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Supplementary Information for

Right temporal alpha oscillations as the neural mechanism for inhibiting obvious associations

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Supplementary Material and Methods

Experiment 1

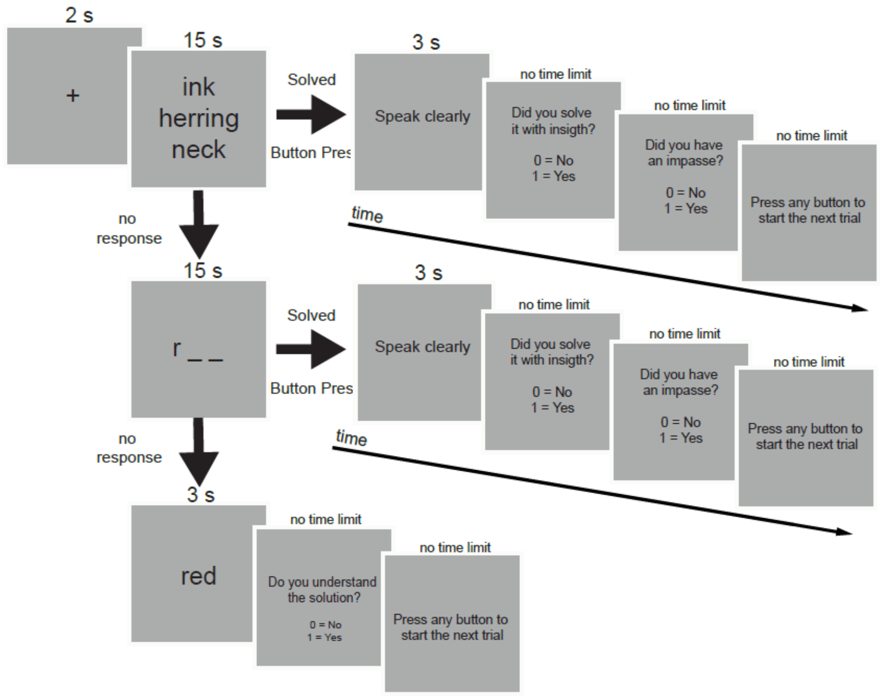
Remote associate task (RAT) procedure. Three sets of RAT problems were compiled with similar degree of average difficulty (Sandkühler & Bhattacharya, 2008). The orders and combinations of stimulation condition and RAT set were counterbalanced across participants using a Latin Square procedure; participants were assigned to a session/set order at random. Each RAT trial was presented on a PC using Cogent toolbox (http://www.vislab.ucl.ac.uk/cogent_2000.php) for MATLAB (version 2006), and participants viewed the screen from approximately 40cm. On each trial (Fig. S1A), participants were initially given 15 seconds to come up with a solution; if not solved within this time period, a hint, revealing the first letter and the number of letters in the solution word, was presented on the screen for another 15 seconds. Participants were instructed to press a key with their right hand as soon as the solution was found and verbalized their solutions. Subsequently they provided a rating on impasse and insight (both on a binary scale). Impasse was defined as experiencing a 'mental block', whereby they felt they had come to a point in their search for the solution where they were making no progress and were unable to generate any more ideas as the possible candidates for the correct solution word (1). Insight was defined as the experience whereby the solution just 'popped into their head' suddenly and without any prior warning or conscious awareness of progression towards the answer (compared with a slower more analytical route towards finding the solution) (2). If no solutions were found within 30 seconds, the correct solution was presented and the participants were asked to state, by pressing a key, whether or not

with the procedure.

Semantic associations. In addition to the shared wrong association analysis, we tested the two following measures.
(i) *Cue-solution association*: This measure refers to how strongly the cues were associated with the solution word. We quantified how many cue words, out of three, contained the solution word amongst the 20 strongest semantic associations (strong association), and in which position on the list (peak and average). Some of the words (n = 11) of the RAT items were not included in the database, and we excluded these RAT items from subsequent analysis. In the remaining 124 RAT items, 38 did not have any cue strongly associated with the solution, 39 items had 1 cue association, 44 items had 2 cues associated with the solution, and only 3 items had 3 cues strongly associated with the solution. We merged the levels with 2 and 3 cues containing a strong association with the solution for analysis.

