2 = 0.14$. Planned contrasts revealed that the alpha-up session ($M = 47.64$) elicited significantly more ($p = .033$) correct solutions than alpha-down session ($M = 42.64$); no such difference ($p = .43$) was found between the beta-up ($M = 50.29$) and beta-down ($M = 51.53$) sessions. Further, a Wilcoxon signed-rank test indicated that hints presented on alpha-up state led to more correct insights than those on alpha-down ($V = 124$, $p = .011$; Figure 2(B). Further descriptions and analysis of various behavioral measures (e.g., average time for a hint to appear, average solution time, average solution rate for non-insights with or without hints) are included (Figures S2-S8) in the *Supplementary Materials*.

Next, we investigated cross-frequency coupling by CFC maps averaged across participants. These maps were used to evaluate the coupling between alpha (low-frequency) and gamma (high-frequency) oscillations around the hint presentation, analyzed separately for alpha-up and alpha-down sessions Figure 3(A). We observed a moderate negative correlation between the frequency of insights and the alpha-coupled gamma power in three brain regions (depicted in Figure 3(B), which are notably associated with semantic processing (right superior temporal: $r(17)=-0.51$, $p = .038$; pars opercularis: $r(17)=-0.52$, $p = .03$; pars triangularis: $r(17)=-0.55$, $p = .022$). Participants reporting more insights exhibited more gamma suppressions by the phase of 12 Hz alpha oscillation around the hint presentation. Importantly, these correlations were observed exclusively for the alpha-up session and were not evident for the alpha-down session Figure 3(B).

We also demonstrated the effectiveness of our brain-state-dependent paradigm by visualizing time-frequency representations of problems solved with

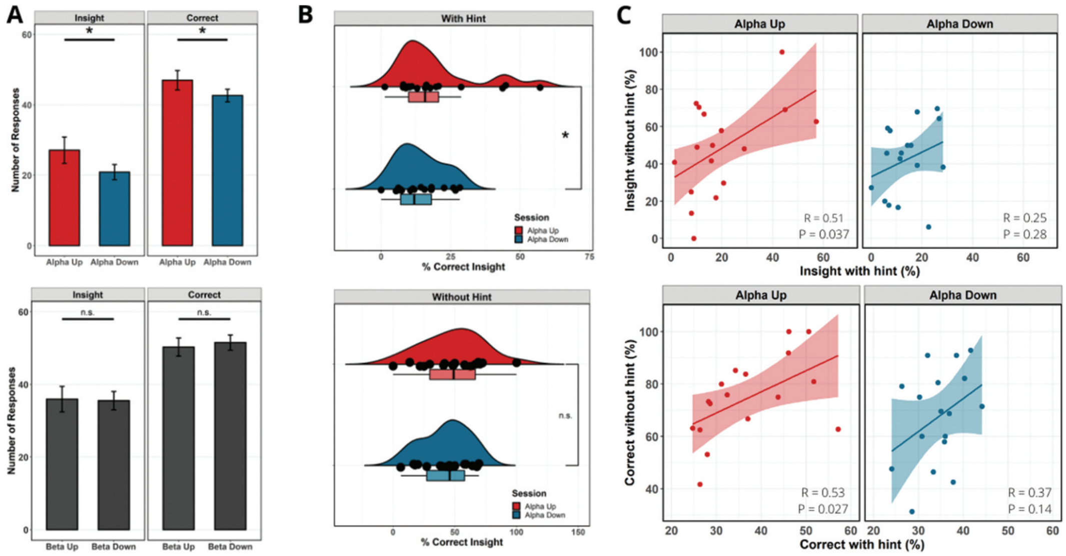

Figure 2. Higher reported insights and correct responses in the alpha-up session. (A) numbers of reported insights (i.e., solutions associated with an Aha! experience) and correct solutions were significantly higher in alpha-up than in alpha-down session; no significant differences were found in control sessions (beta-up vs. beta-down). **(B)** correct insights were more frequent during alpha-up hints than alpha-down. **(C)** insights and correct responses with hints were positively correlated with insights and correct responses without hints.

hints. During the alpha-up session, we observed, as expected according to our experimental manipulation, a substantial increase in the alpha activity approximately 1 s before the hint onset (*Supplementary Materials*: Figure S9A); its scalp map showed increased alpha power concentrated around the right temporal regions (Figure S9B). Further, CFC maps provided additional insights into the power differences between the alpha-up and alpha-down sessions (Figure S9C).

