



Modulation of creativity by transcranial direct current stimulation

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ABSTRACT

Background: Creativity is the use of original ideas to accomplish something innovative. Previous research supports the notion that creativity is facilitated by an activation of the right and/or a deactivation of the left prefrontal cortex. In contrast, recent brain imaging studies suggest that creativity improves with left frontal activation.

Objective: The present study was designed to further elucidate the neural basis of and ways to modulate creativity, based on the modulation of prefrontal cortical activity through the non-invasive brain stimulation technique transcranial direct current stimulation (tDCS).

Methods: Ninety healthy University students performed three tasks on major aspects of creativity: conceptual expansion (Alternate Uses Task, AUT), associative thinking (Compound Remote Associate Task, CRA), and set shifting ability (Wisconsin Card Sorting Task, WCST). Simultaneously, they received cathodal stimulation of the left and anodal stimulation of the right inferior frontal gyrus (IFG), the reverse protocol, or sham stimulation.

Results: The main pattern of results was a superior performance with bilateral left cathodal/right anodal stimulation, and an inferior performance in the reversed protocol compared to sham stimulation. As a potential underlying physiological mechanism, resting state EEG beta power, indicative of enhanced cortical activity, in the right frontal area increased with anodal stimulation and was associated with better performance.

Conclusion: The findings provide new insights into ways of modulating creativity, whereby a deactivation of the left and an activation of the right prefrontal cortex with tDCS is associated with increased creativity. Potential future applications might include tDCS for patients with mental disorders and for healthy individuals in creative professions.

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Introduction

'Logic will get you from A to B. Imagination will take you everywhere.' This quote, thought to originate from Albert Einstein, implies that true progress requires 'thinking outside the box', a defining feature of creativity. Creativity is a motor for success, particularly for human evolution in a competitive environment.

However, creativity is difficult to grasp and the neural underpinnings remain to be further characterized, with the aim of elucidating ways to enhance creativity. This study was designed to further specify the neural basis and possibilities to modulate creativity through activity changes of the human cortex induced by the non-invasive brain stimulation technique transcranial direct current stimulation (tDCS).

Creativity is a multifaceted construct. A common conceptualization is that creativity consists of two processes: idea generation (production of original responses) and idea selection (identification of useful responses) [1]. However, these two processes are difficult to disentangle on a behavioral level, because successful performance in creativity tasks typically depends on both processes. Our

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current work, therefore, centers on three behavioral facets of creativity characterized by the number of potential solutions to a given problem, that is the *space of the search process*: (i) *high space* with an unlimited number of potential solutions, operationalized as conceptual expansion (Alternate Uses Task, [AUT, [2]], (ii) *intermediate space* limited by constituents, operationalized as associative thinking (Compound Remote Associate, CRA, task, [3]; German version: [4]), and (iii) *low space* with a finite set of rules, operationalized as set shifting ability [Wisconsin Card Sorting Test, WCST, [5]].

Prior work on the neural basis of creativity has been integrated in two prominent hypotheses, the *hemispheric balance hypothesis* and the *prefrontal activation hypothesis*. The *hemispheric balance hypothesis* posits that a shift of hemispheric balance resulting in a preponderance of the right over the left prefrontal area (prefrontal cortex, PFC) promotes creativity. This specific balance is thought to facilitate the production of novel ideas along with an inhibition of rule-based mental templates, resulting in a relatively unhindered 'release' of creative ideas [1,6]. In line with this hypothesis, patients with relatively increased activity of the right PFC after lesions of the left PFC show improvements in idea generation tasks, whereas patients with lesions of the right prefrontal cortex (PFC) show impaired creative performance (AUT) [7]. Moreover, healthy humans with increased gray matter volume of the right PFC demonstrate improved conceptual expansion (divergent thinking test) [8], and those with reduced structural integrity (white matter fractional anisotropy) of the left frontal cortex exhibit better creative performance (composite creativity index, including the AUT) [9].

In contrast, recent brain imaging research suggests that left frontal cortical activation promotes creativity. Specifically, brain regions activated during the AUT in fMRI studies in healthy humans include the left PFC and other areas of the left cortex [10–12]. Moreover, activated brain regions during CRA performance comprise the left PFC and the left anterior cingulate cortex [13]. Several studies indicate that set shifting ability (WCST) is associated with bilateral activity of the PFC [14,15]. Together, these fMRI studies, in contrast to lesion or structural brain imaging studies, suggest the particular importance of activity in the bifrontal or left frontal cortex for creative performance. However, fMRI studies provide only associative evidence and interventional studies that modulate cortical activity are needed to further clarify the cause-effect chain of brain activity patterns and creative performance.

