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# Role of Frontal Alpha Oscillations in Creativity

**Caroline Lustenberger**[1], **Michael R. Boyle**[1,2], **A. Alban Foulser**[3], **Juliann M. Mellin**[1], and **Flavio Fröhlich**[1,2,4,5,6]

[1]Department of Psychiatry, University of North Carolina at Chapel Hill, Chapel Hill NC 27599

[2]Department of Biomedical Engineering, University of North Carolina at Chapel Hill, Chapel Hill NC 27599

[3]Department of Psychology, University of North Carolina at Chapel Hill, Chapel Hill, NC 27599

[4]Department of Cell Biology and Physiology, University of North Carolina at Chapel Hill, Chapel Hill NC 27599

[5]Neurobiology Curriculum, University of North Carolina at Chapel Hill, Chapel Hill NC 27599

[6]Neuroscience Center, University of North Carolina at Chapel Hill, Chapel Hill NC 27599

## Abstract

Creativity, the ability to produce innovative ideas, is a key higher-order cognitive function that is poorly understood. At the level of macroscopic cortical network dynamics, recent EEG data suggests that cortical oscillations in the alpha frequency band (8 – 12 Hz) are correlated with creative thinking. However, whether alpha oscillations play a fundamental role in creativity has remained unknown. Here we show that creativity is increased by enhancing alpha power using 10 Hz transcranial alternating current stimulation (10Hz-tACS) of the frontal cortex. In a study of 20 healthy participants with a randomized, balanced cross-over design, we found a significant improvement of 7.4% in the Creativity Index measured by the Torrance Test of Creative Thinking, a comprehensive and most frequently used assay of creative potential and strengths. In a second similar study with 20 subjects, 40Hz-tACS was used in instead of 10Hz-tACS to rule out a general "electrical stimulation" effect. No significant change in the Creativity Index was found for such frontal gamma stimulation. Our results suggest that alpha activity in frontal brain areas is selectively involved in creativity; this enhancement represents the first demonstration of specific neuronal dynamics that drive creativity and can be modulated by non-invasive brain stimulation. Our findings agree with the model that alpha recruitment increases with internal processing



Correspondence should be addressed to: Flavio Frohlich, 115 Mason Farm Rd. NRB 4109F, Chapel Hill, NC. 27599., Phone: 01 919 966-4584, flavio_frohlich@med.unc.edu.

**Conflict of interest**

The UNC conflict of interest office has determined that there is no conflict of interest for this study. UNC has filed a non-provisional patent on tACS-related technology with Flavio Frohlich as the lead inventor. No licensing has occurred and none of the authors are financially or otherwise benefitting from this initial filing.

demands and is involved in inhibitory top-down control, which is an important requirement for creative ideation.

**Keywords**

transcranial alternating current stimulation (tACS); Torrance Test of Creative Thinking (TTCT); divergent thinking; alpha power; gamma activity

## 1. Introduction

Creativity, the ability to produce novel and useful work, is one of the most extraordinary capabilities of the human mind (Sawyer, 2011). Yet, the neural basis of creativity remains poorly understood (Dietrich & Kanso, 2010). At the level of macroscopic brain dynamics measured with electroencephalography (EEG), oscillatory activity in the alpha frequency band (8 – 12 Hz) correlates with creative ideation (Fink & Benedek, 2014). In particular, creative idea generation was associated with increased oscillation power in the alpha band in prefrontal and parietal cortical areas (Fink, Benedek, Grabner, Staudt, & Neubauer, 2007; Jauk, Benedek, & Neubauer, 2012). Also, enhanced alpha power was more pronounced in highly creative people, for more original ideas, and during demanding creative tasks (Fink & Benedek, 2014). In further support of the importance of alpha oscillations, creativity-enhancing, behavioral interventions were associated with increased alpha recruitment, especially at frontal brain sites (Fink, Grabner, Benedek, & Neubauer, 2006; Fink, Schwab, & Papousek, 2011). Despite this convergence of evidence of an association between alpha oscillations and creativity, it has remained unknown whether alpha activity is causally involved in creative ideation since previous studies of cognitive enhancement by brain stimulation have focused on targeting specific brain areas and not network dynamics (Luft, Pereda, Banissy, & Bhattacharya, 2014). Transcranial Alternating Current Stimulation (tACS) is a non-invasive brain stimulation modality that applies weak, oscillating electric currents to the scalp to enhance endogenous cortical oscillations at the applied frequency (Herrmann, Rach, Neuling, & Struber, 2013; Schmidt, Iyengar, Foulser, Boyle, & Frohlich, 2014; Vossen, Gross, & Thut, 2014). TACS has recently provided causal evidence for oscillations in specific frequency bands mediating memory consolidation, motor control, sensory processing, and fluid intelligence (Fröhlich, 2014; Herrmann et al., 2013; Santarnecchi et al., 2013). Alpha oscillations are likely generated and modulated by thalamo-cortical and intra-cortical circuits (Bollimunta, Mo, Schroeder, & Ding, 2011; Hindriks & van Putten, 2013) and are therefore susceptible to cortical brain stimulation. Indeed, recent advances in simultaneous EEG and tACS have demonstrated that stimulation in the alpha frequency band selectively enhanced alpha oscillations during and briefly after stimulation (Helfrich, Schneider, et al., 2014; Zaehle, Rach, & Herrmann, 2010). We here used bifrontal tACS in the alpha frequency range (10Hz-tACS) to determine if alpha oscillations play a functional role in creativity. In a second experiment we applied 40Hz-tACS to rule out a general “electrical stimulation” effect.