Discussion

Efficiently integrating complex semantic information necessitates the seamless merging of external information with preexisting knowledge. In this study, using a novel brain-state-dependent cognitive stimulation paradigm during insight problem solving, we showed that hints were effectively utilized to obtain solutions with creative insights when hints were presented during an up-regulated alpha state as opposed to a down-regulated one. This outcome supports our primary hypothesis and is consistent with our previous study which has indicated the predictive nature of right temporal alpha oscillation in successfully leveraging hints (Sandkühler, Bhattacharya, & Zak, 2008). Further, it aligns with the findings of another of our prior studies that boosting alpha oscillation by 10-Hz tACS resulted in improved access to remote associations (Luft, Zioga, Thompson, Banissy, & Bhattacharya, 2018).

Our real-time-based paradigm demonstrates that the brain's receptivity can be characterized by controlling the timing, intensity, and precision of ongoing alpha oscillation, which acts as a mechanism of pulsed-inhibition (Klimesch, 2012). Through such pulsed inhibition, we postulate that alpha oscillation suppresses gamma band activity and deactivates the neuronal population responsible for decoding the most obvious but incorrect associations. Further, the alpha phase might be linked to stimuli-bound features or associations (Brickwedde, Krüger, & Dinse, 2019), and by suppressing gamma, alpha oscillation can regulate the flow of information, either enhancing or degrading task performance (Bonnefond, Jensen, & Tort, 2015). Thus, our secondary hypothesis was also supported, suggesting that the observed alpha-gamma phase-amplitude coupling when hints were presented could be related to the brain's receptivity. This interaction between slower alpha and faster gamma oscillations may reflect coding principles underlying the brain's ability to retrieve remote ideas and integrate new information (Varga & Manns, 2021).

A recent study hypothesizes that insights occur during cognitive navigation and involve rapid changes in cellular plasticity (Aru, Drüke, Pikamäe, & Larkum, 2023). Insight is thought to happen when a new idea or stimulus is introduced to the brain, activating specific hippocampal neurons and creating connections between previously unrelated concepts. This process results in the formation of a new concept field, and

