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

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Creative cognition requires mental exploration of remotely connected concepts while suppressing dominant ones. Across four experiments using different samples of participants, we provide evidence that right temporal alpha oscillations play a crucial role in inhibiting habitual thinking modes, thereby paving the way for accessing more remote ideas. In the first experiment, participants completed the compound remote associate task (RAT) in three separate sessions: during right temporal cortex alpha (10 Hz) tACS, left temporal alpha tACS, and sham tACS. Participants performed better under right tACS only on RAT items in which two of the three words shared misleading semantic associations. In the second experiment, we measured EEG while the participants solved RAT items with or without shared misleading associations. We observed an increase in right temporal alpha power when participants correctly solved RAT items with misleading semantic associations. The third experiment demonstrated that while solving divergent thinking tasks, participants came up with more remote ideas when stimulated by right temporal alpha tACS. In the fourth experiment, we found that participants showed higher right temporal alpha power when generating more remote uses for common objects. These studies altogether indicate that right temporal alpha oscillations may support creativity by acting as a neural mechanism for an active inhibition of obvious semantic associations.

alpha oscillations | creativity | active inhibition | EEG | brain stimulation

Introduction

A long-standing theory of creativity postulates that the ability to come up with remote and less expected semantic associations is a key characteristic of creative individuals (1). These semantic associations can be represented as edges between different nodes (concepts), linked through their proximity or common use (2). According to the spreading activation theory of semantic processing (3), every time we search for concepts associated with a word, we start from stronger associations to move progressively, in the order of strength of semantic associations, towards weaker or more remote ones (e.g., cat > dog > animal > pet > human > people > family). That is to say that, the activation (concept's retrieval) spreads from strongly connected nodes (concepts) to less connected ones. Creativity requires reaching those more remote associations on the less connected concepts. Using graph theory and an insightful analytical approach, it has been shown that highly creative individuals, compared to less creative ones, show broader and less modular semantic networks (4, 5). Nonetheless, we do not know what are the neural mechanisms which enable to inhibit strongly connected concepts to reach the most remote ones.

A key question is how creative individuals are able to engage flexibility of thought to avoid the "most travelled paths" to get to their alternative routes and draw more remote associations. For instance, more creative individuals are shown to avoid taking obvious routes when solving creative problems (6). Further, a study showed that under low cognitive load, individuals tend to explore alternative routes or more remote associations (7). The authors suggested that inhibition mediates this exploration by actively and naturally inhibiting most immediate associations, which could explain why we expand our semantic networks as we work on a problem.

Creative thinking involves searching through a clutter of associated concepts or ideas, and the presence of obvious associations is a distraction from the desired creative solution (e.g., finding unusual uses for an object or finding a remote association); such obvious but misleading associations are needed to be actively inhibited for producing more creative associations. Here we tested the hypothesis that alpha oscillatory activity enables us to inhibit the most obvious associations in order to get to more remote ideas. Considering the key role of alpha oscillations in the active inhibition of distractions in both visual search (8, 9) and working memory tasks (10), we predicted that this process of actively inhibiting obvious or strong associations could be mediated by an increase in alpha oscillations as it occurs when inhibiting other internal or external distractors.

We suggest that this hypothesis could potentially explain a wide range of findings with regards to the role of alpha oscillations (specially right lateralised) in creative problem solving (11). For example, alpha power increases during both divergent (i.e. ability to come up with a large number of original ideas) and convergent (i.e. ability to come up with one appropriate correct solution) creative thinking processes under higher internal attentional demand (12). Right lateralized alpha oscillations have also been shown to be higher during the generation of more original ideas in a divergent thinking task (13). Further, modulating frontal alpha oscillations with transcranial alternating current brain stimulation (tACS) increased performance on divergent thinking tasks (14).

Significance

'Taking a less travelled path' is often considered an effective approach to creativity, i.e., creative thinking calls for a break from habitual thinking and associations. Yet little is known about its underlying neural mechanism. In a series of four independent experiments involving electrophysiological and brain stimulation methods, we provide evidence that this process is mediated by the right temporal alpha oscillations. Alpha oscillations are known to represent a process of active inhibition to suppress irrelevant information, such as inhibiting distractions during visual search. Through monitoring the brain's electrical activity during different creativity tasks and by stimulating the right temporal brain region at the alpha frequency, we show that a similar process of active inhibition is also key to creative thinking.
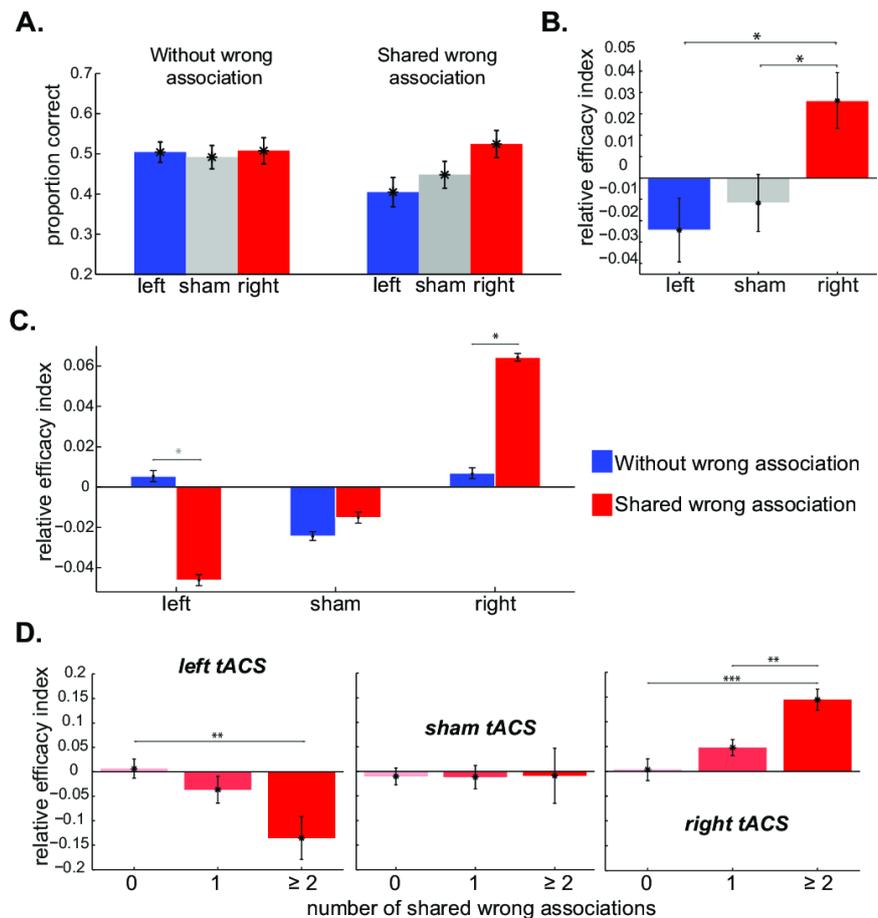
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Fig. 1. **Effects of tACS on performance in the RAT.** **A.** Proportion of correct solutions during left, sham and right tACS averaged over items with vs. without shared wrong semantic associations. **B.** Relative efficacy index during each stimulation condition (left, sham, and right temporal tACS); **C.** Relative efficacy index for each condition for items which have a shared wrong associated word between two of the cues vs. the ones that did not (without shared wrong association); and **D.** Relative efficacy index for items with 0, 1, and 2 or more shared wrong associations for left (first graph), sham (mid-graph) and right tACS stimulation. Error bars represent +/- 1 S.E.M. * $p < .05$, ** $p < .01$, *** $p < .001$.
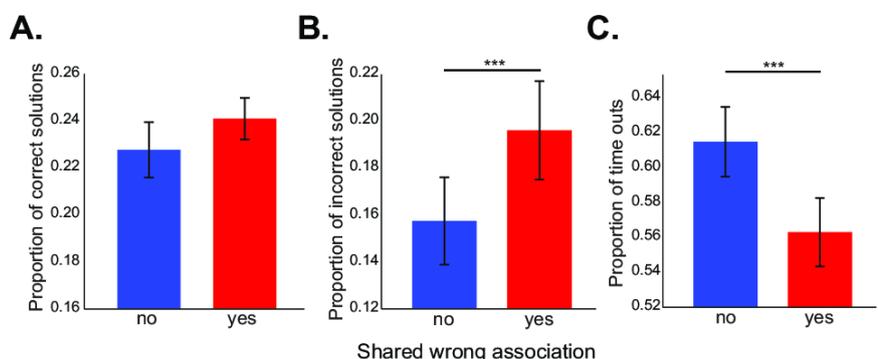