## 2. Materials and Methods

The study is separated into two experiments of which both employed identical methods with the exception of the tACS frequencies used. In Experiment 1, 10Hz-tACS was applied and in Experiment 2, 40Hz-tACS was used.

### 2.1. Participants

All participants were recruited from the University of North Carolina at Chapel Hill (UNC) community and signed written consent prior to participation. This study was approved by the UNC IRB. Exclusion criteria were a history of neurologic or psychiatric illness, family history of psychopathology, chronic diseases, current use of psychoactive agents or other medications, brain implants/devices, history of brain surgery, and pregnancy.

**Experiment 1—**Twenty healthy, right-handed participants (5 males, 15 females) aged 19 – 30 years (20.9 ± 2.7 years; Mean ± SD) were included in the study.

**Experiment 2—**Twenty healthy, right-handed participants (13 males, 7 females) aged 18 – 30 years (20.5 ± 3.2 years; Mean ± SD) were included in the study.

### 2.2. Study procedure

A randomized, crossover design was applied in both experiments; participants were blinded to the stimulation condition and independent scoring of the creativity assay was done by a third party unaware of the study design. Participants attended two experimental sessions on the same day consisting of the two parallel forms of the creativity tests (Torrance Test of Creative Thinking, TTCT) during which participants received either active sham or tACS. The two tests were separated by a 30 minutes break to minimize contamination of the second session with outlasting effects of the stimulation during the first session (Figure 1). During one of the two sessions (verum condition), 10Hz-tACS (Experiment 1) or 40Hz-tACS (Experiment 2) was administered for the entire duration of the TTCT (30 minutes). In the other session, 10Hz-tACS or 40Hz-tACS, respectively, was administered for 5 minutes (active sham condition). We chose the duration of 5 minutes for the active sham stimulation to improve the blinding to the condition since tACS of different frequencies and amplitudes generates neurosensory effects (Kanai, Chaieb, Antal, Walsh, & Paulus, 2008; Raco, Bauer, Olenik, Brkic, & Gharabaghi, 2014; Turi et al., 2013). After completing the first test, participants were asked to wait patiently for 30 minutes. Magazines were provided for the participant to read while they waited in between tests. After 30 minutes, participants were given the other form of the TTCT and received either verum or sham stimulation. All iterations of form type, stimulation type, and session order were randomized and balanced; each participant received both verum and sham stimulation. After the second testing, participants were asked whether or not they believe they received stimulation.

### 2.3. Torrance Test of Creative Thinking (TTCT) – Figural task

The TTCT is the most widely used and well-known measure of creativity (Baer, 1993; Kim, 2006). It was developed to measure divergent thinking, which is a central aspect of creativity. We used the figural version of the task that comes with the two parallel forms A and B (Torrance, 1998). Both forms are composed of three activities: (1) *Picture construction* requires the participant to complete a given shape (e.g. jelly bean shaped figure) and draw a picture that uses this predefined shape as an integral part of it (2) In *picture completion* the participants use 10 different incomplete figures to construct and name a new object (3) *Repeated figures of lines and circles* requires the participants to make new objects from 30 circles or lines and add titles to them (Kim, 2006; Torrance & Ball, 1984). Ten minutes are allocated per activity such that the test is completed in 30 minutes (Torrance, 1998). To define the creative potential of the participant, standard scores of five subscales are determined according to the TTCT- norms technical manual (Torrance, 1998) and averaged. The five subscales are Fluency (number of relevant ideas), Originality (number of statistically infrequent data), Elaboration (number of added ideas), Abstractness of Titles (degree beyond labeling), and Resistance to Premature Closures (degree of psychological openness) (Kim, 2006; Torrance & Ball, 1984). To determine the final Creativity Index score, 13 criterion-referenced measures (creative strengths, e.g. richness of imaginary) are added to the creative potential scoring (Torrance & Ball, 1984). We investigated the effect of tACS at 10Hz and 40Hz on overall Creativity Index and all five subscales. Instructions for the task were administered according to the provided manual (Torrance, 1998).