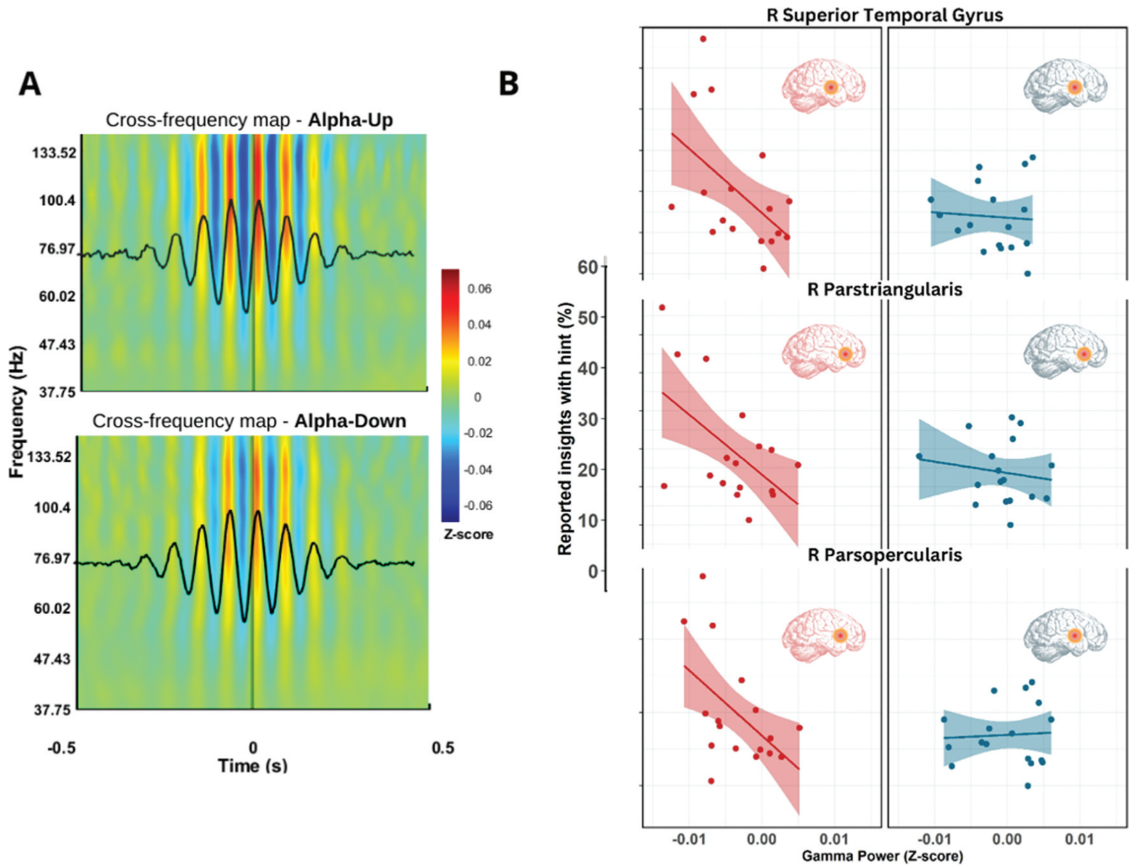

Figure 3. Alpha-gamma phase-amplitude coupling during brain-state-dependent cognitive stimulation. (A) Cross-frequency coupling maps around hint (−4 s to + 3 s after hint presentation) at the right superior temporal gyrus. The time-frequency maps were plotted for low nesting frequency (overlaid black) as alpha at 12 hz while the higher frequency was selected as broadband gamma 37–133 hz showing alpha phase-coupled gamma power. We observed different coupling strengths between the alpha phase and the gamma power for alpha-up and alpha-down sessions. **(B)** the scatter plots between the reported insights and the average gamma (60–100 hz) power (12 hz alpha phase-coupled) at three selected brain regions (right superior temporal, pars opercularis, and pars triangularis) separately for alpha-up and alpha-down sessions. Significant negative correlations (r ~0.5, $p < .05$, see text for details) were observed only during the alpha-up session.

such insight depends on encountering a new stimulus. We suggest that hints, as presented in our study, might trigger such opportunistic integration, leading to the emergence of Aha! moments (Moss, Kotovsky, & Cagan, 2011), supporting the prepared mind account of insight (Seifert, Meyer, Davidson, Patalano, & Yaniv, 1995).

Two surprising findings emerged from our study: (i) the association between alpha-gamma coupling and insight frequency at the participant level and (ii) the session-wide effect of increased insight during the alpha-up session. In our earlier study (Luft, Zioga, Thompson, Banissy, & Bhattacharya, 2018), we did not observe enhanced insight experiences when we boosted temporal alpha by 10-Hz tACS. However, in the current study, we observed that presenting occasional new information during a spontaneously up-regulated alpha state led to an increase in insights. As mentioned earlier, the alpha phase might encode the gamma activity, acting as a gate to control the flow of information from the neuronal population carrying misleading associations. This gating mechanism facilitates the retrieval of distant, remote associations, resulting in a sudden burst of conscious awareness – an insightful experience or an Aha! moment. The session-wide effect of boosting this subjective experience implies a degree of neuroplasticity and cumulative effects. However, it is crucial to note that this accumulation was observed exclusively in the alpha-up session. We could speculate that participants were involved in implicit self-regulation, whose goal was solving a problem (Muñoz-Moldes & Cleeremans, 2020). This active self-regulation strategy appeared to influence the timing of problem presentation, irrespective of hints. We observed an upward trend in right temporal alpha power during the alpha-up session compared to the alpha-down session at the time of problem presentation (Figure S10 in *Supplementary Materials*). This suggests that participants might have implicitly learned to up-regulate their right temporal alpha oscillation. Interestingly, we did not observe a similar boost in right temporal alpha power at the problem presentation during the beta sessions (Figure S11), nor did we detect any enhancement of beta power at the problem presentation in the beta sessions (Figure S12). Therefore, this implicit boosting of brain oscillation was specific to the alpha-up session.