Fig. 2. **RAT performance accuracy.** Proportion of: **A.** correct; **B.** incorrect solutions; and **C.** time outs (non-responses), for non-shared (blue) and shared (red) items. Error-bars represent +/- 1 S.E.M. *** $p < .001$.

Finally, right lateralized alpha oscillations increased prior to cognitive insight (15-17).

Here, across four experiments with independent samples, we investigated how alpha oscillations contribute to both convergent and divergent creative cognition, and provided a neural mechanism linking these two distinct cognitive processes. For brain stimulation, we targeted the right temporal region due to its key role in semantic processing (18-20), integration of associated information (21), and in recognising associations between different concepts (22). The first experiment aimed at understanding the effects of the right temporal alpha (10 Hz) tACS on the remote associates task (RAT), a classical convergent thinking task, relying on the remote associations between presented cues. We predicted that right alpha tACS would improve performance on RAT items containing a shared wrong semantic association, as these require

stronger active inhibition in order to find the remote association. In the second experiment, by recording EEG, we investigated the brain oscillatory responses to the RAT items that contained shared wrong associations compared to the ones that did not. In the third experiment, we applied tACS at the individual alpha peak frequency (IAF) over the same brain regions of experiment 1, before, during, and after an alternative uses task, a classical divergent thinking task. We predicted that the right temporal alpha tACS would be associated with the generation of more remote ideas. In the fourth experiment, by recording EEG, we investigated the IAF power during the alternative uses task. We predicted that more remote ideas would be associated with higher individual alpha power compared to less remote ideas. Therefore, across all four experiments, our common binding hypothesis was that the right temporal alpha oscillations play a key role in
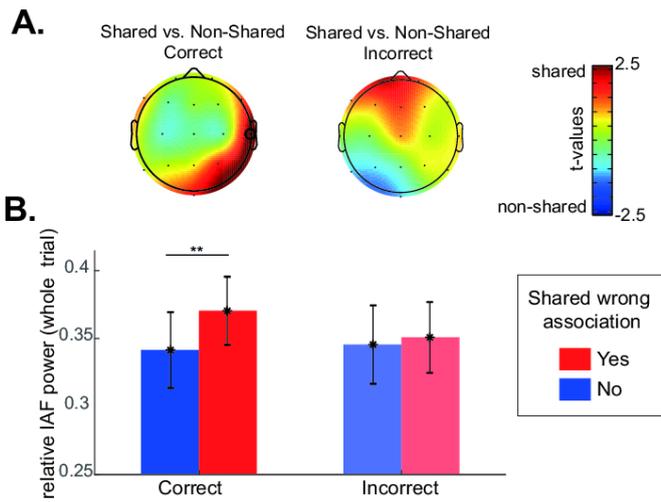
Fig. 3. Individual alpha power during remote associate items with and without wrong shared associations.A. Topographical distribution of the differences represented as t-values in the relative individual alpha power (IAF, log10); **B.** Average relative individual alpha power (IAF, log10) at the right temporal electrode (highlighted in A) averaged over the whole trial, separately for correct and incorrect responses in RAT items with shared wrong associations (red) and without (blue). * $p < .050$, ** $p < .025$, *** $p < .001$.

creative cognition, by inhibiting the obvious semantic associations which can pave the way to more remote and creative ideas.

Experiment 1

Mednick's remote associate task, (RAT, 1, 23) is a typical convergent thinking task which emphasizes the importance of association of remote concepts in creative cognition. In the RAT's compound-word version (24), participants are presented with three cue words (e.g., walker/main/sweeper*)* and are asked to find a solution or target word which makes a compound word with each of these three words (e.g., solution is street: streetwalker/main-street/street-sweeper*)*. People tend to seek the solution word by searching in the pool of semantically related words to the presented cues (25-27). However, there is a trap in this habitual thinking; when two cue words have close semantic association with a word that is not the correct solution, this can get in the way of the true solution, thereby acting as an important distractor which attracts internal attention (6). For example, the two cues (ear and tone) of the RAT item ear/tone/finger share a dominant but misleading association (sound), which needs to be inhibited in order to reach the solution (ring). In contrary, the cues of the RAT item high/teacher/mate (solution: school) do not share any strong common association. The ability to inhibit the most obvious but misleading semantic association is therefore of particular benefit for solving difficult remote associate problems (28), and more creative individuals are found to successfully avoid most common but incorrect candidate solutions (6). Yet, the neural mechanism underlying this process of inhibiting the habitual, most obvious associations and promoting the remote, less dominant associations during creative problem solving has largely been uncharacterized.

Considering that right temporal alpha oscillations have been consistently found to be involved in the insightful solutions of these problems (15-17) and in coming up with original ideas (11, 13), we tested the role of alpha oscillations in the temporal regions (right, left, sham). By stimulating alpha oscillations through tACS during the RAT, we tested whether alpha oscillations are involved in establishing weak or distant associations or in helping to inhibit dominant, but misleading, semantic associations. tACS can be used to modulate brain oscillations in a frequency-specific manner (e.g. 29), and is a powerful tool to examine the role of

cortical oscillations in human behaviour by directly manipulating brain states in a controlled fashion. Considering the key role of alpha oscillations in the active inhibition of distractions (8, 9), we predicted that, rather than boosting creative problem solving in general, right temporal alpha would be specifically involved in inhibiting the most obvious associations.