Scoring of all the tasks was conducted by an external company (Scholastic Testing Service, STS, Inc., Bensenville, Illinois) that is an expert center in scoring the Torrance tasks and was not informed about the aim or the design of the study (all test booklets were given a random 5-digit identifier). According to the TTCT-Figural Manual of 1990 (Torrance, 1990) the inter-rater reliability among the scorers for the scholastic Testing Service was above 0.90. Moreover, a study of 2006 including the Scholastic Testing Service scorers provides an inter-rater reliability over 0.95 (reported in Torrance, 2008). The evaluation of the task performance was therefore done in an objective and unbiased way, blinded to all experimental factors. Once the scores were returned, the study was unblinded and the national percentiles and standard scores for each participant were adjusted based on participant age using tables provided by STS.

### 2.4. Transcranial alternating current stimulation (tACS)

Participants were fitted with three rubber stimulation electrodes in saline-moistened sponge envelopes (5×7 cm; NeuroConn Ltd., Ilmenau, Germany). All tACS electrodes were secured to the scalp with rubber head straps. The scalp was first measured in the 10–20 system to mark the locations of the apex of the head (Cz) and the prefrontal cortex (F3 and F4, bilaterally). Two electrodes were placed at F3 and F4, while the third electrode was placed at Cz. Current was passed through the scalp at the three electrode sites using two NeuroConn DC-Stimulator Plus devices (NeuroConn Ltd., Ilmenau, Germany). The electrode at Cz was common between the two stimulators while one stimulator was connected to the electrode at F3 and the other stimulator was connected to the electrode at F4. The two devices were synchronized by external command signals and the presence of constant zero degree phase offset was verified by control measures before stimulation. This configuration allowed for synchronized stimulation of the two frontal hemispheres. The impedance for each current path was kept below 10 kΩ. The sham condition employed a 5 minutes, 2 mA peak-to-peak 10 Hz sine-wave flanked by 10 second linear envelope ramps in and out for a total duration of 5 minutes and 20 seconds. The verum stimulation employed the same stimulation signal with the one difference that stimulation lasted 30 instead of 5 minutes. Alpha is most pronounced over posterior brain regions but also frontal regions exhibit a peak in alpha activity during wakefulness around 10 Hz (8–12 Hz, e.g. Tinguely, Finelli, Landolt, Borbely, & Achermann, 2006). Frontal alpha has previously been hypothesized to be involved in efficient internal processing and top-down control which is an essential feature of creativity (Benedek, Bergner, Konen, Fink, & Neubauer, 2011; Klimesch, Sauseng, & Hanslmayr, 2007). In the second experiment 40Hz-tACS instead of 10Hz-tACS was applied.

### 2.5. Statistics

Custom-written scripts in R (R Foundation for Statistical Computing, Vienna, Austria) and SPSS software version 22.0 (IBM, Armonk, NY) were used for the analysis. Libraries used in R included lme4 (Bates, Maechler, Bolker, & Walker, 2014) and pbkrtest (Halekoh & Hojsgaard, in press). We performed a linear mixed model analysis of the relationship between Creativity Index derived from the Torrance task and stimulation condition. We entered stimulation condition (sham and verum), session (session 1 and 2) and form (A and B) as fixed factors and participants as a random factor into the model. We used the Kenward-Roger approximation to perform F-tests and to estimate p-values for each factor and their interaction in the mixed model (Halekoh & Hojsgaard, in press). Thereafter, we investigated whether the stimulation condition effect on the Creativity Index was specific to certain subscales of the Creativity Index. We performed a linear mixed model including all the standardized values of the 5 subscales (pooled data), entered stimulation condition (sham or verum) and subscale type (Fluency, Originality, Elaboration, Abstractness of Titles, Resistance to Premature Closures) as fixed factors, and participants as a random factor into the model. F- and p-values were again estimated using the Kenward-Roger approximation (Halekoh & Hojsgaard, in press). Visual inspection of the residual plots of both linear models did not reveal any obvious deviations from normality or homoscedasticity. We handled both experiments and therefore the linear mixed models separately because we had no randomized and balanced design across the 10Hz- and 40Hz-tACS experiments. Furthermore, Experiment 2 was approximately one year later than Experiment 1, was performed by a different clinical trial assistant and in a different room. We therefore avoided comparing both experiments and only focused on within participant statistics for which external factors were similar for both sessions. However, we compared both sham conditions using an unpaired Student’s t-test to investigate differences of baseline levels between the two experiments. We further performed a Fisher’s exact test to compare gender distribution between the two experiments. We provide a simplified method to approximate effect sizes for 10Hz-tACS and 40Hz-tACS related effects on the Creativity Index using the approach of Morris & Deshon (2002). An exact McNemar’s test determined whether there was a statistically significant difference in the proportion of participants perceiving transcranial stimulation between the stimulation conditions. One sample t-tests were used to compare our study populations’ national percentile of the Creativity Index relative to the $50^{th}$ percentile (norm). For correlative analysis Spearman’s rank correlation was used (accounting for outlying participants). Significance levels were set to $p < 0.05$.