Of note, our experimental approach of brain-state-dependent cognitive stimulation overlaps with a covert form of neurofeedback (Ramot & Martin, 2022), where training occurs implicitly. In both approaches, participants, much like in our study, do not receive explicit feedback about their brain activity, resulting in implicit learning without conscious awareness of the association between reward and brain activations. Interestingly, experiencing insight is intrinsically rewarding and is associated with activations of the orbitofrontal cortex (Oh, Chesebrough, Erickson, Zhang, & Kounios, 2020) and the midbrain dopaminergic network (Tik et al., 2018). These rewarding feelings associated with achieving solutions with insight may encourage participants to develop more effective implicit strategies for spontaneous self-regulation of the right temporal alpha oscillation (Oh, Chesebrough, Erickson, Zhang, & Kounios, 2020; Ramot, Grossman, Friedman, & Malach, 2016).

Our study has several limitations. First, while our dataset comprised approximately 70 separate EEG sessions, each consisting of 100 trials, which is adequate for testing our primary hypotheses, the number of participants (= 17) in each condition was relatively on the lower side. Second, we focused our investigation solely on the right temporal brain region. While this choice was entirely based on our previous research (Sandkühler, Bhattacharya, & Zak, 2008) and the prominent role of the right temporal region in semantic processing and integration (Binder, Desai, Graves, & Conant, 2009; Lambon Ralph, Cipolotti, Manes, & Patterson, 2010; Tranel, Damasio, & Damasio, 1997), we could not rule out the potential contribution of other brain areas to the brain's receptivity, as studied here. For instance, it would be useful to explore the role of left temporal regions because alpha oscillation over this brain region in the resting state (Erickson et al., 2018) or the prestimulus state (Kounios et al., 2006) is associated with insight. Our current study could not include additional brain regions due to practical limitations. Introducing more brain regions and other types of oscillations related to insight would have overly complicated the experiment. Future research could investigate this issue further, focusing on other brain regions, including the left temporal and left fronto-polar cortex (Salvi, Beeman, Bikson, McKinley, & Grafman, 2020). Third, we conducted our cross-frequency coupling analysis at the participant rather than the trial level. We acknowledge that evaluating a trial-by-trial cross-frequency coupling approach would have been more informative, especially in the context of dynamically presenting hints. Future research could explore trial-by-trial cross-frequency coupling to study the dynamics of achieving insights. Surprisingly, only a few studies have investigated functional connectivity analysis within a frequency band for insights (Razumnikova, 2007), and virtually nothing is known about insight-related cross-frequency coupling. Therefore, our present findings represent an initial step toward revealing the interdependence between large-scale brain oscillations during insight problem solving. Fourth, our real-time monitoring focused exclusively on right temporal alpha oscillation; however, through offline analysis, we showed that the alpha phase was coupled with gamma oscillation. Therefore, in future studies using a similar brain-state-dependent stimulation approach, it may be interesting to present hints contingent on the nature of alpha-gamma coupling. Finally, while it is not necessarily a limitation per se, we would like to comment on the potentially causal role of right temporal alpha oscillation in the brain's receptivity. Establishing causality is a fundamental question in most scientific domains, including cognitive neuroscience (Marinescu, Lawlor, & Kording, 2018). Inferring causality from noninvasive brain stimulation (Bergmann & Hartwigsen, 2021) and neurofeedback (Bergmann & Hartwigsen, 2021) is not straightforward. We propose that the right temporal brain oscillation may not be the sole cause of the brain's receptivity, but rather, our findings suggest that it could be one component of a causal network contributing to the brain's receptivity.

In conclusion, our results establish a clear association between specific neuronal oscillatory patterns and the brain's receptivity during insightful problem solving. Further, we demonstrate a nonobtrusive way of boosting creative insight.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Author Contributions

J.B. conceived the research idea; A.G. and C.D.B.L collected the data; A.G. analyzed the data; C.D.B.L, S.O-C., K-L. M provided data analysis expertise; J.B. and A.G. wrote the paper; J.B. received the research funding and provided overall research supervision

Funding

The research was partially supported by the CREAM project funded by the European Commission Grant 612022. This publication reflects the views only of the authors, and the European Commission cannot be held responsible for any use which may be made of the information contained therein.

