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Identifying and Engaging Neuronal Oscillations by Transcranial Alternating Current Stimulation in Patients with Chronic Low Back Pain: A Randomized, Crossover, Double-Blind, Sham-Controlled Pilot Study

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Abstract

Chronic pain is associated with maladaptive reorganization of the central nervous system. Recent studies have suggested that disorganization of large-scale electrical brain activity patterns such as neuronal network oscillations in the thalamo-cortical system plays a key role in the pathophysiology of chronic pain. Yet, little is known about if and how such network pathologies can be targeted with non-invasive brain stimulation as a non-pharmacological treatment option. We hypothesized that alpha oscillations, a prominent thalamo-cortical activity pattern in the human brain, are impaired in chronic pain and can be modulated with transcranial alternating current

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Author contributions

F.F., J.H.P., and K.L.M. designed the study. S.A. designed the EEG task. J.H.P. and M.L.A. performed the study. S.A. analyzed the data. S.A. and F.F. wrote the manuscript and all authors contributed to editing the manuscript.

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stimulation (tACS). We performed a randomized, crossover, double-blind, sham-controlled study in patients with chronic low back pain (CLBP) to investigate how alpha oscillations relate to pain symptoms for target identification and if tACS can engage this target and thereby induce pain relief. We used high-density electroencephalography to measure alpha oscillations and found that the oscillation strength in the somatosensory region at baseline before stimulation was negatively correlated with pain symptoms. Stimulation with alpha-tACS compared to sham (placebo) stimulation significantly enhanced alpha oscillations in the somatosensory region. The stimulation-induced increase of alpha oscillations in the somatosensory region was correlated with pain relief. Given these findings of successful target identification and engagement, we propose that modulating alpha oscillations with tACS may represent a target-specific, non-pharmacological treatment approach for CLBP. This trial has been registered in ClinicalTrials.gov (NCT03243084).

Perspective

This study suggests that a rational design of transcranial alternating current stimulation, which is target identification, engagement, and validation, could be a non-pharmacological treatment approach for patients with chronic low back pain.

Keywords

chronic low back pain; electroencephalography; alpha oscillations; transcranial alternating current stimulation

Introduction

Chronic pain is associated with pathological changes in neuronal activity over somatosensory, insular, cingulate, and prefrontal cortices⁴⁶. These brain regions play a fundamental role in the processing of pain^{32,51,57}. Several electroencephalography (EEG) and magnetoencephalography (MEG) studies have shown that patients with chronic pain exhibit abnormal neuronal oscillations^{43,55}. In particular, pathologically increased theta oscillations (4–8Hz)^{34,48,49,53,58} have motivated a conceptual framework of thalamo-cortical dysrhythmia (TCD) in chronic pain^{33,34}. Moreover, the peak frequency of neuronal oscillations measured by EEG and MEG appears lower in patients with chronic pain when compared to healthy control participants^{48,49,53,56,58}. Thus, these findings imply that identifying the relationship between neurophysiological changes and pain severity and engaging the identified target could represent a network-level approach to understand a causal role of chronic pain. Yet, little is known about if and how such network pathologies can be modulated with targeted non-invasive brain stimulation in patients with chronic pain.

Here, we performed a randomized, crossover, double-blind, sham-controlled clinical trial to investigate how non-invasive brain stimulation can target neuronal oscillations in patients with chronic pain. We chose to investigate target identification and engagement of neuronal oscillations in a sample of patients with chronic low back pain (CLBP), which is the single leading cause of disability worldwide²². We built a model of bifrontal montage to target and modulate the bilateral somatosensory cortex in patients with CLBP since previous studies have shown that abnormal neuronal oscillations in the somatosensory cortex reflect pain

perception^{13,20,45,46,60}. In addition, previous brain stimulation approaches such as deep brain stimulation and repetitive transcranial magnetic stimulation (rTMS) successfully reduced pain severity^{6,31,47}. Inspired by these successful approaches and the fundamental role of somatosensory cortex in pain, we built a model bifrontal montage to target the somatosensory cortex.

We formulated two hypotheses in our study. First, patients with CBP exhibit impaired alpha oscillations. This hypothesis is based on previous findings that pain perception suppresses alpha oscillations^{23,24,45} and the suppression is correlated with pain severity^{7,9,25,40,52}. Second, transcranial alternating current stimulation (tACS), which is a non-invasive brain stimulation tool that can modulate neuronal oscillations by applying oscillating electrical currents^{21,54}, can enhance alpha oscillations in the somatosensory cortex and thereby induce pain relief. We recorded alpha oscillations by high-density EEG to investigate the hypothesized association of alpha oscillations with pain severity in patients with CLBP and applied 10Hz-tACS based on the identified target region. We assessed two rating scales for pain severity and perceived disability due to chronic low back pain. We found that alpha oscillations in the somatosensory region were negatively correlated with pain severity. Furthermore, 10Hz-tACS applied in the somatosensory region enhanced alpha oscillations and the enhancement correlated with pain relief. Our findings of successful target identification and engagement with tACS suggests that applying non-invasive brain stimulation to modulate neuronal oscillations may be a non-pharmacological tool to treat CLBP.