(ii) *Solution-cue association*: This refers to whether the solution word contained any of the cues as a strong associated word (amongst the first 20 associations). We quantified how many of the cues were presented as a strong association for the solution. From all valid solutions, 21 did not contain any of the cues as a strong association, 46 contained 1, 43 contained 2, and 14 solutions had the 3 cues as a strong association.

A.



B.

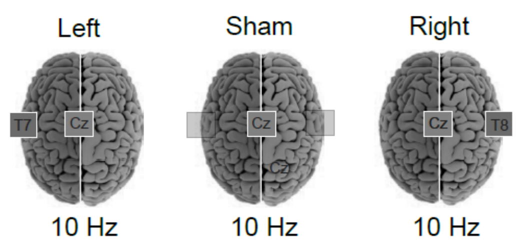


Fig. S1. Experimental design. **A.** RAT trial structure**.** On each trial (45 per condition) participants were shown 3 cue words (e.g. ink, herring, neck), and had to then deduce the correct target solution word, which is a word that combines individually with each of the three cue words to create three new compound words; and **B.** The tACS sessions. Each participant attempted to solve 45 RAT items while receiving either: 1) Left tACS; 2) Sham; 3) Right tACS; the current with 10Hz frequency had an amplitude of 1mA (peak-to-peak) with 10 Hz frequency. The boxes represent the electrode positions (labelled according to the 10-20 system – the box represents the electrodes). In the sham stimulation, the machine was switched on for only 30 s and the electrodes positioned at the vertex and right (T8) or left (T7) randomly.

Additional Measures. The Profile of mood states questionnaire (3), a measure of state mood, was completed immediately prior to the onset of the brain stimulation (pre) and at the end of the session (post). This allowed us to control for the possibility of stimulation effects on mood states. Further, at the end of each session, participants completed the controlled oral word association test (COWAT; (4). One letter (F, A, or S) was used in each session. The order in which participants received each letter, and during which stimulation condition each letter was given, was counterbalanced using a Latin Square procedure. This allowed us to control for stimulation effects on verbal fluency, which could also interfere with the effects of the stimulation on the RAT performance. Participants were given 1 min to generate as many words as they could think of starting from the given letter.

Additional data analysis. We also measured reaction times as the time elapsed between the RAT presentation (three words) until the button press for both pre- and post-hint. This was possible because the hint was presented always 15 seconds after the problem presentation in case the participant could not solve the problem within the initially allotted 15 seconds. For each individual RAT item (n = 135), we calculated the proportion of correct solutions within each condition (% correct in left, sham, and right tACS). The proportion of solutions solved with insight was calculated for correct trials only. Further, we estimated the overall difficulty of each problem by looking at the proportion of correct solutions for each item independent of condition (harder triads had lower solution rates overall).

Experiments 2 and 4

EEG recording and preprocessing. *Preprocessing:* The EEG signals were recorded by eighteen PiStim electrodes placed according to the extended 10-20 electrode placement system (Jasper, 1958) using a battery-driven system (StarStim, Neuroelectrics, Spain). The EEG electrodes were: P8, F8, F4, C4, T8, P4, Fp2, Fp1, Fz, Cz, Pz, Oz, P3, F3, F7, C3, T7, and P7. The EEG data were re-referenced to the algebraic mean of the right and left earlobe electrodes (Essl & Rappelsberger, 1998). Continuous data were high-pass filtered at .5 Hz and low-pass filtered at 47 Hz
For experiment 2, the data was epoched from -2s to 5s time-locked to the stimulus presentation (RAT items). For experiment 4, the data was segmented in epochs of 2 seconds. Artefact rejection was done in a semi-automatic fashion. Data from electrodes with poor signal quality, as observed by visual inspections, was interpolated from neighbouring electrodes. Subsequently, independent component analysis was run to correct for eye-blink related artifacts. Finally, epochs containing amplitude exceeding ±85 μV were removed after visual inspection. Four participants were removed from the EEG analysis due to poor data quality throughout the experiment. The preprocessing was done using EEGLAB toolbox (Delorme & Makeig, 2004), and the data were analysed in Matlab, including custom written scripts.