ORCID

Klaus-Robert Müller http://orcid.org/0000-0002-3861-7685
Joydeep Bhattacharya http://orcid.org/0000-0003-3443-9049

References

Aru, J., Drüke, M., Pikamäe, J., & Larkum, M. E. (2023). Mental navigation and the neural mechanisms of insight. *Trends in Neurosciences*, *46*(2), 100–109. doi:10.1016/j.tins.2022.11.002

Becker, M., Sommer, T., & Kühn, S. (2020). Inferior frontal gyrus involvement during search and solution in verbal creative problem solving: A parametric fMRI study. *NeuroImage*, *206*, 116294. doi:10.1016/j.neuroimage.2019.116294

Bergmann, T. O., & Hartwigsen, G. (2021). Inferring causality from noninvasive brain stimulation in cognitive neuroscience. *Journal of Cognitive Neuroscience*, *33*(2), 195–225. doi:10.1162/jocn_a_01591

Binder, J. R., Desai, R. H., Graves, W. W., & Conant, L. L. (2009). Where is the semantic system? A critical review and meta-analysis of 120 functional neuroimaging studies. *Cerebral Cortex*, *19*(12), 2767–2796. doi:10.1093/cercor/bhp055

Bonnefond, M., Jensen, O., & Tort, A. B. L. (2015). Gamma activity coupled to alpha phase as a mechanism for top-down controlled gating. *PloS One*, *10*(6), e0128667. doi:10.1371/journal.pone.0128667

Bowden, E. M., & Jung-Beeman, M. (2003a). Aha! Insight experience correlates with solution activation in the right hemisphere. *Psychonomic Bulletin & Review*, *10*(3), 730–737. doi:10.3758/BF03196539

Bowden, E. M., & Jung-Beeman, M. (2003b). Normative data for 144 compound remote associate problems. *Behavior Research Methods, Instruments, & Computers*, *35*(4), 634–639. doi:10.3758/BF03195543

Bowden, E. M., Jung-Beeman, M., Fleck, J., & Kounios, J. (2005). New approaches to demystifying insight. *Trends in Cognitive Sciences*, *9*(7), 322–328. doi:10.1016/j.tics.2005.05.012

Bowers, K. S., Regehr, G., Balthazard, C., & Parker, K. (1990). Intuition in the context of discovery. *Cognitive Psychology*, *22*(1), 72–110. doi:10.1016/0010-0285(90)90004-N

Brickwedde, M., Krüger, M. C., & Dinse, H. R. (2019). Somatosensory alpha oscillations gate perceptual learning efficiency. *Nature Communications*, *10*(1), 263. doi:10.1038/s41467-018-08012-0

Buergers, S., & Noppeney, U. (2022). The role of alpha oscillations in temporal binding within and across the senses. *Nature Human Behaviour*, *6*(5), 732–742. doi:10.1038/s41562-022-01294-x

Canolty, R. T., Edwards, E., Dalal, S. S., Soltani, M., Nagarajan, S. S. . . . Knight, R. T. (2006). High gamma power is phase-locked to theta oscillations in human neocortex. *Science*, *313*(5793), 1626–1628. doi:10.1126/science.1128115

Canolty, R. T., & Knight, R. T. (2010). The functional role of cross-frequency coupling. *Trends in Cognitive Sciences*, *14*(11), 506–515. doi:10.1016/j.tics.2010.09.001

Cerf, M., Thiruvengadam, N., Mormann, F., Kraskov, A., Quiroga, R. Q., Koch, C., & Fried, I. (2010). On-line, voluntary control of human temporal lobe neurons. *Nature*, *467*(7319), 1104–1108. Article 7319. doi:10.1038/nature09510

Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, *134*(1), 9–21. doi:10.1016/j.jneumeth.2003.10.009

Desikan, R. S., Ségonne, F., Fischl, B., Quinn, B. T., Dickerson, B. C. . . . Killiany, R. J. (2006). An automated labeling system for subdividing the human cerebral cortex on MRI scans into gyral based regions of interest. *NeuroImage*, *31*(3), 968–980. doi:10.1016/j.neuroimage.2006.01.021

Erickson, B., Truelove-Hill, M., Oh, Y., Anderson, J., Zhang, F. (., & Kounios, J. (2018). Resting-state brain oscillations predict trait-like cognitive styles. *Neuropsychologia*, *120*, 1–8. doi:10.1016/j.neuropsychologia.2018.09.014

Esghaei, M., Treue, S., & Vidyasagar, T. R. (2022). Dynamic coupling of oscillatory neural activity and its roles in visual attention. *Trends in Neurosciences*, *45*(4), 323–335. doi:10.1016/j.tins.2022.01.003

Fink, A., & Benedek, M. (2014). EEG alpha power and creative ideation. *Neuroscience & Biobehavioral Reviews*, *44*, 111–123. doi:10.1016/j.neubiorev.2012.12.002