Results

Using a large dataset of semantic associations (30, 31), we considered the RAT items as having a "shared wrong association" if two out of the three cues were strongly associated with a word which was not the solution (see *Materials and Methods)*. Thirty participants received right, left temporal and sham 10 Hz tACS in three separate sessions while solving RAT items with or without shared wrong semantic associations. We entered the proportion of correct solutions to those problems in a 2 (*shared wrong association*: yes vs. no) x 3 (*stimulation condition*: left, sham, right tACS) within-subjects ANOVA. The results (Fig. 1A) revealed a significant effect of *stimulation condition* ($F_{(2,28)} = 4.52, p = .015$, $\eta^2 = .139$). Importantly, we observed a significant interaction between *shared wrong association* and *stimulation condition* ($F_{(2,28)} = 3.22, p = .047, \eta^2 = .10$), since the proportion of correct solutions was higher during right tACS compared to both sham ($t_{(28)} = 2.27, p = .031$, *Cohen's d = .450*) and left tACS ($t_{(28)} = 2.99, p = .006$, *Cohen's d = .555*) only for the RAT items with shared wrong associations; there was no significant difference between these conditions for the items without shared wrong associations ($p > .2$). There was no difference between left tACS and sham for either shared or non-shared items ($p > .2$). Unsurprisingly, there was a significant main effect for *shared wrong association* ($F_{(1,28)} = 8.17, p = .008, \eta^2 = .226$) since the accuracy was expectedly higher for items which did not have a shared wrong association.

To compare how successful the stimulation was for each of the RAT items according to their semantic associations, we calculated the *relative efficacy index* for each RAT item (*Materials and Methods*) as the difference between the proportion of correct solutions in one condition (e.g., right tACS) and the average of the proportion of correct solutions in the other two conditions (e.g., sham and left tACS). Positive (negative) values of the index indicate a larger (smaller) proportion of correct solutions under a given stimulation/sham condition in relation to the average of the other two. The mean efficacy index for each condition is presented in Fig. 1B. A repeated-measures ANOVA with *stimulation condition* (left tACS, sham, right tACS) as a factor revealed that more RAT items were correctly solved during the right tACS stimulation compared to the left tACS and sham ($F_{(2,268)} = 3.593$, $p = .029, \eta^2 = .026$). Further, we observed a significant linear trend in solved RAT items from left, sham to right ($F_{(2,268)} = 6.04$, $p = .015, \eta^2 = .043$) tACS. Participants correctly solved more RAT items during right than during left stimulation ($p = .015$, *Cohen's d = .425*) and sham ($p = .029$, *Cohen's d = .381*), but there was no difference between left tACS and sham ($p = .612$).

Next, we probed whether the items with shared wrong associations were more likely to be solved during right tACS compared to left tACS and sham, and whether this effect was stronger on items with more shared wrong associations. The relative efficacy index was analysed in a 3 (*shared wrong association*: 0, 1, ≥ 2) x 3 (*stimulation condition*) mixed design ANOVA. We observed a significant main effect of *stimulation condition* ($F_{(2,242)} = 6.06, p = .002, \eta^2 = .052$), as well as a significant interaction between *stimulation condition* and *shared wrong association* ($F_{(4,242)} = 2.57$, $p = .038, \eta^2 = .041$). The effectiveness of right tACS increased with the number of shared wrong associations (Fig. 1C), whereas the opposite was true for left tACS (within-subject effects for the interaction between *stimulation condition* and *shared wrong association*: $F_{(2,121)} = 4.894, p = .009, \eta^2 = .075$). The right tACS
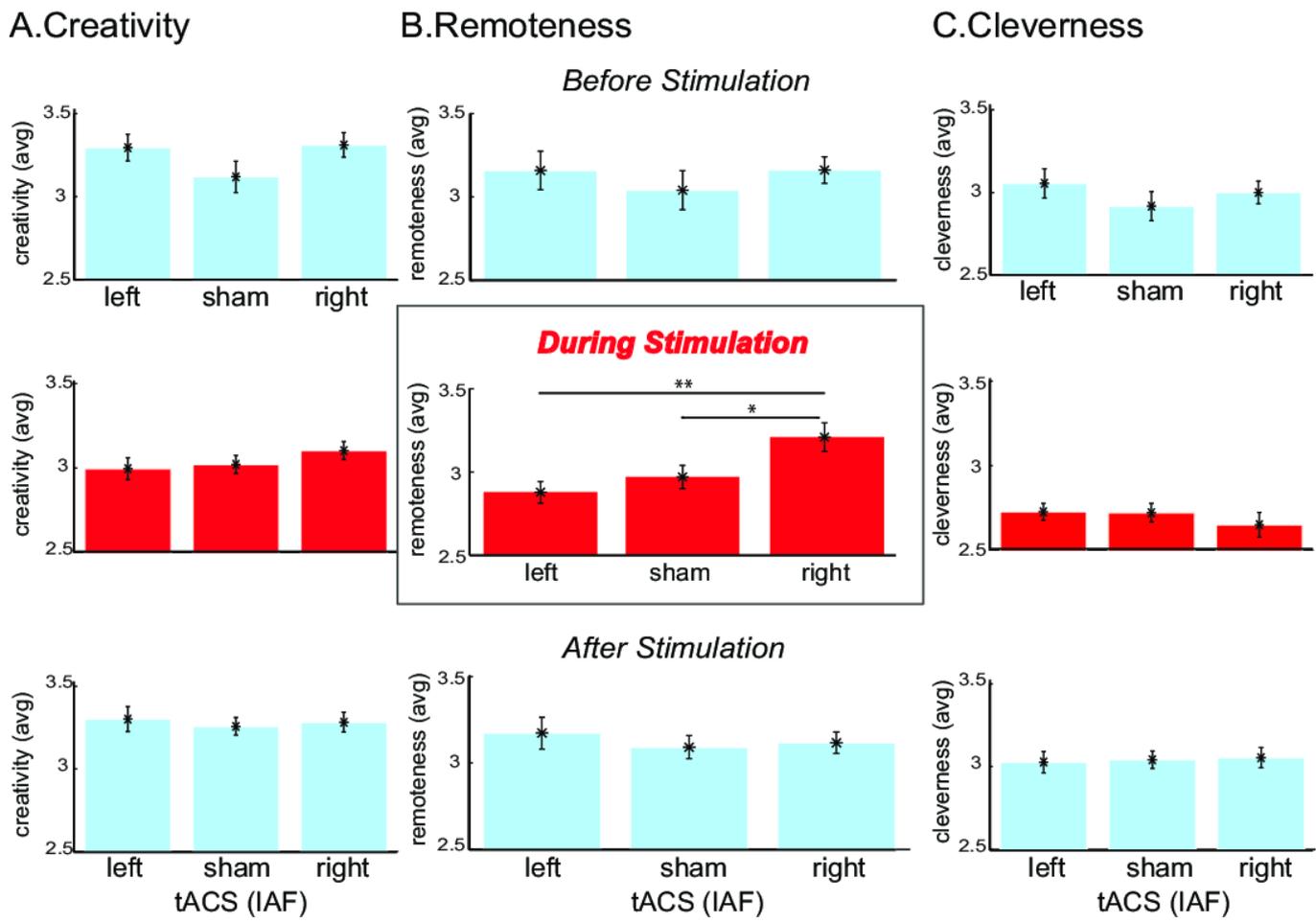
Fig. 4. Average ratings for AUT responses before, during, and after tACS (vs. sham). A. Averaged creativity ratings for items before (top - blue), during (middle - red), and after (bottom - blue) left, sham, and right IAF tACS. **B.** The same analysis as in A for the remoteness. **C.** The same analysis as in A and B for the cleverness ratings. The error bars represent +/- 1 S.E.M. *** $p < .001;$** $p < .01;$ * $p < .05.$
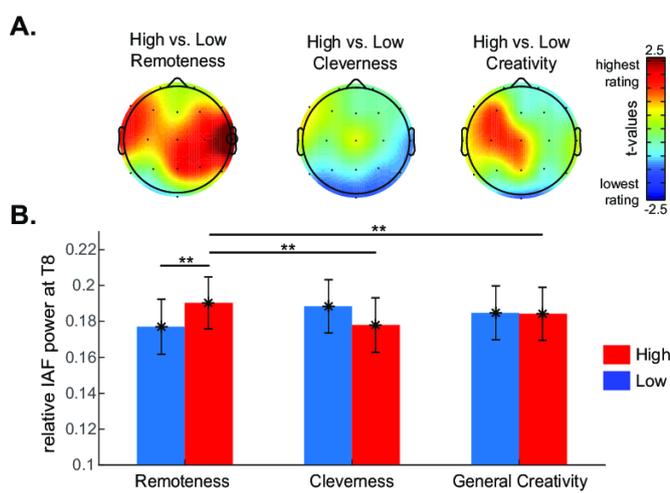