Methods

Participants

Both male and female participants (age 18 to 65) were recruited from local pain and physical therapy clinics in Chapel Hill, NC area. Inclusion criteria consisted of a diagnosis of chronic back pain by a licensed clinician, pain severity ≥ 3 on a 0–10 numerical pain rating scale¹¹, and duration of chronic low back pain for at least five months. (Table 1). All participants signed a consent form. Eligibility of participants was determined by a telephone screening before the first session. Twenty participants participated in two sessions (10Hz-tACS and sham) separated by 1–3 weeks and intervention sequence was randomized and balanced across all participants. Randomization was performed using sequentially numbered assignment. One of the authors (J.H.P) generated the random allocation sequence, enrolled all participants, and assigned the participants to the sequence.

Study design

We performed a randomized, crossover, double-blind, sham-controlled, clinical trial with two stimulation conditions (10Hz-tACS and sham). The study was performed at the University of North Carolina at Chapel Hill (ClinicalTrials.gov, NCT03243084) and approved by the Biomedical Institutional Review Board of the University of North Carolina at Chapel Hill. Behavioral questionnaires were administered before and after the stimulation at each session. All participants completed the Defense and Veterans Pain Rating Scale (DVPRS)⁸ and Oswestry Disability Index (ODI)¹⁸ to assess the severity of chronic low back

pain and perceived disability, respectively. The DVPRS comprises a validated numerical rating pain scale (0 to 10) with detailed verbal descriptions and facial expressions. We used the back pain specific ODI, which consists of ten questions pertaining to perception of disability in daily life activities. Although participants completed both self-report measures at the beginning of each session by phone, participants only completed the DVPRS after stimulation. Since the ODI encompasses questions about daily living, the follow-up was taken two days after each session for a more valid measure of any disability change. EEG data were recorded from participants with their eyes closed for two minutes before the stimulation and with their eyes open before and after the stimulation for two minutes. EEG signals were recorded using a 128-channel Geodesic EEG system (EGI Inc., Eugene, OR) at a sampling rate of 1kHz. Electrode Cz and one electrode between Cz and Pz were used as the reference and as the ground, respectively. Instructions for the tasks were implemented in Presentation (Neurobehavioral Systems, Inc., Berkeley, CA). Participants were instructed by a computer voice to fixate on a crosshair and open their eyes while staying relaxed for the eyes-open condition. Here we report on the primary and secondary outcome with regards to modulation of alpha oscillations and associated changes in pain symptoms. Results on heart rate variability will be reported elsewhere. The sample size was determined by the amount of funding available for the grant that supported this work. The study was performed between September and November 2017. The trial was ended when the target of 20 participant receiving stimulation was reached. The study protocol will be made available in response to written request to the corresponding author (F.F.)

Transcranial alternating current stimulation

We applied three carbon-silicone electrodes to the scalp with Ten20 conductive paste (Bio-Medical Instruments, Clinton Township, MI) and used the XCSITE 100 stimulator (Pulvinar Neuro LLC, Chapel Hill, NC) to administer tACS. Five-digit codes were used to ensure blinding of the study coordinators with regards to the stimulation conditions. The XCSITE 100 device does not display any information that would provide insights into whether verum or sham stimulation is applied. Two of the three electrodes (5×5cm each) were placed at F3 and F4 according to 10–20 international coordinate system and these two electrodes were connected together for 10Hz-tACS. The other electrode (5×7cm) was placed at Pz as a “return” electrode. Stimulation montage and modeling of electric field distribution were calculated with the tES LAB 1.0 software (Neurophet Inc., Seoul, South Korea) as depicted in Figure 1. In this software, we used a T1-weighted MRI (adult male) from the human connectome project¹⁴. The MRI data were segmented by 8 tissues (cerebrum gray matter, cerebrum white matter, cerebellar gray matter, cerebellar white matter, ventricles, CSF, skull and skin) and each tissue was assigned isotropic conductivity values²⁹. To obtain electric field distributions, we used the finite element method with tetrahedron volume meshes. The number of tetrahedron mesh was about 4.3 million and the quasi-static Maxwell’s equation was used. The two electrodes placed at the frontal lobe delivered an in-phase sinusoidal waveform with 1mA amplitude each (zero-to-peak). Stimulation duration was 40 minutes for both conditions. Verum stimulation delivered 40 minutes of 10Hz-tACS with 10 seconds of ramp-up and ramp down. Sham stimulation delivered 10 seconds of ramp-up, followed by 60 seconds of 10Hz-tACS, followed by 10 seconds of ramp-down for a total of 80 seconds. The choice of such an “active sham” is an established strategy to enhance blinding of the