# 3. Results

## 3.1. Effect of 10Hz-tACS on creative ideation (Experiment 1)

Participants were successfully blinded to the condition; the number of participants that subjectively reported to perceive tACS was not significantly different between the stimulation conditions (verum: 18 out of 19; sham: 14 out of 19, McNemar exact $p > 0.2$). One participant was excluded from the analysis because of the creativity test score during one session that was in the lowest national percentile and clearly deviant from the mean (Creativity Index = 50 < mean - 3*SD, during verum condition).

Creativity Index, the overall measure of creative potential and strengths derived from the TTCT (Torrance, 1998), was significantly higher under 10Hz-tACS stimulation compared to active sham (mean percentage difference 7.45 % ± 3.11 % s.e.m.; $F_{1,16} = 5.14$, $p = 0.036$; Fig. 2A, Cohen's d = 0.56, medium effect size). Twelve out of 19 participants showed a pronounced increase in creative thinking during 10Hz-tACS compared to sham (Fig. 2B). Linear mixed model analysis further revealed that there was no effect of session ($F_{1,16} = 0.57$, $p = 0.46$), form ($F_{1,16} = 1.18$, $p = 0.29$), or any interaction between the included factors (all $p > 0.25$). During sham, the Creativity Index national percentiles of our study population was not significantly different from the 50$^{th}$ percentile (one sample t-test, $p > 0.2$). However, during verum condition a significant number of subjects were above the 50$^{th}$ percentile (one sample t-test, $p < 0.01$).The Creativity Index in the TTCT is comprised of five subscales (Fluency, Originality, Elaboration, Abstract of Titles, and Resistance to Premature Closures) that all showed on average a 10Hz-tACS related improvement (Fig. 3). Besides the composite score Creativity Index also the subscales should be taken into account since they measure independent characteristics of creativity. We therefore next tested whether the stimulation effect was different for these specific subscales of the Creativity Index; we included the standard scores of all five subscales into a linear mixed model and tested whether there was an interaction between the factor subscale and stimulation condition. No significant interaction was found ($F_{4,162} = 1.58$, $p = 0.18$) indicating that the stimulation condition effect was not related to specific subscales. In agreement with the significant enhancing effect of 10Hz-tACS on the Creativity Index, we again found a strong stimulation condition effect in this analysis ($F_{1,166} = 15.43$, $p < 0.001$).

## 3.2. Effect of 40Hz-tACS on creative ideation (Experiment 2)

To exclude the possibility that tACS (independent of the stimulation frequency used) or electrical stimulation in general affects creativity we applied 40Hz-tACS in a second experiment. The number of participants that subjectively reported to perceive 40Hz-tACS was not significantly different between the stimulation conditions, but there was a tendency that more subjects perceived the stimulation during verum condition compared to sham (verum: 18 out of 20; sham: 11 out of 20, McNemar exact $p = 0.065$).

In contrast to 10Hz-tACS, gamma electrical stimulation did not improve the Creativity Index compared to the sham condition (mean percentage difference 0.46 % ± 2.80 % s.e.m.; $F_{1,17} = 0.01$, $p = 0.93$; Fig. 4; Cohen's d = 0.09, negligible small effect size). In addition, no significant effect of session, form or any interaction between included factors was found (all p>0.25). Including the subscales into a linear mixed model, no interaction between subscale and condition was found ($F_{1,171} = 0.40$, $p = 0.81$) as well as no general condition effect ($F_{1,171} = 0.02$, $p = 0.89$). During sham and verum condition, a significant number of subjects had Creativity Indices above the 50$^{th}$ national percentile (one sample t-test, both $p < 0.01$).

## 4. Discussion

Our results demonstrate that enhancement of bilateral frontal alpha activity during a standardized divergent thinking test results in enhanced creativity, whereas 40Hz-tACS does not. This finding represents the first direct evidence for a functional role of alpha oscillations in creative ideation.