Fig. 5. Differences between AUT answers rated as high vs. low in three rating dimensions. A. Topographical distribution of the differences (paired *t*-tests) between IAF power during the generation of ideas which were rated as high (above the median) vs. low (below the median) in remoteness, cleverness and general creativity. **B.** Mean and variability of IAF power at the right temporal electrode T8 during the generation of ideas rated as high and low in the three criteria. The error bars represent +/- 1 S.E.M. *** $p < .001;$ ** $p < .01;$ * $p < .05.$

efficacy was higher on RAT items with 2 or more associations as evidenced by a large effect size (≥ 2 vs. zero) shared wrong associations: *Cohen's d* = .848, CI: .811 to .886, $t_{(73)}$ = 4.59, $p < .001$). Sham stimulation efficacy was independent of the items' semantic associations ($p > .3$).

Experiment 2

The second experiment was designed to investigate the role of alpha oscillations in inhibiting strong misleading associations in a new group of participants. Based on the semantic analysis we performed for Experiment 1, we selected a set of 45 RAT items, which share a misleading semantic association, and another set of 45 RAT items, which do not. Of note, these two sets were matched for difficulty based on the performance accuracy in Experiment 1. We conducted an EEG study comparing individual alpha frequency (IAF) oscillatory power in response to RAT items containing shared vs. non-shared associations. This experiment was also designed to analyse the frequency and spatial specificity of the differences between shared vs. non-shared RAT items. We hypothesized that, in order to solve RAT items with a shared wrong association, participants would need to actively inhibit the prominent, but incorrect association in order to reach the desired solution. Therefore, on the neural level, we predicted that RAT items with shared wrong associations would elicit stronger right temporal IAF power compared to the non-shared RAT items. Further, correct responses to shared items was predicted to be associated with higher IAF power than incorrect responses, due to successful inhibition of the wrong association. At the behavioural

level, we predicted that shared RAT items would induce a higher rate of false alarms (incorrect responses), as suggested by others (6, 32).

Results

Fig. 2A shows the proportion of correct solutions with or without shared wrong association; no difference between the two was observed ($t_{(56)} = -1.041, p = .302$, *Cohen's d* = .138), showing that the shared and non-shared categories are matched for difficulty as expected since the two sets of items (shared and non-shared) were earlier matched for accuracy. Fig. 2B shows the proportion of incorrect solutions for the two types of RAT items; as predicted, the participants made more mistakes on items with shared wrong associations compared to non-shared (paired *t*-test: $t_{(56)} = -3.756$, $p < .001$, *Cohen's d* = .498), suggesting that shared items induced more false alarms compared to non-shared items. Fig. 2C shows the proportion of no responses or time-out trials; a paired *t*-test revealed that participants tended to answer more to the items with shared associations ($t_{(56)} = 3.865, p < .001$, *Cohen's d* = .512), which is not surprising since misleading associations might cause the participants to provide the associate word as a solution.

For EEG data, we compared relative power of the individual alpha frequency (IAF) in response to RAT with vs. without shared wrong associations for correct and incorrect solutions (Fig. 3A). IAF power values were analysed by a three-way repeated measures ANOVA with *shared wrong association* (yes, no), *accuracy* (correct, incorrect) and *ROI* (right frontal: RF, left frontal: LF, right temporal: RT, left temporal: LT, right parietal: RP, left parietal: LP, mid-central: MC) as factors. We found that IAF power was higher for shared compared to non-shared items but the effect was dependent on the ROI (interaction between *shared wrong association and ROI*: $F_{(6,246)} = 3.775, p = .001, \eta^2 = .084$), and a three-way interaction between *shared wrong association, ROI,* and *accuracy* ($F_{(6,246)} = 2.251, p = .039, \eta^2 = .052$). There was no main effect for *accuracy* ($F_{(1,41)} = 2.432, p = .127, \eta^2 = .056$) nor *shared wrong association* alone ($F_{(1,41)} = .185, p = .669, \eta^2 = .005$), neither interactions between the two ($F_{(1,41)} = .431, p = .515, \eta^2 = .010$), indicating that the effects of shared wrong associations on alpha power was specific to the ROIs and dependent on whether the item was solved correctly. To investigate the interaction further, we compared alpha power between shared and non-shared on each of these ROIs (*t*-maps shown on Fig.3A). We observed that for correctly solved trials, individualised frequency alpha power was higher when the participants were solving shared compared to non-shared items (*RT:* $t_{(41)} = 2.685, p = .010$, *Cohen's d* = .416). IAF power at the right temporo-parietal electrode was also higher during RAT items with shared associations ($t_{(41)} = 2.395, p = .021$, *Cohen's d* = .369), but not at the right parietal region (*RP:* $t_{(41)} = 1.904, p = .064$, *Cohen's d* = .293, see methods for ROI definition).

In order to investigate whether this effect was specific to alpha oscillation, we conducted the same analysis on the average power over alpha band power (8-12 Hz) and also over the traditional frequency bands, including theta (4-8 Hz), beta (13-30 Hz) and gamma (30-40 Hz). The results showed that the effects were non-significant in other frequency bands ($p > .05$) except for the alpha frequency band in which we observed similar effects compared to the IAF (see SI Appendix, *Fig. S2*).