Supplementary Analyses

A number of control and supplementary analyses was conducted.

Additional analyses Experiment 1

The reaction times (from the RAT words presentation to the response) were entered in a 2 (*shared wrong association*: yes vs. no) x 3 (*stimulation*: left, sham, right tACS) within-subjects ANOVA. We observed no significant effects, including *stimulation* ($F_{(2,28)}$ = 0.255, p = .776), *shared wrong association* ($F_{(1,28)}$ = .049, p = .827), or interaction ($F_{(2,28)}$ = 0.2, p = .980). There was also no significant effects of *stimulation* and *shared wrong association* in relation to the number of hints (proportion) (p > .05) nor the proportion of correctly solved problems before and after the hints (p > .2). These findings indicate that the observed effects of higher accuracy for right tACS were unrelated to speed of response and the usage of hints.

We investigated whether the efficacy of each stimulation condition was affected by other semantic characteristics as well as by the wrong shared association including: (i) *cue-solution association* - whether the solution word is amongst the most frequent associations for each cue word, and (ii) *solution-cue association* - whether the solution word has any of the cue words as a top association. We conducted three separated one-way ANOVAs for each semantic characteristic as a factor with the efficacy index for each condition (dependent variable). First, we observed that the number of cue-solution association (0, 1, or 2) had no effect on the right tACS relative efficacy index ($F_{(2,121)}$ = 1.18, p = .310), nor on the left ($F_{(2,121)}$ = 2.09, p = .150) or sham ($F_{(2,121)}$ = .972, p = .381). Second, the same analysis for the *solution-cue association* revealed no effects on the right tACS relative efficacy ($F_{(2,121)}$ = .187, p = .905), nor left ($F_{(2,121)}$ = 1.80, p = $F_{(2,121)}$ = 1.46, p = .219). Third, the same analysis using the number of wrong shared association between the cues (0, 1, or $\geq$ 2) confirmed significant effects on the relative efficacy of right tACS ($F_{(2,121)}$ = 4.32, p = .015) and left tACS ($F_{(2,121)}$ = 3.33, p = .039), but not of sham ($F_{(2,121)}$ = 0.02, p = .998).

Control Analyses

We conducted several additional analyses as follows to investigate effects of the three stimulation protocols on various characteristics of creative problem solving in order to scrutinize their potential contributions for the reported enhanced efficacy of the right tACS.

First, we investigated whether the difficulty of the RAT items affected the efficacy index, we included the item difficulty as a factor (the items were divided using a median split), and conducted a 3 (*shared wrong association:* 0, 1, $\geq$ 2) x 2 (*difficulty:* easy vs. hard) ANOVA for each stimulation index (left, sham, right tACS). We observed that the right tACS efficacy index was higher for items with more shared wrong associations ($F_{(2,118)}$ = 3.5, p = .033, η^2 = .06), but it did not interact with the difficulty of the items ($F_{(2,118)}$ = .39, p = .676). A trend for higher right tACS efficacy for harder items was observed, but it was not statistically significant ($F_{(1,118)}$ = 1.7, p = .194), suggesting that the effect of right tACS could not be explained by the difficult of the items alone. The opposite trend was observed for the efficacy of left tACS, but the effect was marginal (*shared wrong association:* $F_{(2,118)}$ = 2.84, p = .062, η^2 = .05). There were no effects of difficulty or any other significant interactions on left tACS efficacy (p > .05) and on sham efficacy (p > .15).