Why do alpha oscillations mediate creativity? A potential meaning of alpha oscillation in creative ideation is cortical idling. Early findings have assumed that alpha oscillations reflect a state of reduced mental activity, since alpha power decrease was found as a function of brain activations during a task (Pfurtscheller, Stancak, & Neuper, 1996). Thus, alpha power increase in the frontal cortex was hypothesized to reflect a hypoactivity of this brain area or "hypofrontality" which leads to improved creativity (Dietrich, 2003; Fink & Benedek, 2014). However, recent literature suggests creativity to be an active cognitive process rather than the result of reduced activity of the frontal cortex. First, there is an increasing number of studies showing an alpha power reduction during other cognitively demanding tasks (Buzsaki & Draguhn, 2004; Klimesch et al., 2007) and second, recent fMRI studies have shown an increased frontal activation during creative ideation (Fink et al., 2009; Green, Cohen, Raab, Yedibalian, & Gray, 2014). Therefore, an alternative explanation is that alpha activity, especially in frontal brain areas, may reflect high-demand internal processing (e.g. imagination) and top-down, inhibitory control processes (e.g. inhibition of task-irrelevant processes), which is an important requirement for creative ideation (Benedek et al., 2011; Klimesch et al., 2007). In particular, creative ideation or divergent thinking requires the generation of internal ideas with an inhibitory cognitive control mechanism that prevents disruption of this internal process by incoming salient but irrelevant stimuli (Benedek, Franz, Heene, & Neubauer, 2012; Fink & Benedek, 2014). Thus, increased alpha activity elicited by frontal 10Hz-tACS might improve top-down control of internal demands and thereby allow better creative ideation.

We simultaneously applied in phase alpha frequency stimulation to both frontal areas in both hemispheres. Besides increased alpha power, our stimulation paradigm may have also enhanced phase synchronization between frontal regions that could also account for improved creativity. Synchronization of oscillatory phases between different brain regions, especially in the theta and gamma frequency range, fosters working memory and long-term memory by facilitating neural communication and by supporting neural plasticity (Fell & Axmacher, 2011). However, it is unknown if and how creativity relates to phase-synchronization or coherence in the alpha range between left and right frontal regions. Future experiments are needed to investigate the importance of alpha synchronization between hemispheres for creativity by comparing in-phase and anti-phase tACS.

### How specific is frontal alpha activity involved in creativity?

First, the lack of a 40Hz-tACS effect on creativity points to a frequency-specific improvement. We chose 40Hz-tACS for our control experiment to demonstrate a frequency-specific modulation of creativity. Given that different frequencies are coupled with each other and that most other cortical oscillation frequencies have been associated with cognitive function that could contribute to creativity, other stimulation frequencies such as theta would have also been interesting choices. However, the close proximity of the theta and the alpha band would make delineating frequency-specific effects possibly more difficult. Other possible approaches that are interesting to consider in future studies of creativity enhancement by transcranial current stimulation include transcranial random noise stimulation (tRNS) that has been previously shown to enhance cortical excitability and higher-order cognitive abilities (Snowball et al., 2013; Terney, Chaieb, Moliadze, Antal, & Paulus, 2008). A limitation of our control experiment is that creativity baseline levels were higher in the study population of Experiment 2 (unpaired t-test, $t_{37} = -2.36$, $p = 0.25$) and a ceiling effect could be responsible for the null-effect of this stimulation. To rule out this possibility we performed correlations between baseline levels of the Creativity Index and the tACS related relative difference to sham. No significant correlations were found for both, 40Hz-tACS (Spearman-Rho, $r_{20} = -.38$, $p= 0.10$) and 10Hz-tACS (Spearman-Rho, $r_{20} = -.36$, $p = 0.13$).

Second, cross frequency-interactions could further be responsible for the improvement in creativity. Recent publications provide evidence that specific frequency bands are not independent of each other. In particular, gamma and alpha activity are presumably inversely related (Helfrich, Knepper, et al., 2014; Jensen, Bonnefond, & VanRullen, 2012; Sellers, Bennett, & Frohlich, 2014). As a consequence, 10Hz-tACS may not only increase alpha but also decrease gamma activity which could have accounted for creativity changes. However, in our second experiment 40Hz gamma stimulation did not worsen creative ideation which we would expect from such an inverse relationship. Rather, only direct interaction with the alpha band provides behavioral effects on creativity.

Third, our stimulation montage (bifrontal stimulation electrodes and return path to Cz) provided a widely distributed frontal stimulation in order to increase the likelihood to detect a possible contribution of frontal alpha activity in creativity. However, our study design does not allow for a specific identification of frontal brain regions in creativity (e.g. left vs. right hemisphere). Besides the frontal cortex also posterior-parietal and temporal regions as well as their interaction are hypothesized to be important during creative ideation (Beaty et al., 2014; Fink & Benedek, 2014; Wei et al., 2014). Thus, additional experiments that target more specifically frontal areas (e.g. smaller stimulation electrodes or other stimulation modalities, e.g. transcranial magnetic stimulation (TMS)), posterior-parietal/temporal regions or a combination of those are necessary to map cortical regions involved in creativity.