Experiment 3

Experiments 1 and 2 focused on investigating the role of alpha oscillations in inhibiting strong associations in a RAT task. However, if right temporal alpha oscillations are indeed associated with the inhibition of obvious associations in general, we expected that they would also promote more remote responses in other tasks involving creative cognition. Therefore, we conducted a third experiment to investigate the effects of right temporal tACS on the alternative uses task (33), a commonly employed

measure of divergent thinking, i.e. capacity to generate a number of original ideas. A new sample of participants was asked to generate alternative uses to commonly used objects whilst receiving either sham, left or right temporal tACS at their individual alpha frequency (IAF, see *Materials and Methods*) based on their resting state EEG.

Three raters, blind to the conditions (double blinded), rated each response for general creativity, remoteness, and cleverness. The ratings were based on items generated before, during, and after tACS (left, sham, and right IAF). We tested each period separately because the objects used during the stimulation were different (*Materials and Methods*). As the effects of tACS are mainly limited to the stimulation period, we expected that the effects of right IAF tACS would be significant during stimulation. For each participant, we calculated the average fluency (number of non-obvious responses) and the average ratings for general creativity, remoteness, and cleverness (see *Materials and Methods*). Since we expected the effects to be most significant for *remoteness* ratings, we analysed each rating separately by a one-way ANOVA with *stimulation condition* as a within-subjects factor. We predicted that the participants would come up with more remote responses during the right temporal alpha stimulation. We did not run a mixed ANOVA due to the fact that the items in the pre- and post-were counterbalanced but the items during the stimulation were always the same (see *Materials and Methods* for more details).

Results

First, we observed no significant differences between groups in the pre-test for any of the measures, including fluency ($F_{(2,33)} = .38, p = .688$), general creativity ($F_{(2,33)} = 1.66, p = .206$), remoteness ($F_{(2,33)} = .42, p = .663$), and cleverness ($F_{(2,33)} = .73, p = .489$), suggesting no pre-existing differences between groups. Second, during tACS, we observed, as predicted, a significant effect of *stimulation condition* on the remoteness of the uses ($F_{(2,33)} = 5.27, p = .010$, *partial* $\eta^2 = .24$), but not on their general creativity ($F_{(2,33)} = .94, p = .401$, *partial* $\eta^2 = .054$), *fluency* ($F_{(2,33)} = .89, p = .421$, *partial* $\eta^2 = .051$), or cleverness ($F_{(2,33)} = .48, p = .623$, *partial* $\eta^2 = .028$). Post-hoc contrasts revealed that the right IAF tACS group came up with significantly more remote items compared to both left IAF tACS ($p = .003$, *Cohen's d* = 1.3, *C.I.* = 1.18-1.39) and sham ($p = .030$, *Cohen's d* = 0.92, *C.I.* = 0.82-1.03) groups (Fig. 4). There was no significant difference between sham and left IAF tACS ($p = .385$). Third, we observed that these effects vanished in the post-test period (i.e. after stimulation had ended) as there was no difference between groups in relation to the remoteness of the ideas ($F_{(2,33)} = .33, p = .724$, *partial* $\eta^2 = .019$), nor in any other measure including fluency ($F_{(2,33)} = .80, p = .458$, *partial* $\eta^2 = .046$), general creativity ($F_{(2,33)} = .129, p = .879$, *partial* $\eta^2 = .008$), and cleverness ($F_{(2,33)} = .46, p = .955$, *partial* $\eta^2 = .003$).

Experiment 4

In experiment 3, we demonstrated that stimulating right temporal alpha at the IAF is associated with an increase in remoteness of the items generated during a divergent thinking task. Since the stimulation was delivered during the task, we tested whether IAF would be higher for more remote items. In order to address this question, we measured EEG while a new sample of participants generated a number of different ideas in an alternative uses task (AUT). We measured power at each participant's individual alpha frequency peak (IAF) during the generation of each separate idea. All responses were judged by raters blind to the experimental conditions (see *Materials and Methods*).

Results

We compared IAF power on trials with average ratings above (high) or below (low) the median using a 3 (*rating type:* remoteness, cleverness, general creativity) x 2 (*performance:* high vs. low*)* x 7 (*ROI:* LF, LT, LP, ML, RF, RT, RP) within-subjects ANOVA. We observed a significant three-way interaction between *rating type*, *performance*, and ROI ($F_{(12,1476)} = 2.030$, $p = .019$, *partial* $\eta^2 = .020$) since we only observed significant differences in IAF between high and low remoteness ratings. To investigate the interaction further, we run additional 2 (*performance:* high vs. low) x 7 (*ROI:* LF, LT, LP, ML, RF, RT, RP) ANOVAs per rating type. We observed a significant interaction between *performance* and *ROI* only for remoteness ratings ($F_{(6,774)} = 3.454$, $p = .002$, *partial* $\eta^2 = .026$), but not for cleverness ($F_{(6,774)} = 1.349$, $p = .233$, *partial* $\eta^2 = .010$) or for general creativity ($F_{(6,774)} = 0.738$, $p = .619$, *partial* $\eta^2 = .006$). The topography of the differences between high and low performance on each rating (Fig.4) provides evidence that the differences between items with high vs. low remoteness peaked at the right temporal electrode ($t_{(123)} = 2.756$, $p = .007$, *Cohen's d* = .247). There was no statistically significant difference in IAF power between high and low performance on cleverness and general creativity in any of the ROIs (all contrasts $p > .1$). Furthermore, there was no main effect of *rating performance* ($F_{(1,123)} = .092$, $p = .762$, *partial* $\eta^2 = .001$), indicating that the differences were not a result of a better performance in general. We conducted the same analysis in the traditional frequency bands (theta: 4-8Hz, alpha: 8-12 Hz, beta:12-30 Hz, and gamma: 30-40 Hz), but observed no significant three-way interaction in any of them nor a main effect of rating performance (for more details of the analysis and the topoplots of the contrasts, see SI Appendix).

Discussion

In this paper we provide evidence supporting the role of right temporal alpha oscillations in creative cognition. We suggest that alpha oscillations in the right temporal brain region shapes inhibition of the most common or obvious associations. We presented evidence in support of this hypothesis in four separate experiments. In our first experiment, we observed that right temporal alpha tACS was most beneficial for those RAT items that required participants to override prominent but wrong candidate solutions, indicating that right temporal alpha oscillations play a critical role in the ability to override habitual, but misleading, associations. In a second experiment, we observed higher right temporal alpha power while the subjects were trying to solve RAT items with shared wrong associations. In a third experiment, we observed that the right temporal tACS at the IAF was associated with an increase in remoteness of uses in an alternative uses task, but not in cleverness or general creativity. In a fourth experiment, we observed that the participants showed higher right temporal alpha activity (IAF) when they were generating items with higher as compared to lower remoteness. Altogether, our results provided robust evidence supporting the hypothesis that right temporal alpha oscillations are involved in actively inhibiting strong semantic associations, in both convergent and divergent thinking tasks. In the remainder of this discussion, we consider the principal ways our findings critically advance our understanding on the role of alpha oscillations on creative cognition, its neurophysiological mechanisms and the limitations in our approach.