Second, we investigated whether the enhanced efficacy of the right tACS for items with shared wrong association was associated with the subjective perception of an insight. We conducted a 2 (*wrong word association*: yes vs. no) x 3 (*stimulation condition*: left, sham, right tACS) within-subjects ANOVA. We found no effects for *stimulation condition* ($F_{(2,56)}$ = 2.34, p = .105), suggesting that the insight ratings were similar across three stimulation conditions. We found no significant effect of *wrong word association* ($F_{(1,28)}$ = 0.65, p = .426) nor interaction between the two ($F_{(2,56)}$ = 1.38, p = .261). The wrong shared association or the stimulation seem to not affect the experience of insight.

Third, we investigated the effects of alpha tACS on the subjective experience of impasse during the task (see *Materials and Methods*). A 2 (*wrong word association*) x 3 (*stimulation condition*) ANOVA on the average proportion of impasse for each participant revealed no effect of *stimulation* ($F_{(2,56)}$ = 1.04, p = .360), *wrong word association* ($F_{(1,28)}$ = 1.92, p = .177) nor interaction between the two ($F_{(2,56)}$ = .572, p = .568). Therefore, stimulation did not seem to affect the impasse experiences.

Fourth, we probed whether there was an interaction between stimulation condition and the effective use of hints. We split the RAT items into two groups: 1) *easy*: items which were solved above the median of the proportion of correct solutions; and 2) *hard*: items which were solved lower than the median. This division was necessary because harder problems are more likely to be solved with hint. Within each stimulation condition and within each difficulty, we calculated the proportion of correct solutions before and after hint. As expected, we observed a higher proportion of correct solutions for easy problems, and a slightly higher proportion of correct for the right-tACS condition. We conducted a 2 (*hint*: with vs. without hint) x 2 (*difficulty*: easy vs. hard) x 3 (*stimulation*: left, sham, right) mixed design ANOVA on the proportion of correct solutions. We found a significant effect of hint ($F_{(1,133)}$ = 13.79, p < .001), as there were more solutions for both easy and hard items after the hint (hint*difficulty: $F_{(1,133)}$ = .211, p = .647). There was a significant effect for stimulation ($F_{(2,266)}$ = 3.66, p = .027, η^2 = .022) since the proportion of correct solution was higher for right tACS than for left (p = .014) and sham (p = .027). Importantly, there were no interaction between hint and stimulation ($F_{(2,266)}$ = 1.06, p = .267), indicating that the stimulation worked independently of the use of the hint. Third, we investigated whether the stimulation affected the response time to the RAT items.

Fifth, we asked whether the brain stimulation affected the ability to understand the solutions rather than solving them (if the participants did not find a solution for a given RAT item, the solution was presented on the screen and they had to indicate whether they understood the solution or not). We compared the items' proportion of understood solutions between our stimulation conditions using a 2 (difficulty: easy vs. hard) x 3 (stimulation: left, sham, right) mixed design ANOVA. We observed no effect of stimulation on understanding of the solutions ($F_{(2,246)}$ = 1.45, p = .237), and no effects of item difficulty ($F_{(1,123)}$ = .219, p = .640) or interactions between the two factors ($F_{(2,246)}$ = .268, p = .765). Thus, we concluded that the brain stimulations did not influence the ability to understand the solutions.

We compared the differences in verbal fluency following the brain stimulation, found that the stimulation condition had no effect on the verbal fluency ($F_{(2,246)}$ = .268, p = .765). Finally, we compared the mood states following each of the stimulation sessions on the following dimensions: anger, depression, vigour, confusion, fatigue, and tension (see *Methods*). We compared the scores on each using the Friedman's nonparametric test for dependent samples. None of the mood states was significantly different between stimulation conditions (p > .10 across all mood states).

Additional analyses Experiment 2

We compared the reaction times and insight ratings between RAT items with shared vs. without shared wrong associations. There was no difference in reaction times and insight ratings between items with vs. without shared wrong associations (p > .2, correctly responded items).