participants to the stimulation condition. To ensure blinding, participants were asked to fill out a questionnaire how sure they were of receiving stimulation on a visual analog scale (0–100) after each stimulation session. We found no significant difference of the visual analogue scale between the two stimulation conditions ($p=0.1555$, Wilcoxon signed rank test, supplementary Fig 1). All participants completed the 10Hz-tACS and sham stimulation. On average, the stimulation sessions were spaced by 14.4 ± 6.5 days. During the stimulation, all participants were seated comfortably and watched Reefscapes (Undersea Productions, Queensland, Australia) that displays tropical fish underwater scenes to minimize the phosphenes induced by stimulation. Participants were asked to stay relaxed, watch the video, and keep their eyes open.

EEG analysis and statistical testing

Offline processing was performed by EEGLAB¹², FieldTrip⁴², and custom-built scripts in MATLAB. First, all data were downsampled to 250Hz with anti-aliasing filtering and band-pass filtered from 1 to 50Hz. Second, the data were preprocessed by an artifact subspace reconstruction algorithm³⁹ to remove high-variance and reconstruct missing data. Briefly, the algorithm first finds a minute of data that represents clean EEG as a baseline. Then, principle component analysis is applied to the whole data set with a sliding window to find the subspaces in which there is activity that is more than five standard deviations away from the baseline EEG. Once the function has identified the outlier subspaces, it treats them as missing data and reconstructs their content using a mixing matrix that is calculated from the clean data. Third, bad channels that were found in the previous step were interpolated and common average referencing was performed. Fourth and lastly, infomax independent component analysis (ICA)²⁶ was performed to remove eye blinking, eye movement, muscle activity, heartbeats, and channel noise. All ICA components were visually inspected and components were manually selected for rejection. These initial pre-processing steps were carried out on the full EEG dataset before unblinding of the study.

Resting-state EEG data were epoched into 2-second windows. Each epoch was visually inspected in the temporal domain and bad epochs that contained abnormal spikes or high-frequency noise were removed. Power spectral density (PSD) was computed by Welch's method with a 2-sec window and a 12.5% overlap resulting in a PSD with 0.5Hz frequency bins. Individual alpha frequency (IAF), which we defined as the frequency of peak power in the occipital alpha (8–12Hz) from eyes-closed EEG data, was selected for each participant. The power of the alpha oscillations was obtained by averaging of the PSD around the IAF ($\text{IAF} - 1\text{Hz}$ – IAF – $\text{IAF} + 1\text{Hz}$) and the alpha oscillations were normalized by the average of all electrodes to minimize the inter-subject variability of alpha oscillations^{1,2}. Thirty-eight electrodes outside of the scalp were excluded and the remaining 90 electrodes inside of the scalp were used for topographical representation.

For statistical testing, we used a linear mixed model analysis with fixed factors of “condition” (tACS and sham), “session” (session1, session2), and “sequence” (tACS-sham, sham-tACS), with random factor “participant” written in R (R Foundation for Statistical Computing, Vienna, Austria). We assumed that no carry-over effect was observed since there were sufficient washout period between the two sessions and outlasting treatment effects of

stimulation are negligible. Kenward-Roger approximations were used to perform F-tests for each factor and interaction and obtain *p*-values. Post-hoc statistical tests were performed using student's *t*-test across participants at each electrode and it was corrected by false discovery rate (FDR)⁵. Changes of measured values over sessions were quantified with a modulation index (MI),

$$MI(a, b) = \frac{a - b}{a + b}, \quad (1)$$

Changes in spatially-normalized alpha oscillations were calculated by ($\overline{Alpha}_{before}$, $\overline{Alpha}_{after}$). In contrast, changes in DVPRS and ODI were calculated by ($DVPRS_{before}$, $DVPRS_{after}$) and (ODI_{before} , ODI_{after}), respectively. Given the non-normal distribution of the modulation indices for the assessments, we also performed exploratory analysis using the Wilcoxon sign-rank test.