First, our findings support the hypothesis that right lateralized alpha is a core feature of creative cognition, which might underlie our capacity to override strong semantic associations that are shaped by prior experience. Our results also support the hypothesis that exploration is mediated through active inhibition. This idea was put forward by Baror & Bar (7) who observed that when the cognitive load was high, participants tended to fail in supressing stronger semantic associations. Alpha oscillations have earlier been linked to the process of active inhibition (34): they do not merely signalise idle activity, but an energy consuming suppression process. Our study provides the first evidence suggesting that right temporal alpha oscillations may be critical to the inhibition of strong semantic associations.

Second, our results shed new light on our understanding of both convergent and divergent creativity. Although the neuroscience of creativity has shown some inconsistent results in relation to its neural mechanisms (35), most of the EEG research on the topic showed a robust association between alpha oscillations and creativity both during task and at rest (for a review see: 11). This involvement with alpha oscillations is evident in a number of studies showing increases in right hemispheric alpha during creative ideation (12, 13, 36-38). For example, alpha oscillations increase over the right hemisphere during idea generation and this increase is higher for more creative ideas (13). Higher alpha oscillations are also predictive of cognitive insight (17). Furthermore, right hemispheric alpha power previous to a hint presentation in an RAT task was predictive of whether the participants would successfully use the hint to correctly solve the problem (16). These studies, though informative, have no control over how much the RAT items or specific tasks required the participants to override immediate semantic associations, yet this process is crucial in both divergent and convergent creative problem solving (39). For instance, if we need to generate alternative uses of a glass, first we must inhibit our past experience leading to think of a glass as a container. Our study is the first (to our knowledge) to demonstrate that right temporal alpha oscillations is linked with overriding these strong associations in both convergent and divergent thinking.

Third, by providing a fine-grained analysis of two well-known creativity tasks (RAT and AUT), we offer a new approach for the investigation of higher order cognition and how it links to more basic neurophysiological processes. For instance, our findings support the account that right hemispheric alpha is involved in inhibiting common or more obvious associations which might get on the way of generating non-obvious creative solutions, i.e. remote associations. We provide evidence that inhibiting wrong semantic associations can be facilitated by alpha tACS on the right, but not left, temporal area. Previous tACS work (14) showed a general effect of frontal alpha (F3, F4 and Cz) on creativity, which could be related to general top-down mechanisms necessary to complete the task rather than specific cognitive processes associated with higher originality of the responses. This is consistent with a previous EEG study (12) showing that both convergent and divergent creativity were associated with higher prefrontal alpha oscillations when these tasks are done under higher internal attentional demand. It is possible that alpha oscillatory activity could represent different processes depending on the brain regions they occur during creative ideation.

Alpha synchronization is known to represent a process of heightened attention by blocking both external and internal distractions, which is necessary for creativity and consistent with the role of alpha oscillations in active inhibition of distractions (8, 9). Previous studies showed that higher alpha-band power is associated with the suppression of distracting information in both working memory (e.g. 10) and attentional tasks (e.g. 40). For creative cognition, we suggest prominent associations between two cues (i.e. wrong candidate solutions) or between an object and its common use need to be inhibited in order to reach more remote ones. Our findings suggest that this inhibitory process is stronger in the right temporal area, which is a key region for processing semantic associations (18, 19, 21, 22). This is relevant since here we show the role of alpha oscillations in a task-relevant area. Considering that alpha oscillations were found to coordinate the timing of the action potentials (41), it has been suggested

(42) that higher alpha frequency power leads to more precise timing of neuronal activity, and therefore reflects the temporal structure for the processes controlling the access to information stored in complex knowledge systems. Selective access to higher order information would depend on inhibiting task-irrelevant memory entries. In our study, both tasks required semantic search for remote associations that might be facilitated by sustained inhibition of stronger associations, which could be considered as task-irrelevant memories. According to Klimesh, Sauseng, & Hanslmayr (42), higher alpha amplitude in task-relevant areas promote inhibition by silencing weakly excited cells inducing a pulsed pattern of action potentials in cells with higher excitation level (threshold), a process which would increase the signal-to-noise ratio in the region, shaping the access to the knowledge systems. Here we speculate that the inhibition of the obvious associations requires a similar tuning of semantic association brain regions. We suggest future studies to combine EEG and fMRI to investigate how alpha oscillations shape the inhibition of the semantic association networks as in our study, we did not have enough spatial resolution to understand the anatomo-functional substrates of this process. It is important to notice that the strongest effects were observed in the individual alpha frequency which we measured based on the peak power at the right temporal region. Although the effects were similar in the traditional alpha frequency band and also pronounced when we stimulated at 10Hz, we cannot rule out that different findings could have emerged if we had compared the conditions using the individual alpha frequency of other regions or stimulated other regions at their own individual peak frequencies.

In summary, we provided robust evidence that the right temporal alpha oscillations play a critical role in the ability to override habitual, but misleading, associations during creative problem solving. 'Taking a less travelled path' is often considered an effective path to creativity (i.e. creative thinking calls for a break from habitual thinking and associations), and our findings support that the underlying cognitive mechanisms are served by the temporal alpha oscillations. In order to understand the processes underlying the production of novel and adequate ideas, we need to break down its constituent processes, dissecting creativity as much as possible at first, and then analyzing them in context, putting them back together through careful consilience.

Materials and Methods

All participants across four experiments gave written informed consent before the beginning of each experiment. The study protocols of experiments 1 and 3 were approved by the local ethics committee at Goldsmiths, University of London. The study protocols of experiments 2 and 4 were approved by the local ethics committee at Queen Mary University of London. All experiments were conducted in accordance with the World Declaration of Helsinki (1964).

Experiment 1

Participants. Thirty (15 females) right-handed participants was recruited from the student population at Goldsmiths, University of London. Participants received course credit or monetary reimbursement at a rate of £10 per hour. Exclusion criteria were: a personal or family history of epilepsy and/or neuropsychiatric disorders, pregnancy and the presence of any metallic or medical implants. Participants were also excluded if they took any recreational drugs within the past month or consumed any alcohol within 24 hours preceding each experimental session. One participant took part in another experiment on RAT prior to completing this study, and was excluded from analysis. The final sample (n = 29) was aged between 18-46 years (24.6 ± 5.9 years; Mean ± SD).