Transcranial direct current stimulation (tDCS) is a brain stimulation technique that provides the opportunity to non-invasively modulate neural membrane potentials and excitability in the human cortex [16]. To date, tDCS studies on creativity are inconclusive. Some studies are consistent with the balance hypothesis insofar as they observed improved performance (AUT and arithmetic creativity task) with right prefrontal anodal stimulation (increased excitation, 'activation') and/or left prefrontal cathodal stimulation (decreased excitation, 'deactivation') [17–20]. In these studies, stimulation protocols include a setup with right anodal and left cathodal stimulation [17,19] and a setup with left cathodal stimulation only [18]. A major criticism of these studies is that they do not unequivocally support the balance hypothesis. Another potential conclusion is that in bilateral setups, the right frontal electrode is unnecessary for the efficacy of the protocol, and left cathodal stimulation is sufficient to improve creativity. This alternative "left frontal deactivation hypothesis" is, at least in part, supported by previous research [18]. Other tDCS studies seem to contradict the balance hypothesis reporting improved creativity with anodal stimulation ('activation') of the left dorsolateral PFC [21] for the CRA, [22] for the AUT]. Moreover, cognitive training

augmented by anodal tDCS over the left dorsolateral PFC (compared to sham stimulation) improved performance in the WCST in patients with multiple sclerosis [23]. One reason might be that MS patients show compensatory bilateral activation in tasks where healthy humans only show unilateral activation. Together, the existing literature is inconclusive and additional research is needed to further specify the neural basis of creativity.

The aim of the present research was to further elucidate the neural basis of and ways to improve creativity based on well-defined behavioral tasks and systematic activity changes of the right and left frontal cortex through tDCS along with electroencephalographic (EEG) monitoring of induced brain activity changes in healthy humans. Our hypothesis, based on prior tDCS research, was that cathodal stimulation of the left IFG, paired with anodal stimulation of the right IFG (L-R+), compared to the reverse protocol and sham, would improve behavioral creativity measured with the AUT (higher number of correct solutions), the CRA (higher number of correct solutions) and the WCST (reduced number of perseveration errors).

Materials and methods

Materials and methods used in this study are described in detail in the Appendix. The study had been approved by the local Ethics Committee and was conducted in accordance with the Declaration of Helsinki. In brief, the sample consisted of ninety healthy university students (45 female, 45 male, mean age 23.8 ± 2.3 years). In a parallel-group, between-subject design, behavioral performance in three creativity tasks was compared between two different stimulation conditions and sham (Fig. 1). In a baseline session, participants performed the AUT, the CRA, and the WCST without stimulation. For the test session that took place one week after the baseline session, participants were randomly allocated to one of three groups (activation of the left and deactivation of the right inferior frontal gyrus [L + R-], reverse stimulation protocol [L-R+], and sham stimulation). In the test session, the participants performed parallel versions of the AUT, the CRA, and the WCST while simultaneously receiving active stimulation or sham. Practice items for each of the three tasks were provided prior to the actual test session (without stimulation). All tasks are common, validated, and were administered according to the instructions given in the user manual. For the AUT, the main outcome was fluency (number of correct solutions, i.e. reasonable uses excluding the most common use). The number of correctly solved items was the primary outcome of the CRA. With the instruction for the CRA, participants received a definition of the term 'insight', informing them that insight is a form of problem solving that is characterized by sudden understanding, whereby the person cannot fully describe how he or she reached the solution, but is sure that it is correct. After every item for which a solution had been provided, participants were asked whether they had solved the item with or without insight. The primary outcome for the WCST was the number of perseveration errors (trial in which the 'old' rule is applied again, although negative feedback has already been provided).

TDCS with a constant current of 1 mA was delivered for 22 min by a constant current stimulator (neuroConn GmbH, Illmenau, Germany). Two electrodes (5×7 cm) were placed over the inferior frontal gyrus (IFG) bilaterally. The electrode size and current density are standard parameters for effective, prolonged stimulation within the safety recommendations [24,25]. The right IFG was determined as the crossing point between T4-Fz and F8-Cz in the 10/20 EEG system, while the left IFG was determined as the crossing point between T3-Fz and F7-Cz. An electric field simulation for the tDCS was performed with SimNibs [26]. An example