Results

Pain assessments and endogenous alpha oscillations

We first examined how endogenous alpha oscillations were correlated with CBP severity measured by the DVPRS and ODI, i.e., target identification. Baseline spatially-normalized alpha oscillations were calculated from 2-minute eyes-open data at the first study session regardless of the stimulation condition for that session. We calculated the Spearman's rho between the baseline alpha oscillations and the assessments across all participants at each scalp EEG channel. We found significant negative correlations over the bilateral and left somatosensory region for the DVPRS and ODI, respectively (Fig. 2A). The black dots represent EEG channels with statistically significant correlations ($p < 0.05$, FDR corrected). Negative correlations indicate endogenous alpha oscillations were lower for patients with higher pain severity (DVPRS) and higher perceived disability (ODI). Given the similarity in the topographic distribution of these correlations, we confirmed that the DVPRS and ODI scores were positively correlated ($r = 0.6375$, $p = 0.0025$, Fig. 2B). These results suggest that reduced endogenous alpha oscillations could represent the severity of CBP and its impact on the perceived disability.

Enhanced alpha oscillations by 10Hz-tACS

Our finding that a reduction in alpha oscillations is associated with pain severity in CBP suggests that tACS could restore these pathological reduced oscillations. Thus, we next examined modulation, i.e., target engagement, of endogenous alpha oscillations by 40 minutes of bifrontal 10Hz-tACS and sham stimulation. Changes in spatially-normalized alpha oscillations from eyes-open data for 2 minutes were obtained immediately before and after stimulation for conditions. The increase in alpha oscillations was significantly higher in the 10Hz-tACS condition (Fig. 3, left) compared to the sham condition (Fig. 3, middle, $F_{1,18} = 6.5$, $p = 0.02$). The black dots in the topographic map (Fig. 3, right) represent the location of EEG channels with statistically significant differences in modulation of alpha oscillation between 10Hz-tACS and sham, ($p < 0.05$, FDR corrected). These results suggest

that 10Hz-tACS selectively enhanced endogenous alpha oscillations over the somatosensory region in patients with CBP.

Changes in pain assessments and alpha oscillations

Given the correlation between a reduction of alpha oscillations and pain severity, we next asked if the stimulation-induced changes in alpha oscillations modulated pain severity. We examined how enhanced alpha oscillations by 10Hz-tACS were correlated with changes in pain severity. We calculated the Spearman's rho between changes in spatially-normalized alpha oscillations, ($Alpha_{after}$, $Alpha_{before}$), and the two assessments ($DVPRS_{before}$, $DVPRS_{after}$), $MI(ODI_{before}$, ODI_{after}) for each stimulation condition at each EEG channel. We found significant positive correlations over the somatosensory and frontal regions for the DVPRS in the 10Hz-tACS condition (Fig. 4, top row). The black dots in the topographic map represent statistically significant EEG channels ($p < 0.05$, FDR corrected). In contrast, no significant correlations were obtained in the sham condition for the DVPRS. Similarly, for the ODI, we found significant positive correlations over the left somatosensory and frontal regions ($p < 0.05$, FDR corrected) in the 10Hz-tACS condition and no significant correlations in the sham condition. Thus, increasing alpha oscillations improved pain severity and perceived disability, which suggests a causal of pathological reduced alpha oscillations in chronic pain.

Clinical improvement of chronic low back pain

As secondary outcome, we determined the improved in the DVPRS and ODI scores independent of the neurophysiological changes. We calculated changes of the two assessments (DVPRS and ODI) by using the modulation indices $MI(DVPRS_{before}$, $DVPRS_{after})$ and $MI(ODI_{before}$, $ODI_{after})$ across the stimulation conditions. Statistical testing with a linear mixed model and Kenward-Roger approximations revealed no significant effect for the stimulation conditions, ($F_{1,18}=1.13$, $p=0.3$). However, the DVPRS and ODI data were not normally distributed as determined by the Kolmogorov-Smirnov tests for the null hypothesis that the data comes from a standard normal distribution ($p=0.005$). We thus performed exploratory analysis with the Wilcoxon sign-rank test, a non-parametric test for non-normally distributed data. We found a significant effect only for change in DVPRS ($p=0.0488$, Fig. 5A) and not or change in ODI ($p=0.17$, Fig. 5B).