Fries, P., Reynolds, J. H., Rorie, A. E., & Desimone, R. (2001). Modulation of oscillatory neuronal synchronization by selective visual attention. *Science*, *291*(5508), 1560–1563. doi:10.1126/science.1055465

Gruzelier, J. H. (2014). EEG-neurofeedback for optimising performance. II: Creativity, the performing arts and ecological validity. *Neuroscience & Biobehavioral Reviews*, *44*, 142–158. doi:10.1016/j.neubiorev.2013.11.004

Hartmann, T., Schulz, H., & Weisz, N. (2011). Probing of brain states in real-time: Introducing the ConSole environment. *Frontiers in Psychology*, *2*, 2. doi:10.3389/fpsyg.2011.00036

Herrmann, C. S., Strüber, D., Helfrich, R. F., & Engel, A. K. (2016). EEG oscillations: From correlation to causality. *International Journal of Psychophysiology*, *103*, 12–21. doi:10.1016/j.ijpsycho.2015.02.003

Jensen, O., Bahramisharif, A., Oostenveld, R., Klanke, S., Hadjipapas, A., Okazaki, Y. O., & van Gerven, M. A. (2011). Using brain–computer interfaces and brain-state dependent stimulation as tools in cognitive neuroscience. *Frontiers in Psychology*, *2*, 100. doi:10.3389/fpsyg.2011.00100

Jensen, O., Gips, B., Bergmann, T. O., & Bonnefond, M. (2014). Temporal coding organized by coupled alpha and gamma oscillations prioritize visual processing. *Trends in Neurosciences*, *37*(7), 357–369. doi:10.1016/j.tins.2014.04.001

Jung-Beeman, M., Bowden, E. M., Haberman, J., Frymiare, J. L., Arambel-Liu, S. ... Dehaene, S. (2004). Neural activity when people solve verbal problems with insight. *PLoS Biology*, *2*(4), 500–510. doi:10.1371/journal.pbio.0020097

Klimesch, W. (2012). Alpha-band oscillations, attention, and controlled access to stored information. *Trends in Cognitive Sciences*, *16*(12), 606–617. doi:10.1016/j.tics.2012.10.007

Klimesch, W., Sauseng, P., & Hanslmayr, S. (2007). EEG alpha oscillations: The inhibition–timing hypothesis. *Brain Research Reviews*, *53*(1), 63–88. Article 1. doi:10.1016/j.brainresrev.2006.06.003

Kounios, J., & Beeman, M. (2009). The Aha! Moment: The cognitive neuroscience of insight. *Current Directions in Psychological Science*, *18*(4), 210–216. doi:10.1111/j.1467-8721.2009.01638.x

Kounios, J., Frymiare, J. L., Bowden, E. M., Fleck, J. I., Subramaniam, K., Parrish, T. B., & Jung-Beeman, M. (2006). The prepared mind: Neural activity prior to problem presentation predicts subsequent solution by sudden insight. *Psychological Science*, *17*(10), 882–890. doi:10.1111/j.1467-9280.2006.01798.x

Lambon Ralph, M. A., Cipolotti, L., Manes, F., & Patterson, K. (2010). Taking both sides: Do unilateral anterior temporal lobe lesions disrupt semantic memory? *Brain A Journal of Neurology*, *133*(11), 3243–3255. doi:10.1093/brain/awq264

Luft, C. D. B., Zioga, I., Thompson, N. M., Banissy, M. J., & Bhattacharya, J. (2018). Right temporal alpha oscillations as a neural mechanism for inhibiting obvious associations. *Proceedings of the National Academy of Sciences*, *115*(52), E12144–E12152. doi:10.1073/pnas.1811465115

Lustenberger, C., Boyle, M. R., Foulser, A. A., Mellin, J. M., & Fröhlich, F. (2015). Functional role of frontal alpha oscillations in creativity. *Cortex*, *67*, 74–82. doi:10.1016/j.cortex.2015.03.012

Marinescu, I. E., Lawlor, P. N., & Kording, K. P. (2018). Quasi-experimental causality in neuroscience and behavioural research. *Nature Human Behaviour*, *2*(12), 891–898. Article 12. doi:10.1038/s41562-018-0466-5