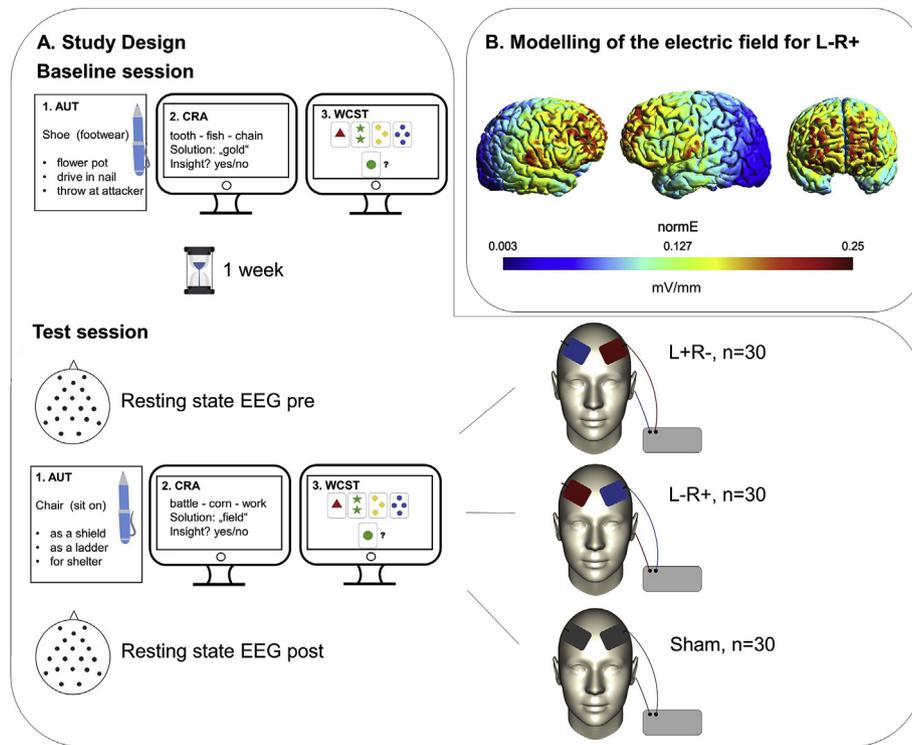


Fig. 1. Study design and simulation of the electric field. A. Study design. Ninety healthy participants performed the Alternate Uses Task, the Compound Remote Associate task, and the Wisconsin Card Sorting Task in a baseline session. They were then randomized to L + R-stimulation, L-R+ stimulation, or sham. They performed parallel versions of the tasks under stimulation/sham in a test session one week after the baseline session. Resting state EEG was performed for 5 min before and after the test session. B. Electric field simulation for the left cathodal/right anodal tDCS montage. Simulation was performed with SimNibs. As shown, the electric field induced by tDCS comprised the targeted regions of the frontal cortex.

mesh provided with the software was used for the simulation. The resulting model was visualized with the software GMSH.

Wake resting state EEG was recorded for 5 min prior to and after the stimulation. During recording time, participants were verbally instructed to keep their eyes open for 30 s, and then close their eyes for the remaining 30 s, following a modified version of the Karolinska Drowsiness Test. EEG was recorded from the electrode positions Fp1, FC1, C3, CP1, CP5, P3, P7, TP9, O1 on the left side, the corresponding electrodes on the right side, and Fz, Pz and Cz, referenced to Fpz, according to the 10–20 system.

We included assessments of baseline performance of the three main tasks without stimulation, vigilance (Psychomotor Vigilance Task, PVT, measured directly after the three main tasks), the brain derived neurotrophic factor (BDNF) genotype, self-estimated performance in the three tasks (visual analogue scales), the guessed stimulation group, as well as several self-reported measures (depression, Beck Depression Inventory, sleep quality, Pittsburgh Sleep Quality Index, perceived stress, Perceived Stress Questionnaire, and trait creativity, Cognitive Flexibility Inventory) as control variables, because these may influence performance in creativity tasks.

For statistical analysis, a hierarchical testing plan was applied: If significant differences between the three groups were found on the AUT, the WCST was analyzed. In case of significant group differences in the AUT and the WCST, the CRA was analyzed. The order for the hierarchical testing plan has been predefined as AUT, WCST, CRA because we chose to enter the upper and lower extreme ends of our conceptual order ('space of the search process') as the two first steps into the hierarchical testing plan. For all three tests, an analysis of covariance (ANCOVA) with the between-subject factor Group (L + R-, L-R+, sham) and the covariate cognitive flexibility baseline score was conducted. In case the ANCOVA yielded a

significant result, post-hoc tests (Tukey honest significant differences, Tukey HSD) were performed to analyze which of the three groups differed significantly. For the estimation of effect sizes, Cohen's d was calculated (small effect: $d = 0.2–0.5$; medium effect: $d > 0.5–0.8$ and large effect: $d > 0.8$). The level of significance was set at $p < .05$ (two-sided). Exploratory analyses were used to investigate group differences regarding the EEG recordings, correlations between behavioral performance and EEG measures, as well as the effect of potential modulators of creativity (control variables). Data and code are available from the corresponding author upon request.

Results

Baseline characteristics and control parameters

As listed in Table 1, we did not find any significant group difference for the baseline assessments of the main tasks or for the control parameters (Table 1). Of particular note, there were no significant group differences (χ^2 test) regarding the guessed stimulation group, indicating that patients were unable to distinguish active stimulation from sham stimulation. Together, there is no indication that changes in behavior and brain activity could be biased by random group differences in the absence of an intervention (baseline assessment) or driven by unspecific parameters, such as vigilance, BDNF genotype, depression, sleep quality, perceived stress, or trait cognitive flexibility.

tDCS modulates creativity

The main pattern of results is that creative performance was increased with deactivation of the left and activation of the right

Table 1
Baseline characteristics and control parameters.