Fourth, significantly more females were included in the first experiment than in the second (Fisher’s exact test $p=0.025$). In addition, hormonal levels might further play an important role in tACS mediated effects (Krause & Cohen Kadosh, 2014). Thus, gender differences between both Experiments might account for the null-effect in the 40Hz-tACS condition.

Since the groups are too small to have enough power to compare the gender effect within an experiment we cannot give a statistically underlined statement that gender did not modulate tACS related improvement in creativity. However, a visual inspection of all individuals shows that a gender-related effect of tACS on creativity is highly unlikely (Supplementary Fig. 1).

Fifth, during our 40Hz-tACS experiment, all participants reported flickering lights during tACS and/or for a short period during 5 minutes of active sham. In addition, there was a tendency that more participants perceived stimulation during real 40Hz-tACS compared to active sham. Thus, phosphenes may have prevented a possible increase in creativity due to distraction. However, this explanation is unlikely since participants who identified both conditions correctly, and therefore likely only experienced phosphenes during 40Hz-tACS, did not show a consistent decrease or no change in the Creativity Index during the stimulation condition compared to sham (Supplementary Fig. 2).

Finally, it remains unclear whether frontal alpha enhancement exclusively modulates creativity or whether general improvement in cognitive abilities could be observed. Frontal brain regions and top-down inhibitory control processes are not only involved in creative thinking but are also strongly associated with other cognitive tasks (e.g. working memory, Gazzaley & Nobre, 2012; Sauseng et al., 2005). Given our findings on the effect of 10Hz-tACS on creativity, further examination of the functional role of alpha activity in those inhibitory processes in cortical areas seems warranted.

Modulations of alpha oscillations using repetitive TMS have previously been successful in manipulating higher-order cognitive processes as visual attention (Romei, Gross, & Thut, 2010) and mental rotation (Klimesch, Sauseng, & Gerloff, 2003). These processes also likely rely on inhibitory top-down control processes (Mechelli, Price, Friston, & Ishai, 2004; Zanto, Rubens, Thangavel, & Gazzaley, 2011). In future applications, alpha activity enhancement through tACS might be used to target deficits in higher-order cognitive function such as creativity and fluid intelligence, and top-down control processes in particular.

## Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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## Abbreviations

**TTCT** Torrance Task of Creative Thinking

**tACS** transcranial alternating current stimulation

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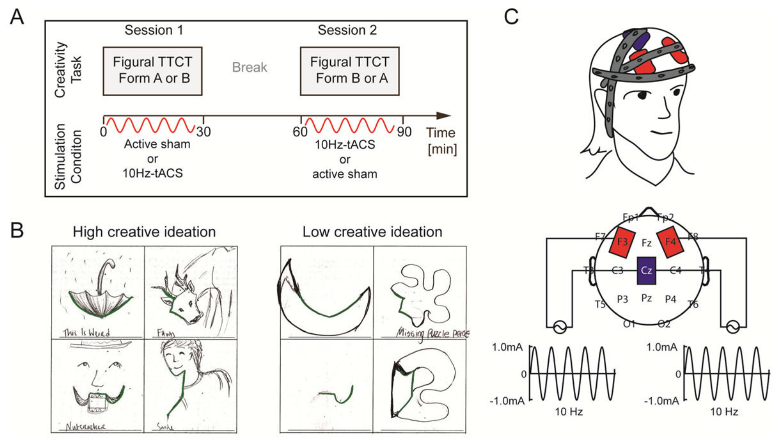


**Fig. 1. Study design, creativity task, and tACS paradigm**

**(A)** Each participant had two experimental sessions during the same day. 10Hz-tACS (verum condition) was applied during one of the two sessions (for the duration of the creativity task) and an active sham condition was applied in the other. Stimulation condition and test forms (A or B) of the Torrance Test of Creative Thinking (TTCT, Torrance, 1998) were applied in a randomized and balanced cross-over design.

**(B)** Sample responses of the TTCT picture completion task performed by two participants with different creativity levels. Participants had to use incomplete predefined forms (green), form a new picture, and make up a title for each drawing as original and unique as possible (e.g. “nutcracker” in sample response). Left: Sample response form participant with Creativity Index of 138 (high creative ideation). Right: Participant with Creativity Index of 98 (low creative ideation).