Experimental design and task. A counter-balanced, within-participants design was adopted; participants attended three separate stimulation sessions in three different days with an inter-session interval of 7 days. In each session, participants completed a computerised version of the compound word version (24) of the remote associate task (1, 23) under one of three online tACS stimulation conditions – 10 Hz right temporal, 10 Hz left temporal, and sham stimulation. Participants were blind to the condition. On each RAT trial (SI, Fig. S1A), participants were shown three cue words (e.g., line/house/palm), and had to come up with the solution word (tree), which would form a valid compound word with each of the three cue words (treeline, treehouse, palm-tree). The solution word can be joined either at the beginning or end of the cue words, and the resultant compound word may be one that would be written as one word, or as two separate words

(with or without a hyphen). There were 45 trials per stimulation condition (counterbalanced, see *SI Materials and methods* for details).

Semantic Word Association. We extracted the word association measures based on the largest database for word associations (30, 31), available online at http://www.smallworldofwords.com/new/visualize/#. This database draws word associations based on a large corpus of English words (12000 English words, with over 70000 participants) and was built based on primed associations by asking participants to give the strongest three associated words for a given word (31). For each cue and solution word of each RAT item (i.e. triplet or triad), we checked the top 20 associated words as listed in the database. To observe if there was a shared wrong association, we looked into the first 20 associated words for each cue and found whether the cues shared a same word as top association. Subsequently, we classified the RAT items according to whether or not they shared a wrong candidate solution (yes = 59/ no = 65). Two additional measures (cue-solution and solution-cue association) were also employed as a control measure (see SI methods and SI additional analyses).

Transcranial Alternating Current Stimulation (tACS). Transcranial alternating current stimulation (tACS) was delivered using a Neuroconn DC-Plus Stimulator, a constant current device (NeuroConn Ltd., Ilmenau, Germany). Electrodes were positioned based on the international 10-20 EEG electrode placement system, with one electrode (5cm x 7cm) positioned over the vertex (Cz), and the target electrode (5cm x 5cm) positioned over either the left (T7) or right (T8) anterior temporal lobe, depending on the stimulation condition (Fig. S1B). In each session, a 10 Hz sinusoidal current (1 mA peak-to-peak), with a zero-degree phase offset and no DC offset, was delivered via two saline soaked sponge-covered rubber electrodes, attached to participants' scalps with rubber head straps. The current was ramped up and down over 10 seconds at the beginning and end of stimulation. In both active stimulation sessions, participants received 30 minutes of online stimulation. For the sham condition, the stimulation was delivered for just 30 seconds at the start and the current was subsequently ramped down and remained off for the remainder of the session. In both active sessions, stimulation began five minutes prior to commencement of the experimental task, and then continued for the subsequent 25 minutes during which participants completed the computerised RAT. Across all sessions, electrode impedance was kept below 20 kΩ throughout.

Data analysis. We calculated the accuracy as the percentage of correct solutions for each participant in each condition. To quantify the effectiveness of a stimulation condition on individual RAT item performance, we calculated an index, termed as the relative efficacy index, which was the difference between the proportion of correct solutions for the stimulation condition (e.g., right tACS) and the average of the proportion of correct solution for the other two conditions (left tACS and sham).

Experiment 2

Participants. Sixty-two neurologically healthy adults (39 female) aged between 18 and 27 years (20.47 ± .25 years: mean ± SD) took part in this experiment. All participants were native speakers of English and right-handed (self-reported). Three participants were excluded due to technical problems (computer crashed at the end - data was not recorded), and two more due to poor performance (less than 10 correct responses), resulting in 57 participants used for the behavioural analysis. For the EEG analysis, 5 participants were further excluded due to noisy EEG recording (coughing, muscle artifacts) resulting in a total of 52 participants (5 excluded due to behavioural data and 5 due to poor EEG quality). Because we focused on the comparisons between items with vs. without shared associations which were correctly responded (vs. incorrect), we included in the analysis only participants who had at least 5 valid trials in each condition, resulting in a total number of 42 participants. All participants received a monetary compensation of £10/hour for their participation.

Experimental task and procedures. The task was identical to the one in experiment 1 (Fig. S1A) except that there were 90 RAT items in total. There were 45 items with 1 or 2 shared wrong associations, and 45 items with no shared associations (see Experiment 1). We selected these 90 items strategically by excluding items that presented ceiling (>90% correct) or floor (< 10% correct) effects in order to control for difficulty. Further, two categories were matched for difficulty (p > .05, i.e. no significant differences between the accuracy of the shared vs. nonshared items based on participants' performance in experiment 1). The presentation order of RAT items was randomised across participants.

EEG recording and analysis. The EEG was recorded using a Starstim 20 (Neuroelectrics, Spain) and preprocessed according to standard procedures (see SI Materials and Methods). To compute the time-frequency representation (TFR), the EEG signal (entire duration from stimulus presentation to response) was convolved with a complex Morlet wavelet on a trial-by-trial basis. The TFR was calculated from 2 to 40 Hz, in steps of 0.5 Hz, using 6-cycle wavelets. The TFR values were averaged for each of the four conditions - correct shared, correct non-shared, incorrect shared, and incorrect non-shared - for each participant over the whole epoch and also from 0 to 1 second after stimulus presentation. The individual alpha frequency (IAF) was calculated as the frequency with the highest power from 8 to 12 Hz at the right temporal electrode (T8). The mean IAF was 10.02 (SD = 1.05).

Data analysis. For behavioural data, we compared the proportion of correct and incorrect (false alarms) responses, reaction times and insight

ratings of each participant, for shared vs. non-shared items. For EEG data, we compared brain responses to shared and non-shared RAT items separately for correct and incorrect solutions; time-out trials were excluded from future analysis. Spectral power in each frequency immediately following the RAT item presentation (whole trial and also 0 to 1s) was log-transformed (base 10) due to its positively skewed distribution and divided by the total power (2 to 40 Hz). Therefore, we analysed relative power in each frequency band: theta (4-8 Hz), alpha (8-12 Hz), beta (12-30 Hz) and gamma (30-40 Hz), as well as the IAF, defined as the frequency with the highest power from 8 to 12 Hz (+/- 2 Hz).

Experiment 3

Participants. Thirty-six participants aged between 19 and 35 years (23.9 ± 4.45 years; Mean ± SD) took part in this study in exchange for course credit or a monetary reimbursement at £10/hr. Participants were randomly assigned to one of the three conditions: left, sham, and right tACS. There were no differences between age and sex distribution between groups. Standard exclusion criteria were applied (the same criteria for Experiments 1 and 2).

Alternate Uses Task (AUT). In this divergent thinking task (Guildford, 1967), participants were asked to come up with unusual uses for an everyday object within a time period of 2 min per object. There were two sets, one containing 4 objects (*Set 1:* tin can, newspaper, spoon, baseball cap) and another containing 3 objects (*Set 2:* brick, shoe, cardboard box). The first set was used before and after the stimulation (2 objects each, counterbalanced across participants), and the second set was used during the stimulation (presented in random order). Additionally, in the post stimulation period, the objects presented in the before the stimulation were presented again, in order to check for changes in performance of the new versus old objects. The order of the objects was alternated (each subsequent participant started with a different order).