Mayseless, N., & Shamay-Tsoory, S. G. (2015). Enhancing verbal creativity: Modulating creativity by altering the balance between right and left inferior frontal gyrus with tDCS. *Neuroscience*, *291*, 167–176. doi:10.1016/j.neuroscience.2015.01.061

Michail, G., Toran Jenner, L., & Keil, J. (2021). Prestimulus alpha power but not phase influences visual discrimination of long-duration visual stimuli. *European Journal of Neuroscience*, *55*(11–12), 3141–3153. doi:10.1111/ejn.15169

Moss, J., Kotovsky, K., & Cagan, J. (2011). The effect of incidental hints when problems are suspended before, during, or after an impasse. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *37*(1), 140–148. doi:10.1037/a0021206

Muñoz-Moldes, S., & Cleeremans, A. (2020). Delineating implicit and explicit processes in neurofeedback learning. *Neuroscience & Biobehavioral Reviews*, *118*, 681–688. doi:10.1016/j.neubiorev.2020.09.003

Oh, Y., Chesebrough, C., Erickson, B., Zhang, F., & Kounios, J. (2020). An insight-related neural reward signal. *NeuroImage*, *214*, 116757. doi:10.1016/j.neuroimage.2020.116757

Park, H., Lee, D. S., Kang, E., Kang, H., Hahm, J., & Jensen, O. (2016). Formation of visual memories controlled by gamma power phase-locked to alpha oscillations. *Scientific Reports*, *6*(1) Article 1. 10.1038/srep28092.

Peylo, C., Hilla, Y., & Sauseng, P. (2021). Cause or consequence? Alpha oscillations in visuospatial attention. *Trends in Neurosciences*, *44*(9), 705–713. doi:10.1016/j.tins.2021.05.004

Ramot, M., Grossman, S., Friedman, D., & Malach, R. (2016). Covert neurofeedback without awareness shapes cortical network spontaneous connectivity. *Proceedings of the National Academy of Sciences*, *113*(17), E2413–E2420. doi:10.1073/pnas.1516857113

Ramot, M., & Martin, A. (2022). Closed-loop neuromodulation for studying spontaneous activity and causality. *Trends in Cognitive Sciences*, *26*(4), 290–299. doi:10.1016/j.tics.2022.01.008

Razumnikova, O. M. (2007). Creativity related cortex activity in the remote associates task. *Brain Research Bulletin*, *73*(1–3), 96–102. doi:10.1016/j.brainresbull.2007.02.008

Romei, V., Brodbeck, V., Michel, C., Amedi, A., Pascual-Leone, A., & Thut, G. (2008). Spontaneous fluctuations in posterior -band EEG activity reflect variability in excitability of human visual areas. *Cerebral Cortex*, *18*(9), 2010–2018. doi:10.1093/cercor/bhm229

Rothmaler, K., Nigbur, R., & Ivanova, G. (2017). New insights into insight: Neurophysiological correlates of the difference between the intrinsic "aha" and the extrinsic "oh yes" moment. *Neuropsychologia*, *95*, 204–214. doi:10.1016/j.neuropsychologia.2016.12.017

Roux, F., & Uhlhaas, P. J. (2014). Working memory and neural oscillations: Alpha–gamma versus theta–gamma codes for distinct WM information? *Trends in Cognitive Sciences*, *18*(1), 16–25. doi:10.1016/j.tics.2013.10.010

Salvi, C., Beeman, M., Bikson, M., McKinley, R., & Grafman, J. (2020). TDCS to the right anterior temporal lobe facilitates insight problem-solving. *Scientific Reports*, *10*(1), 946. doi:10.1038/s41598-020-57724-1

Sandkühler, S., Bhattacharya, J., & Zak, P. (2008). Deconstructing insight: EEG correlates of insightful problem solving. *PLoS One*, *3*(1), e1459. doi:10.1371/journal.pone.0001459

Santarnecchi, E., Sprugnoli, G., Bricolo, E., Costantini, G., Liew, S.-L. ... Rossi, S. (2019). Gamma tACS over the temporal lobe increases the occurrence of Eureka! Moments. *Scientific Reports*, *9*(1) Article 1. 10.1038/s41598-019-42192-z.