	L-R+	L + R-	Sham	p ANOVA/Chi ²
Age (years)	24.1 ± 2.9	23.9 ± 2.0	23.4 ± 1.8	.426
Sex ratio (male/female)	15/13	15/15	13/16	.802
Years in school and university	16.7 ± 2.8	16.6 ± 2.2	16.6 ± 1.8	.941
Guessed stimulation group (L-R+/L + R-/Sham)	16/9/3	9/16/5	13/9/7	.175
BDNF genotype (met/met/val/met/val/val)	1/6/21	0/5/25	1/4/24	.791
<i>Baseline creativity tasks</i>				
AUT correct solutions	3.2 ± 1.5	3.4 ± 1.3	3.3 ± 1.1	.921
WCST persever. error	9.7 ± 6.0	9.1 ± 2.2	9.0 ± 4.6	.846
CRA correct solutions	15.0 ± 4.4	14.4 ± 4.8	15.3 ± 3.5	.789
CRA reaction time	6.8 ± 2.3	5.5 ± 2.1	6.1 ± 2.6	.565
<i>Subjective performance</i>				
Subjective AUT	35.8 ± 19.2	33.0 ± 16.4	35.7 ± 20.9	.794
Subjective WCST	70.7 ± 11.8	66.8 ± 10.7	65.2 ± 12.9	.189
Subjective CRA	36.1 ± 20.1	33.2 ± 20.7	32.3 ± 14.8	.686
AAQ	15.6 ± 6.2	14.2 ± 5.4	12.7 ± 2.5	.106
BDI	2.1 ± 2.5	2.0 ± 2.7	1.4 ± 1.7	.534
CFI	114.5 ± 16.2	108.3 ± 13.3	108.7 ± 8.4	.148
PSQ	23.0 ± 14.7	21.8 ± 12.7	21.6 ± 9.6	.916
PSQI	3.5 ± 2.0	3.3 ± 1.7	3.4 ± 1.4	.907
MWT-B	31.4 ± 2.2	30.8 ± 2.4	31.4 ± 2.1	.514
PVT baseline	3.3 ± 0.2	3.2 ± 0.2	3.3 ± 0.3	.302
PVT test session	3.2 ± 0.2	3.1 ± 0.4	3.3 ± 0.2	.168
CRA % insight baseline	48.7 ± 28.7	42.9 ± 30.3	43.2 ± 31.4	.717
CRA % insight test session	58.8 ± 28.6	48.2 ± 27.4	46.0 ± 30.5	.209

Values are given as mean ± standard deviation. p Anova/Chi²: significance value in analysis of variance with factor 'group' (L-R+, L + R-, Sham), or, for categorical variables, significance value of Chi² test. BDNF brain derived neurotrophic factor, AUT alternate uses task, WCST Wisconsin card sorting task, CRA compound remote associate task, AAQ acceptance and action questionnaire (sum score experiential avoidance), BDI Beck depression inventory, CFI cognitive flexibility inventory, PSQ perceived stress questionnaire, PSQI Pittsburgh sleep quality index, MWT-B Mehrfachwahl-Wortschatztest B (estimate of verbal intelligence), PVT Psychomotor vigilance test (primary outcome: psychomotor speed (1/reaction time (ms)*1000), CRA % insight percentage of correctly solved CRA items that have been solved with insight.

prefrontal cortex (L-R+ group) and reduced with the reverse protocol (L + R-group) (Fig. 2). Specifically, in the AUT (number of solutions), an ANCOVA with the between subject factor Group and baseline performance as covariate yielded a highly significant main effect of the factor Group ($F_{2,83} = 5.5, p = .006$). Post-hoc tests revealed that this effect was driven by a significantly poorer performance in the L + R-compared to the sham ($p = .041, d = 0.51$) and L-R+ group ($p = .006, d = 0.70$). In the WCST (perseveration errors), we also observed a highly significant main effect for the factor Group (ANCOVA, $F_{2,83} = 7.5, p < .001$). Post-hoc tests showed that this effect was driven by a significantly better performance in the L-R+ compared to the sham ($p = .001, d = 0.88$) and L + R-group ($p = .014, d = 1.1$). In the CRA, we did not observe a significant main effect of the factor Group on the primary outcome parameter of this task (number of solutions) (ANCOVA, $F_{2,83} = 0.4, p = .652$). However, a secondary analysis demonstrated a highly significant main effect of the factor Group on the outcome parameter response speed defined as $1 - \text{solution time} + 10$ for items that were solved correctly and with insight (ANCOVA, $F_{2,70} = 6.5, p = .003$). Here, post-hoc tests showed that the L + R-group had a significantly slower response speed compared to the sham ($p = .04, d = 0.63$) and L-R+ group ($p = .002, d = 0.89$). Together, these data on the behavioral level support the notion that a deactivation of the left and an activation of the right IFG is associated with better creativity (medium to large effect sizes).

With the same statistical approach, we tested for group differences in subjective ratings of task performance. While the ANCOVAs were insignificant for subjective performance in the AUT ($F_{2,82} = 1.0, p = .357$) and CRA ($F_{2,83} = 1.5, p = .237$), we found a significant main effect of the factor Group for subjective performance in the WCST ($F_{2,83} = 3.2, p = .048$), driven by better subjective performance in the L-R+ group compared to the sham group ($p = .040$). This group difference in subjective WCST performance mimics the objective finding in this task.

tDCS modulates brain activity

To investigate potentially performance-relevant cortical activity alterations associated with stimulation, we explored changes in the EEG before vs. after stimulation/sham. We observed EEG indices of increased brain activity associated with anodal stimulation ('activation') and EEG indices of decreased brain activity associated with cathodal stimulation. More precisely, anodal stimulation was paralleled by an increase in fast frequency spectral power (beta range), and cathodal stimulation was paralleled by an increase in slow frequency spectral power (delta and theta range) referred to baseline (Fig. 3).