Creativity ratings. Responses were rated by three independent evaluators who were blind to the conditions and to the objectives of the experiment. We used the *Consensual Assessment Technique,* CAT (43), which is considered by some as the gold standard method for assessing creativity (44). CAT relies on intuitive ratings by two or more trained evaluators, and has been successfully used to evaluate creativity in previous studies (e.g. 45, 46). Ratings of creativity have been based on the idea that creativity depends on three core factors: uncommonness, remoteness, and cleverness (47, 48). According to the three-factor definition, uncommonness relates to how unique ideas are (inversely related to their frequency) whereas remoteness refers to how far the suggested use for an object is from its common or everyday use (49). Cleverness in this context refers to how insightful, ironic, humorous, fitting or smart a given use is. In order to investigate how alpha oscillatory activity relates to each of these processes, the judges provided ratings of all responses (presented in random order) on three attributes separately: (i) *general creativity*: how creative they felt that response was based on intuition and their own ideas of creativity; (ii) *remoteness:* how remote they thought that the idea was from the original use; (iii) *cleverness:* how clever or appropriate the idea was. We observed a reasonable agreement between the three raters (intra-class correlation: IC for the *general creativity* (IC = .67; CI: .64 - .70) and *remoteness* (IC = .70; CI: .68 - .72), and a slightly reduced agreement on the *cleverness* judgments (IC = .56; CI: .50 - .62). The ratings of three judges were z-scored (all responses, per object) and averaged for analysis.

EEG and tACS protocol. EEG was recorded before the brain stimulation session using a *StarStim* (Neuroelectrics, Spain) with 8 channels. The EEG was recorded at a sampling frequency of 500 Hz, referenced to the arithmetic average of the left and right mastoids, high-pass filtered at 1 Hz, and low-pass filtered at 45 Hz. Automatic artefact rejection was applied at ±85 μV. Power was estimated in each frequency from 1 to 45 Hz in steps of 0.5 Hz using Welch's Periodogram (50% overlap). For tACS, the stimulation frequency was set at the alpha peak frequency (largest power during eyes-closed resting period, from 8 to 12 Hz) at the stimulated region (left or right temporal) and the current was 1mA (peak to peak). For the sham group, half were stimulated (only ramp up) at the IAF on the left temporal and the other half at the right. The mean IAF for the left tACS group was 10.00 (SD = 0.64) and for the right tACS it was 9.99 (SD = 1.16). There was no significant difference in the IAF between the left and the right tACS groups ($t_{(22)}$ = .027, p = .979).

Procedures. At the beginning, participants were instructed to keep their eyes closed for a period of 3 minutes while their EEG were recorded; we estimated the IAF from this EEG recording. Subsequently, the participants responded to 2 practice items and carried on with the pre-test task. Following the pre-test, the EEG electrode corresponding to the stimulation condition (left or right) was replaced by a round rubber stimulation electrode (25 cm^2) soaked in saline solution. In each session, a sinusoidal current (1mA peak-to-peak) at the individual alpha peak frequency, with a zero-degree

phase offset and no DC offset, was delivered via two saline soaked sponge-covered rubber electrodes. One electrode was positioned on either T8 (right temporal) or T7 (left temporal) and the other was always positioned at Fz. During sham, half of the participants had the electrodes positioned at T8-Fz and the other half at T7-Fz. The participants were blind to the stimulation condition. The AUT started after 5 minutes of the start of the stimulation. The total duration of the stimulation was 25 minutes, during which the participants performed three AUT items and 2 figural creativity tasks (not analysed in this paper). Following the stimulation, the stimulation electrode (T7 or T8) was removed, the area was cleaned and the EEG electrodes were placed. The signal was visually inspected to assure good quality. The EEG was recorded immediately after the signal passed this check, including 3-minute eyes-closed and 3-minute eyes-open (fixating on a cross on the wall) recordings. Following the EEG, the participants completed the AUT and figural creativity tasks.

Experiment 4

Participants. One-hundred thirty participants (67 females) aged between 18 and 32 (21.2 ± 2.63 years: Mean ± SD) took part in this experiment in exchange for course credit or a monetary reimbursement at a rate of £7.5/h. The exclusion criteria were the same as in the previous experiments.

Alternate Uses Task (AUT). The experimental task was the same as in Experiment 3. The participants were presented with one object (e.g., table) and were asked to generate unusual uses for it within a 2-min time period. The participants were instructed to fixate at the centre of the screen while thinking and press a button to enter an idea. Once they typed and confirmed this idea, they kept generating other ideas until the 2 minutes were finished. In total, the participants were presented with 4 objects (table, shoe, tin-can, and umbrella) and provided an average of 25 ideas for all the objects (SD = 11.8, range: 2-67).

EEG recording and analysis. The EEG was recorded using a Starstim 20 (Neuroelectrics, Spain) and preprocessed according to standard procedures (see *SI*: Materials and Methods). The IAF was estimated as with procedures identical to experiments 2 and 3. For estimating the power spectrum during the generation of ideas in the AUT trials, we used the whole epoch, from the word to the button press (to type the response). We only used those epochs which contained more than 2 seconds of usable data. We estimated alpha power using Welch periodogram with 1s time-windows with an overlap of 50%. The spectrum was first estimated from 4 to 40 Hz in steps of 1 Hz. The IAF was defined as earlier as in experiment 2 and 3. The mean IAF was 9.73 (SD = 1.15). For normalization, we divided the power in the IAF adjusted band power (peak +/- 2 Hz) by the average power of the whole spectrum (4 to 40 Hz).

Creativity ratings. As in experiment 3, each response to the AUT was rated for general creativity, remoteness, and cleverness, on a scale from 0 (least) to 10 (most), as described in Experiment 3. Due to the large number of responses (130 participants – 4810 responses in total), 2 raters rated all responses related with 2 objects, and other 2 raters rated another two objects. Another 2 raters rated the entire pool of responses. The ratings were subsequently z-scored separately, per item and per rater. This procedure resulted in a good agreement (intra-class correlation) between raters for the creativity (α = .88), remoteness (α = .89) and cleverness (α = .84). This procedure resulted in an average of 12 ideas per condition (high and low), with the average idea (+/- SD) of 12.8 (SD=6) for high and 12.6 (SD = 5.88) for low remote, 12.8 (SD=5.9) for high and 12.7 (SD=5.9) for low cleverness, 12.8 for high (SD=6) and 12.6 (SD=5.9) for low creativity. There was no difference in the number of trials between any of the conditions (p > .8). However, because some participants had a low number of ideas, we conducted the main analysis using data of the participants who had a minimum of 5 ideas per condition (n = 124). Nonetheless, we present the analysis with all participants in the *SI*.

Data analysis. We compared the whole epoch alpha band power (IAF +/- 2 Hz) during the idea generation phase (or "thinking time"), i.e. when the subjects were engaged with generating ideas. For each participant, we selected the trials with ratings higher or lower than the median for each rating individually (remoteness, cleverness, general creativity). We calculated the relative alpha power (by dividing it by total power) on the individual alpha frequency band (as in Experiments 2 and 3) in the low vs. high rating trials of each subject.

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