Control analyses

First, we checked whether the main interactions observed in the experiment 2 would be affected in case we included all participants in the analysis rather than only the ones with 5 or more trials per condition. We found that the effects are also significant when we include all participants, both for the interaction between *shared wrong association and ROI* ($F_{(6,276)} = 3.681$, $p = .002$, $\eta^2 = .074$) and for our three-way interaction ($F_{(6,276)} = 2.301$, $p = .035$, $\eta^2 = .048$). To check whether the effects of shared association and accuracy were specific to the individual alpha frequency (IAF), we performed two-way repeated-measures 2 x 2 x 7 ANOVAs with *shared wrong association* (yes, no), *accuracy* (correct, incorrect) and *ROI* (RF, LF, RT, LT, RP, LP, MC) as the within-subjects' factors, separately on the average power of the traditional frequency bands, including theta band (4-8 Hz), alpha (8-12 Hz), beta (13-30 Hz) and gamma (30-40 Hz). We focused on the three-way interaction between *shared wrong association*, *accuracy* and *ROI,* but we also analysed the two-way interactions between *shared wrong association* and *accuracy*. We observed a significant three-way interaction on the alpha frequency band ($F_{(6,246)} = 2.628$, $p = .017$, $\eta^2 = .060$), similarly to what was found in the individualized alpha frequency band (Fig. S2), with higher right temporal alpha for shared compared to non-shared correct trials ($t_{(41)} = 2.366$, $p = .020$, *Cohen's d* = .365). There was no three-way interaction or main effect of shared wrong association for any of the other frequency bands, including theta ($F_{(6,246)} = 1.299$, $p = .258$, $\eta^2 = .031$), beta ($F_{(6,246)} = 1.618$, $p = .143$, $\eta^2 = .038$), and gamma ($F_{(6,246)} = 1.108$, $p = .358$, $\eta^2 = .026$). There was no significant difference between shared and non-shared RAT items in any of the other frequency bands, as expected (all contrasts: $p > .05$). We did not find an *shared wrong association*accuracy* interaction in any of the traditional frequency bands, including theta ($F_{(1,41)} = 0.651$, $p = .424$, $\eta^2 = .016$), alpha ($F_{(1,41)} = 0.858$, $p = .360$, $\eta^2 = .021$), beta ($F_{(1,41)} = 0.018$, $p = .895$, $\eta^2 < .001$), and gamma ($F_{(1,41)} = 0.481$, $p = .492$, $\eta^2 = .012$). The topographies for the contrasts between shared and non-shared over each frequency band can be observed in Fig.S2.

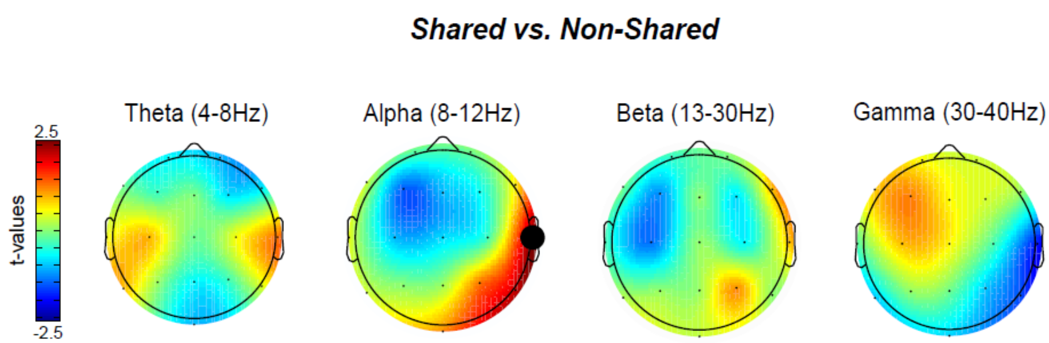


Figure S2. Topographical differences in relative power in each traditional frequency bands: theta (4-8Hz), alpha (8-12 Hz), beta (12-30 Hz) and gamma (30-40 Hz). The colours represent the t-values for the contrast between correct trials with *shared vs. non-shared* associations.