EEG electrodes around the stimulation electrodes were investigated (Fp1, FC1, C3 and CP1 for the left side, and the corresponding electrodes for the right side). EEG signals of these sets of four electrodes were averaged, resulting in a 'left brain set' and a 'right brain set'. We then calculated a lateralization index, defined as the right minus the left brain set. A positive lateralization index (>0) indicates higher EEG power on the right side, whereas a negative lateralization index (<0) indicates higher EEG power on the left side of the brain. ANCOVAs with the between subject factor Group, the lateralization index at baseline as a covariate and the lateralization indices of every EEG frequency band after stimulation as the dependent variables demonstrated significant Group effects for beta1 ($F_{2,83} = 3.8, p = .026$), theta ($F_{2,83} = 7.2, p = .001$), and delta2 ($F_{2,83} = 4.2, p = .019$). Post-hoc tests revealed a significant difference between the two stimulation groups for beta1, insofar as the lateralization index was more positive (indicating a shift to the right) in the L-R+ group, compared to the L + R-group ($p = .021, d = 0.23$). For theta, the lateralization index was more positive (indicating a shift to the right) in the L + R-compared to the sham ($p = .006, d = 0.26$) and L-R+ group ($p = .003, d = 0.43$). For delta2, the lateralization index was more positive (indicating a shift to the right) in the L + R-group compared to the L-R+ group ($p = .016$).

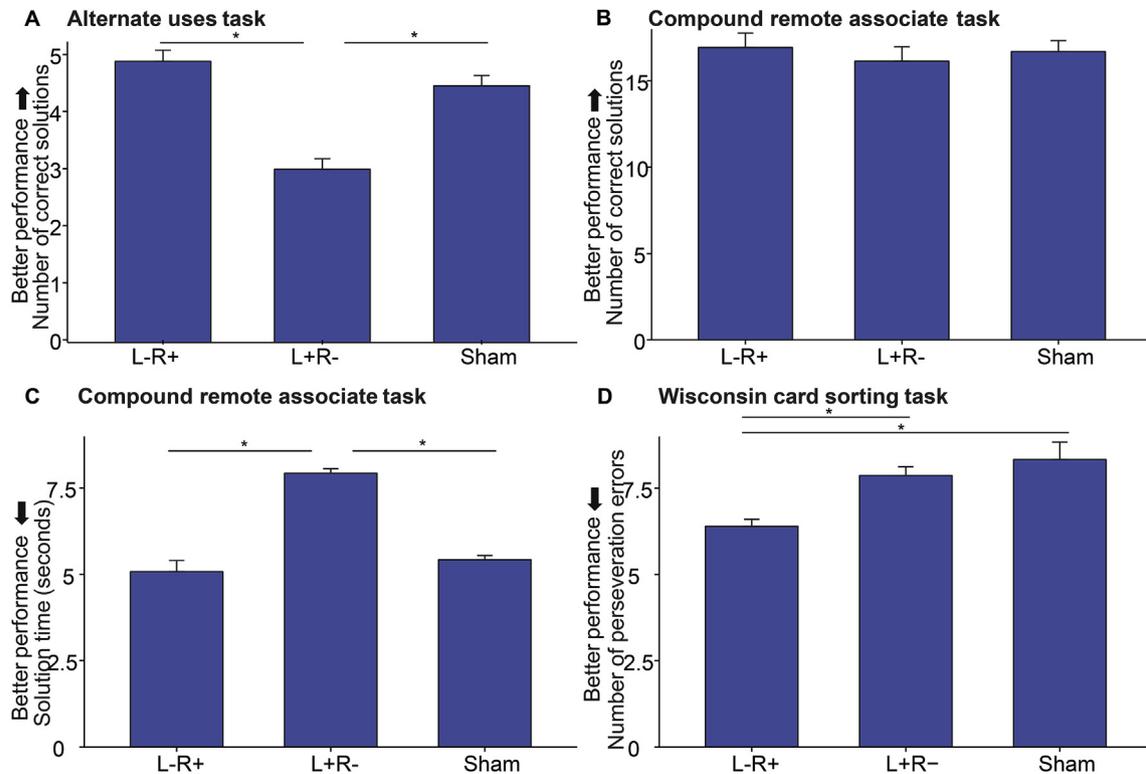


Fig. 2. Behavioral data. 'L-R+' refers to cathodal stimulation over the left IFG and anodal stimulation over the right IFG, 'L + R-' refers to the reverse montage. Asterisks refer to significant p-values in post-hoc tests of an ANCOVA with the between-subject factor Group (L-R+; L + R-; sham), the covariate creativity baseline score, and creativity in the test session as an outcome.

$d = 0.24$). Other contrasts and analyses of other frequency bands did not reach statistical significance (for all analyses, $p > .05$).