Schneider, D., Herbst, S. K., Klatt, L., Wöstmann, M., & Keitel, C. (2022). Target enhancement or distractor suppression? Functionally distinct alpha oscillations form the basis of attention. *European Journal of Neuroscience*, *55*(11–12), 3256–3265. doi:10.1111/ejn.15309

Sederberg, P. B., Schulze-Bonhage, A., Madsen, J. R., Bromfield, E. B., Litt, B., Brandt, A., & Kahana, M. J. (2007). Gamma oscillations distinguish true from false memories. *Psychological Science*, *18*(11), 927–932. doi:10.1111/j.1467-9280.2007.02003.x

Seifert, C., Meyer, D., Davidson, N., Patalano, A., & Yaniv, I. (1995). Demystification of cognitive insight: Opportunistic assimilation and the prepared-mind hypothesis. In R. J. Sternberg & J. E. Davidson (Eds.), *The Nature of Insight* (pp. 65–124). Cambridge, MA: MIT Press.

Sheth, B. R., Sandkühler, S., & Bhattacharya, J. (2009). Posterior Beta and Anterior Gamma Oscillations Predict

Cognitive Insight. *Journal of Cognitive Neuroscience*, *21*(7), 1269–1279. doi:10.1162/jocn.2009.21069

Sitaram, R., Ros, T., Stoeckel, L., Haller, S., Scharnowski, F. . . . Sulzer, J. (2017). Closed-loop brain training: The science of neurofeedback. *Nature Reviews Neuroscience*, *18*(2), 86–100. Article 2. doi:10.1038/nrn.2016.164

Stevens, C. E., & Zabelina, D. L. (2019). Creativity comes in waves: An EEG-focused exploration of the creative brain. *Current Opinion in Behavioral Sciences*, *27*, 154–162. doi:10.1016/j.cobeha.2019.02.003

Stramaccia, D. F., Penolazzi, B., Altoè, G., & Galfano, G. (2017). TDCS over the right inferior frontal gyrus disrupts control of interference in memory: A retrieval-induced forgetting study. *Neurobiology of Learning and Memory*, *144*, 114–130. doi:10.1016/j.nlm.2017.07.005

Summerfield, C., Jack, A. I., & Burgess, A. P. (2002). Induced gamma activity is associated with conscious awareness of pattern masked nouns. *International Journal of Psychophysiology*, *44*(2), 93–100. doi:10.1016/S0167-8760(02)00003-X

Tadel, F., Baillet, S., Mosher, J. C., Pantazis, D., & Leahy, R. M. (2011). Brainstorm: A user-friendly application for MEG/EEG analysis. *Computational Intelligence and Neuroscience*, *2011*, 1–13. doi:10.1155/2011/879716

Tik, M., Sladky, R., Luft, C. D. B., Willinger, D., Hoffmann, A. . . . Windischberger, C. (2018). Ultra-high-field fMRI insights on insight: Neural correlates of the Aha!-moment. *Human Brain Mapping*, *39*(8), 3241–3252. doi:10.1002/hbm.24073

Tranel, D., Damasio, H., & Damasio, A. R. (1997). A neural basis for the retrieval of conceptual knowledge. *Neuropsychologia*, *35*(10), 1319–1327. doi:10.1016/S0028-3932(97)00085-7

Turner, M., & Fauconnier, G. (1999). A mechanism of creativity. *Poetics Today*, *20*(3), 397–418.

Varga, N. L., & Manns, J. R. (2021). Delta-modulated cortical alpha oscillations support new knowledge generation through memory integration. *NeuroImage*, *244*, 118600. doi:10.1016/j.neuroimage.2021.118600

Vigué-Guix, I., Morís Fernández, L., Torralba Cuello, M., Ruzzoli, M., & Soto-Faraco, S. (2022). Can the occipital alpha-phase speed up visual detection through a real-time EEG-based brain–computer interface (BCI)? *European Journal of Neuroscience*, *55*(11–12), 3224–3240. doi:10.1111/ejn.14931

Wischnewski, M., Alekseichuk, I., & Opitz, A. (2023). Neurocognitive, physiological, and biophysical effects of transcranial alternating current stimulation. *Trends in Cognitive Sciences*, *27*(2), 189–205. doi:10.1016/j.tics.2022.11.013

Yun, K., Bhattacharya, J., Sandkühler, S., Lin, Y.-J., Iwaki, S., & Shimojo, S. (2020). Causally linking neural dominance to perceptual dominance in a multisensory conflict. *NeuroReport*, *31*(13), 991–998. doi:10.1097/WNR.0000000000001505