Additional analyses experiment 3

Inter-rater agreement. After the resting period in the pre-test, the participants did the AUT and the FT (alternated by item) before, during and after the stimulation condition. First, we checked the inter-rater reliability using intraclass correlation, which revealed an acceptable degree of agreement for the *general creativity* (r = .67; CI: .64 - .70) and *remoteness* (*r* = .70; CI: .68 - .72) judgements on the AUT. We observed a lower agreement on the *cleverness* judgments (r = .56; CI: .50 - .62). For the FT items, the three judges' creativity ratings were fairly similar (r = .67; CI: .64 - .69).

Additional analyses experiment 4

We conducted the statistical analysis including all participants (and not only the ones with 5 or more trials in each condition). We compared IAF power on trials rated at the as above (high) or below (low) the median for each rating using a 3 (*rating type: remoteness, cleverness, general creativity*) x 2 (*performance: high vs. low)* x 7 (*ROIs: LF, LT, LP, ML, RF, RT, RP*) within-subjects ANOVA. We observed a similar significant three-way interaction between rating type, performance, and ROI ($F_{(12,1548)} = 2.575$, $p = .002$, *partial* $\eta^2 = .020$) since we only observed significant differences in IAF between high and low remoteness ratings. The topography of the differences between high and low performance on each rating was also very similar with the differences between items with high vs. low remoteness peaking at the right temporal electrode ($t_{(129)} = 2.42$, $p = .013$, *Cohen's d* = .28).

We also conducted the same analysis using power over the traditional frequency bands: theta (4-8Hz), alpha (8-12 Hz), beta (12-30 Hz) and gamma (30-40 Hz). We did not find any three-way interaction between *rating type, rating performance and ROI* in theta ($F_{(12,1464)} = 1.211$, $p = .269$, *partial* $\eta^2 = .010$), alpha ($F_{(12,1464)} = 1.031$, $p = .417$, *partial* $\eta^2 = .008$), beta ($F_{(12,1464)} = 0.722$, $p = .731$, *partial* $\eta^2 = .006$), gamma ($F_{(12,1464)} = 1.047$, $p = .403$, *partial* $\eta^2 = .008$). Neither we observed a main effect or rating performance or interaction between rating performance and ROI ($p > .05$). However, by looking at the differences between high and low remoteness in each frequency band, we do observe a difference in the alpha band at the right temporal electrode ($t_{(123)} = 2.767$, $p = .007$, *Cohen's d* = .28), coherent with the difference observed in the IAF analysis.

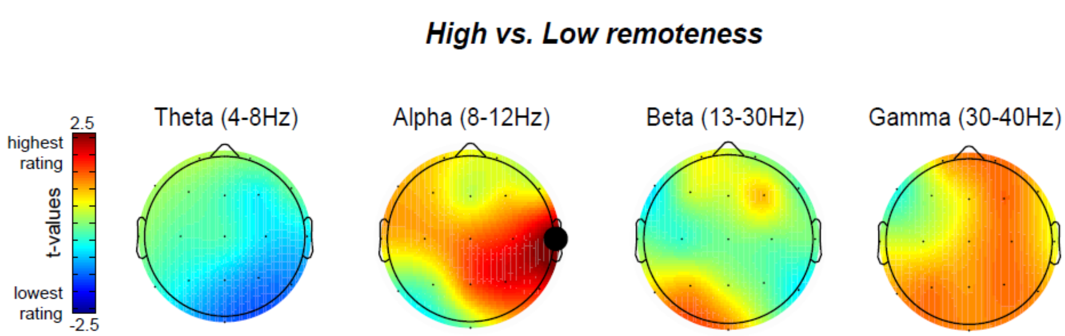


Figure S3. Topographical differences in relative power in each traditional frequency band: theta (4-8Hz), alpha (8-12 Hz), beta (12-30 Hz) and gamma (30-40 Hz). The colours represent the t-values for the contrast between trials with high vs. low remoteness ratings.

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