As a location control, we performed the same analyses for the posterior electrodes (P3, P7, TP9 for the left side and the corresponding electrodes for the right side). These analyses did not yield significant effects for any frequency band for the factor Group (for all analyses, $p > .05$), indicating that power spectral changes were specific for the locations around the tDCS electrodes.

tDCS effects on the brain correlate with its behavioral effects

To further specify potential mechanisms, we correlated behavioral task performance and the lateralization index of EEG spectral power at the stimulation site (right minus left frontal brain set, see above). The analyses demonstrated that a higher power of fast frequencies (beta range) in the right frontal area was correlated with better performance in the WCST. Not directly mapping on the behavioral results, but in line with the overall concept, higher power in the beta range in the right frontal area was also correlated with better performance in the CRA (Fig. 4). This pattern of results suggests that tDCS modifies brain activity near the tDCS electrodes, and that these activity changes might drive, or are at least associated with behavioral modifications.

Discussion

The main pattern of results shows that creativity improves with left cathodal and right anodal tDCS and deteriorates with the reverse stimulation protocol. This pattern is in line with the balance hypothesis, but is also consistent with an alternative left frontal deactivation hypothesis. Importantly, we demonstrate, to our knowledge for the first time, tDCS induced brain activity changes

(EEG indices) that are associated with effects on creative performance.

Prior work on the neural basis of creativity does not result in a homogeneous picture. This difficulty likely emerges from differences in considered brain areas (inferior frontal vs. dorsolateral prefrontal) or task characteristics (for instance, space of the search process). On the one hand, improvements of creative performance have been observed with a preponderance of activation of right prefrontal areas over left prefrontal areas (balance hypothesis), supported by lesion studies and prior tDCS investigations, [e.g. 19]. On the other hand, increased activation of the left dorsolateral prefrontal cortex has also been associated with increased creative performance (left prefrontal activation hypothesis, supported by fMRI studies and prior tDCS investigations, [21]). Differences might relate to verbal vs. non-verbal task characteristics. Our study provides a new contribution using, for the first time, a systematic variation of anodal, cathodal, and sham stimulation of the right and left inferior frontal gyrus, demonstrating inverse behavioral effects with inverse stimulation protocols (i.e., improvement with L-R+ and deterioration with L + R-). A limitation is that the spatial resolution of tDCS is generally low and may not have allowed for a targeted stimulation of the IFG. Recent research has demonstrated that cathodal tDCS can also have beneficial effects, for instance through the reduction of dysfunctional activity [27] and anodal tDCS can impair performance via an increase of neuronal noise [28]. Since our study compared two bilateral montages and included no unilateral control montage, it remains unclear whether both active electrodes were necessary to induce the effects. It is possible that a unilateral montage (only L-, or only R+) would have been sufficient to improve creativity. Specifically, previous behavioral research suggests that left frontal deactivation may be sufficient to modulate creativity [18]. This, however, is at odds with our EEG results, that