**(C)** Stimulation electrodes were positioned bilaterally over the frontal cortex (centered on EEG electrode locations F3 and F4) with a common electrode over the apex (Cz). Each electrode pair (F3-Cz, F4-Cz) was controlled by a separate stimulation channel that both applied a synchronized 10 Hz sine-wave stimulation waveform with zero phase offset. This configuration allowed for synchronized stimulation of both frontal lobes. Experiment 2 included a 40 Hz sine-wave stimulation (not shown in figure)

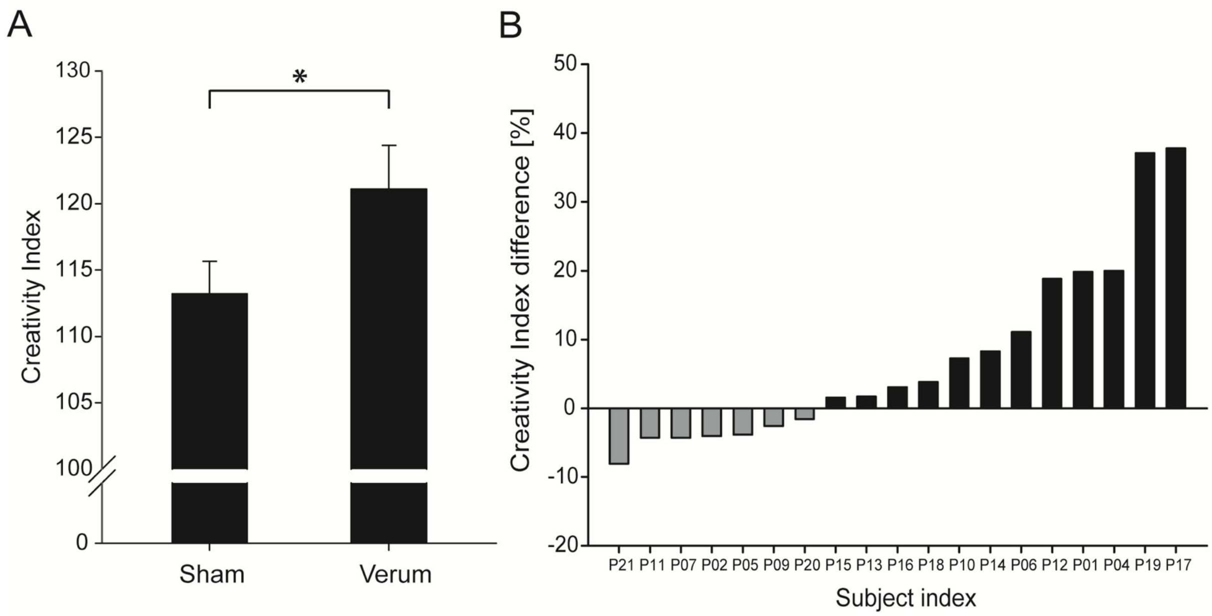


**Fig. 2. 10Hz-tACS increases creative thinking**

**(A)** Creativity Index score, a summary measure of creative potential and strengths, for the verum (10Hz-tACS) and sham stimulation condition (mean + s.e.m). Significance of higher Creativity Index for 10Hz-tACS compared to sham was determined by linear mixed model analysis ($F_{1,16} = 5.14$, $p = 0.036$ for factor condition, indicated by star).

**(B)** Individual percentage change in Creativity Index relative to sham (no change to sham denoted as 0 %). Participants were sorted according to their tACS related relative improvement in creative thinking. Black bars illustrate participants with a relative increase (N = 12) and grey bars participants with a relative decrease (N = 7).