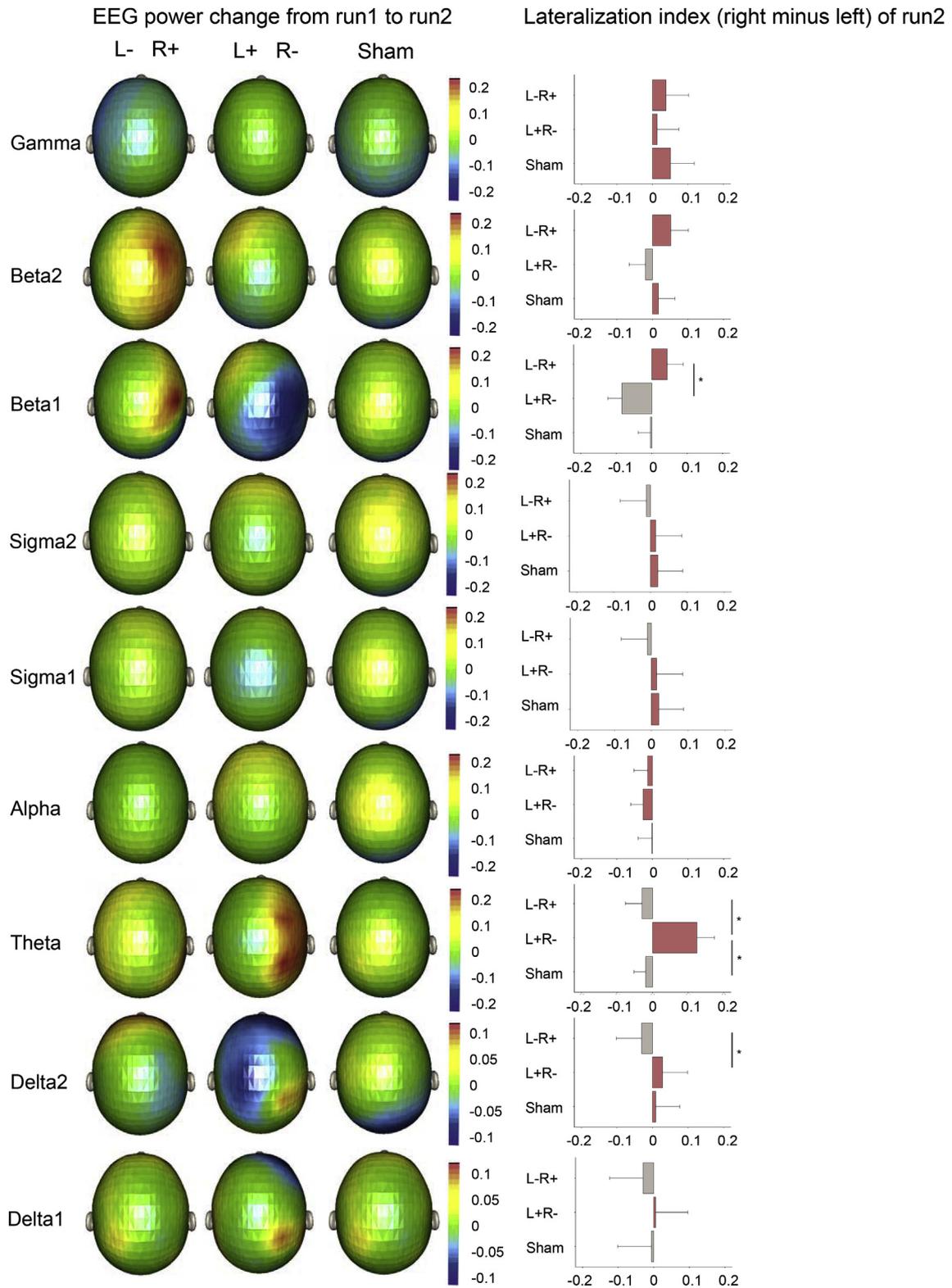


Fig. 3. EEG analyses. 'L-R+' refers to cathodal stimulation over the left IFG and anodal stimulation over the right IFG, 'L + R-' refers to the reverse montage. EEG power refers to sets of EEG electrodes covering the areas under the tDCS electrodes (average of Fp1, FC1, C3, and CP1 for the left side and average of Fp2, FC2, C4 and CP2 for the right side). 'Lateralization index' is defined as right average minus left average. A positive (>0) lateralization index indicates that EEG power was larger on the right side of the brain, whereas a negative (<0) lateralization index indicates that power was larger on the left side of the brain. Run 1 and run 2 refer to the time points directly before and after tDCS stimulation. Power is given in log mV². Asterisks refer to a significant p-value in post-hoc tests of an ANCOVA with the between subject factor 'group' (L-R+ (n = 28); L + R- (n = 30); sham (n = 29)), the lateralization index at run1 as a covariate, and the lateralization index at run2 as an outcome.

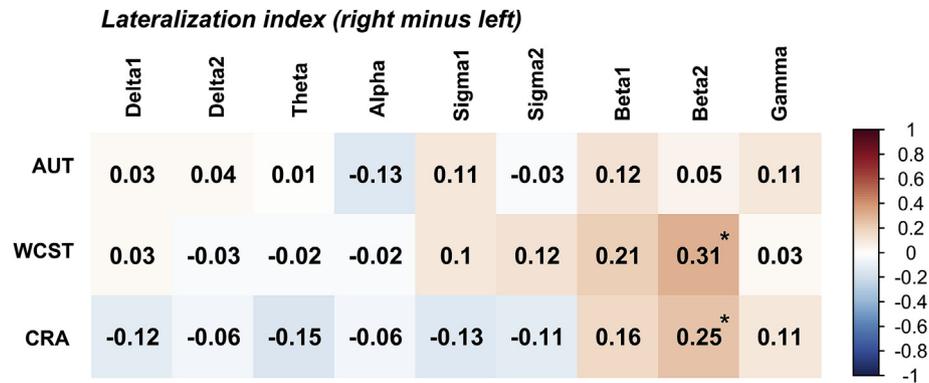


Fig. 4. Correlational analyses. AUT alternate uses task, WCST Wisconsin card sorting task, CRA compound remote associate task, here referring to the response speed in items that were solved correctly and with insight. 'Lateralization index' is defined as right average minus left average. A positive (>0) lateralization index indicates that EEG power was larger on the right side of the brain, whereas a negative (<0) lateralization index indicates that power was larger on the left side of the brain. Given values refer to Pearson's correlation coefficient between behavioral performance and the lateralization index.

suggest a key role of the right hemisphere. So far, no definite conclusions regarding the role of circumscribed brain areas can be drawn. In addition, we cannot exclude that cross-task effects have influenced our results, since, due to constraints of tDCS timing, a fixed task order has been used. Fewer items than usual have been used for the CRA and the WCST, which may have restricted power in these two tasks.

Our data extend previous research on tDCS and creativity insofar as we complement behavioral with EEG data that are indicative of a potential neural mechanism of action. Particularly, our resting-state EEG analyses prior to and after tDCS suggest increased cortical activity after anodal stimulation, indexed by a power increase in fast (beta) frequencies. This is in line with pivotal work on the biological mechanisms of electrical brain stimulation [16,29,30] as well as previous research on EEG after-effects of tDCS [31,32]. More precisely, anodal stimulation is thought to lead to a slight depolarization of the resting membrane potential of stimulated neurons, increasing neural excitability and firing rates [16]. Increased neural excitability in a right prefrontal area after right anodal stimulation may thus explain the observed improvement in performance in the WCST. In turn and consistent with prior work, our resting-state EEG analyses prior to and after tDCS stimulation suggest decreased cortical activity after cathodal stimulation, indexed by a power increase in slow (delta and theta) frequencies [33–35]. As a limitation, our EEG analysis was exploratory and not controlled for multiple comparisons. EEG could only be measured around the stimulation site, because we aimed for a fast onset of EEG recording directly after the end of tDCS stimulation, and a simultaneous application of both electrodes was not possible. However, our analysis demonstrates EEG power changes in the anterior region around the tDCS electrodes, but not in posterior regions, indicating that the observed changes are location specific. In addition, our line of interpretation fits well with the correlational analyses that demonstrated an association between higher power in fast frequency bands in the right frontal cortex and high performance levels. To prevent stimulation artifacts, we used pre- and post-stimulation EEG measures. After-effects lasting for up to an hour after the termination of long-lasting (>9 min) anodal and cathodal stimulation are a well replicated finding [30,33,36]. However, it is not fully clear whether after-effects mimic fully the situation during stimulation. In addition, the behavior of the participants during and after stimulation influences online- and after-effects of tDCS [37,38]. Together, the results indicate that a relative activation shift towards the right compared to the left prefrontal cortex is

critically involved in the execution of creativity tasks (balance hypothesis).

Of note, our investigation addresses the neural assembly level. Whereas this precludes conclusions on activity changes at the single neuron level, a computational output level seems appropriate because it is more closely related to observable behavior [39]. Our findings in the context of prior work suggest that creativity emerges from an interplay of different cognitive functions, including but not limited to idea generation, idea inhibition, and language. In line with this assumption, we hypothesize that creativity is not located in one isolated brain area such as the right IFG, but depends on a cortical brain network, most prominently involving the IFG and the DLPFC. Activation of the right IFG has quite robustly been associated with inhibitory cognitive control [40,41]. Whereas the creativity tasks used in the present study are not classical inhibitory control tasks, all three include an inhibitory component (common use in the AUT; words associated with only one or two stimulus words in the CRA; old rule in the WCST). The role of the right IFG may thus consist in the suppression of common, but uncreative content. The most prominent function of the left IFG, in contrast, is language production and comprehension. Language-related demands are relatively low in the AUT and CRA and absent in the WCST, which could explain why a deactivation of the left IFG does not hinder performance in these tasks. One can speculate that a decreased activity in a brain area that promotes verbal fluency may even encourage a more visual, metaphorical way of thinking that stimulates creative insight. The role of the left DLPFC is somewhat unclear since different cognitive functions have been associated with this area. Creativity has a substantial conceptual overlap with other higher order cognitive functions such as planning, that has consistently been associated with the DLPFC. Research on the neural basis and modifiability of planning has, similar to creativity research, resulted in discussions about the exact localization within the prefrontal cortex and hemispheric lateralization [42–44]. Future studies are needed to clarify whether and how these results can be integrated, or whether, possibly, manmade categories such as creativity and planning, may not consistently map on brain function.

Our findings have potential clinical implications. Cognitive flexibility, a component of creativity, has been linked to mental health [45] and reduced cognitive flexibility has been identified as a transdiagnostic aspect of psychopathology [46,47]. Enhancing cognitive flexibility is a goal of psychotherapy, and tDCS might be used to augment this process. A tDCS protocol that increases state-like creativity could be applied during a psychotherapy session to

increase the efficacy of selected therapeutic interventions. As an example, in acceptance and commitment therapy [48], patients are instructed to react to thoughts in multiple unusual ways (e.g., assigning a color or shape) instead of an automatic response, the goal of which is to increase flexibility and reduce the impact of difficult thoughts on emotional wellbeing. The idea of using tDCS during specific therapy sessions follows a broader development of using neurobiological interventions to systematically augment selected components of the psychotherapy process [49]. Another potential application is the improvement of creative performance in healthy humans, e.g. in creative professions. Of note, tDCS has become easily available, even for the general public. Caveats include ethical considerations and the lack of knowledge regarding potential negative effects of stimulation protocols in other domains and the effects of long-term repeated application. Of note, a translation from laboratory tasks to everyday creativity is required.

In conclusion, our study provides new insights into ways of modulating creativity, whereby a deactivation of the left and an activation of the right prefrontal cortex with tDCS is associated with increased creativity. This work might inform future interventions to modulate creative processes. Future research is needed to further clarify the neural mechanisms and to translate this knowledge into clinical applications.

Conflicts of interest

The authors have no conflicts of interest to declare.

Author's contributions

Designed research: EH, LF, CN, MN, CK. Performed research: EW, LF, DR. Analyzed data: EH, CN, BF, EW, LF. Wrote the paper: EH, LF, CN, DR, MN, CK, BF.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.brs.2019.06.004>.

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