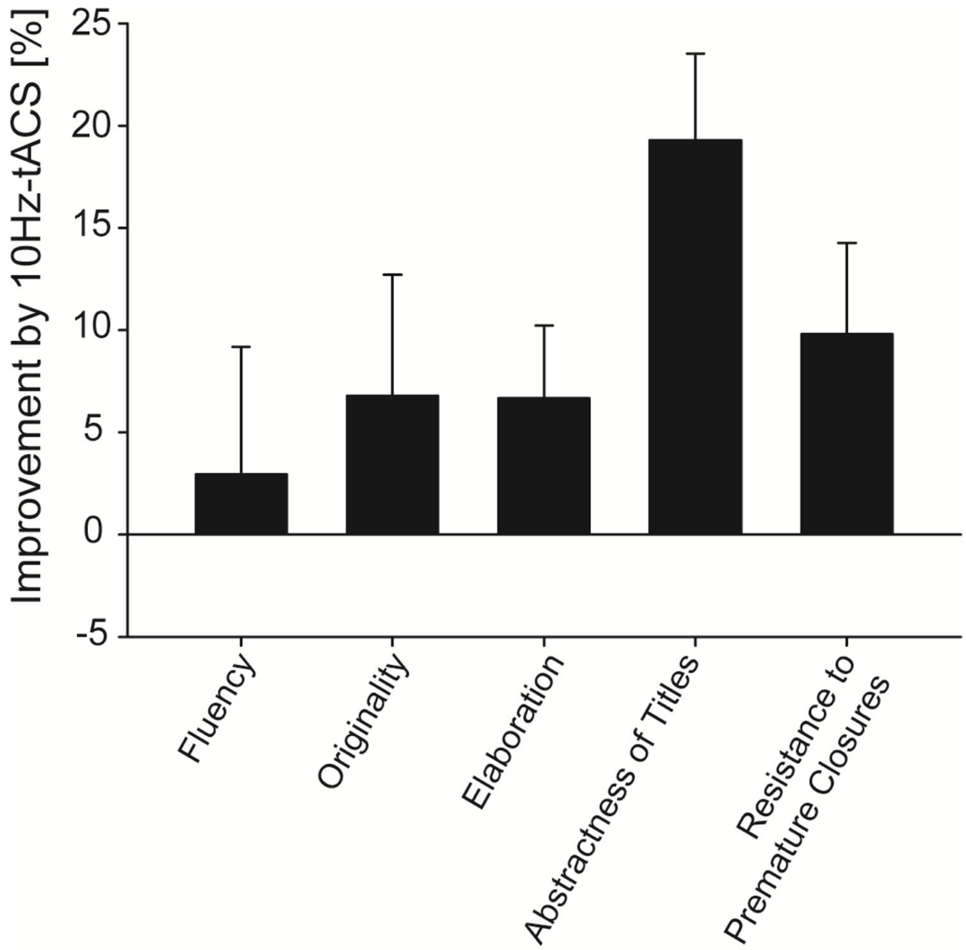


**Fig. 3. Effects of 10Hz-tACS on individual creativity subscales**

10Hz-tACS increased creative thinking across all subscales (mean + s.e.m. percentage change in TTCT subscales relative to sham). Linear mixed model analysis revealed overall significant stimulation condition effect including all subscales ($F_{1,166} = 15.43$, $p<0.001$) but no significant interaction between subscales and stimulation condition ($F_{4,162} = 1.58$, $p = 0.18$).

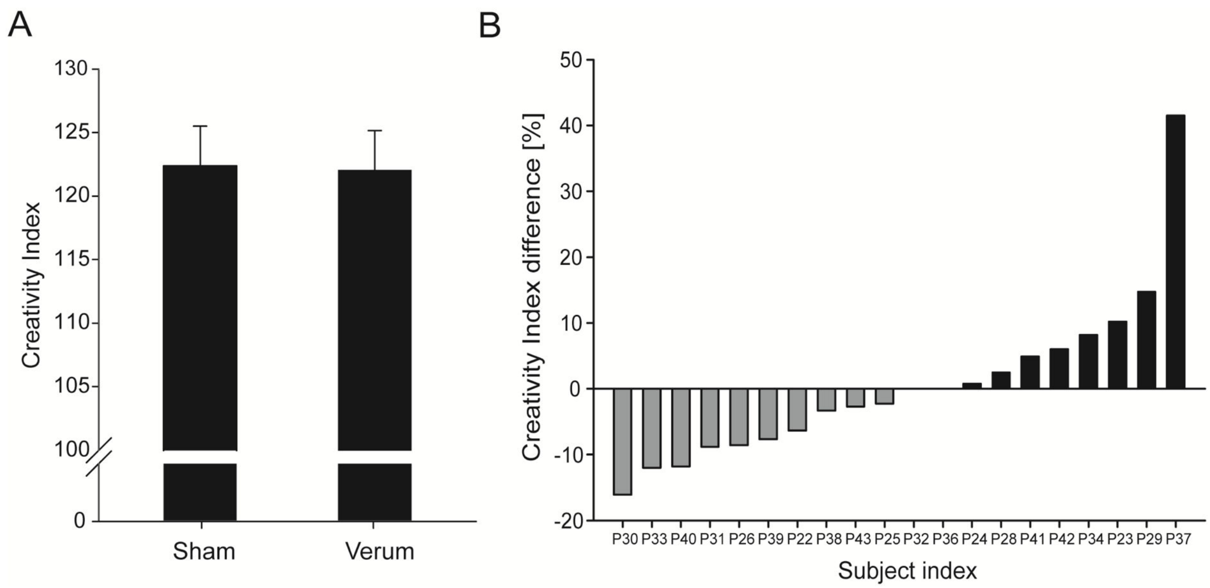


**Fig. 4. 40Hz-tACS does not affect creative thinking**

**(A)** Creativity Index score, for the verum (40Hz-tACS) and sham stimulation condition (mean + s.e.m). No significant difference of the Creativity Index for 40Hz-tACS compared to sham as determined by linear mixed model analysis ($F_{1,17} = 0.01$, $p = 0.93$ for factor condition).

**(B)** Individual percentage change in Creativity Index relative to sham (no change to sham denoted as 0 %). Participants were sorted according to their tACS-related relative improvement in creative thinking. Black bars illustrate participants with a relative increase (N = 8) and grey bars participants with a relative decrease (N = 10). Participants P32 and P36 had no change.