Discussion

Previous studies have shown that patients with chronic pain exhibit abnormal neuronal oscillations⁴⁶. In particular, alpha oscillations have been hypothesized to be involved in chronic pain^{9,25,45,52}. Yet, to our knowledge we are the first to examine if non-invasive brain stimulation can enhance alpha oscillations and thereby improve symptoms of chronic pain. We performed a randomized, crossover, double-blind, sham-controlled clinical trial to examine the association between endogenous alpha oscillations and pain severity in patients with CLBP and the modulation of alpha oscillations by 10Hz-tACS. We found that endogenous alpha oscillations in the somatosensory region were negatively correlated with pain severity assessed by the assessments for back pain (DVPRS) and perceived disability due to back pain (ODI). Bifrontal 10Hz-tACS targeting the somatosensory region

successfully enhanced alpha oscillations compared to sham stimulation. Further, we found that changes of pain relief were correlated with changes of endogenous alpha oscillations in the frontal and somatosensory regions. Our findings of successful target identification and engagement of alpha oscillations by 10Hz-tACS for patients with CBP demonstrates the potential of tACS for treating pain by modulating neuronal oscillations.

TCD has been proposed as a framework for understanding underlying mechanisms of chronic neurogenic pain³⁴. According to the framework, increased theta oscillations and slowing a dominant peak were consistently observed in previous studies^{48,49,53,56}. A decreased inhibition of the thalamus seems to be linked to increased theta oscillations in patients with chronic neurogenic pain. However, a study failed to replicate these findings in patients with CLBP⁵⁰. In this study, they recruited patients with CLBP (duration of illness at least 1 year) and compared with age- and gender-matched healthy participants. The authors did not find any significant difference in terms of increased theta oscillations and peak shift to lower frequency and concluded that different pain location may have caused the discrepancy. Interestingly, none of the patients with chronic neurogenic pain suffered from low back pain in previous studies for testing the TCD hypothesis^{48,49,53,56}. In contrast, our study focused on the strength of the alpha oscillation motivated by the inverse correlation between neuronal activity and alpha oscillation power. We hypothesized that alpha oscillations are reduced in CLBP due to disinhibition associated with pathologically increased cortical excitation in chronic pain⁶², which indicates dysfunction of inhibitory neurotransmitters⁶¹. Testing the TCD was not a goal of this study and thus a direct comparison of the results is not possible. Instead, our findings may represent fundamental neurophysiological correlate of pain symptoms in patients with CLBP. In the view of translation to a population with neuropathic pain using our approach, theta oscillations may be targeted by theta-tACS. However, identifying the relationship between theta oscillations and pain intensity should be performed first to target and modulate abnormal theta oscillations. Once the relationship is consistent across patients with neuropathic pain, detailed spatial targeting can be applied based on the identified target region.

Inspired by a previous study¹⁹, which found the relationship between peak alpha frequency and pain sensitivity, we investigated this relationship in our data. We found no significant correlation between peak alpha frequency and the two pain assessments (DVPRS and ODI) at baseline (Supplementary Fig. 2). This discrepancy may come from a different population of participants since our study population is patients with chronic low back pain. In addition, patients with long-term chronic pain exhibit some degree of depression as a comorbidity¹⁵ thus we assessed Hamilton Depression Rating Scale (HAM-D) from all participants to investigate a relationship pain severity and depression level. We found no significant correlation between HAM-D scores and the two pain assessments (DVPRS and ODI) at baseline (Supplementary Fig 3). We only assessed HAM-D at baseline since tracking depression level was not a goal of this study. This relationship needs to be investigated further in a larger sample with multiple assessments.

Deep brain stimulation that stimulates periventricular/periaqueductal gray matter, internal capsule, and sensory thalamus has shown promising improvement of pain relief^{6,47}. Due to substantial risks of surgical implantation of electrodes in the brain, non-invasive brain

stimulation techniques including rTMS have been investigated for the treatment chronic pain^{28,31,44}. Similar to our study, these studies considered chronic pain as a disorder associated with reorganization of the central nervous system¹⁷. The first rTMS study showed that 10Hz-rTMS for 20 minutes applied to the motor cortex decreased pain severity in a sham-controlled clinical trial³⁰. In a follow-up study, 10Hz-rTMS also reduced pain compared to 20Hz-rTMS and sham¹⁶. Although these rTMS studies showed a substantial reduction in pain, several similar studies failed to replicate these findings. One study with 20Hz-rTMS found no significant differences between real and sham groups²⁸ and another double-blind, sham-controlled clinical trial with 1Hz- and 20Hz-rTMS found no significant treatment effects compared to sham stimulation³. Recent meta-analysis showed that rTMS for treating pain does not achieve the minimum clinically important difference threshold of 15% or greater⁴¹. In addition to rTMS, transcranial direct current stimulation (tDCS) has also been investigated. A recent meta-analysis found similar heterogeneity of outcomes as for the tDCS studies⁴¹.

It is of note that alpha oscillations have been investigated in depth in the context of pain stimuli in healthy control participants. Most of these studies have provided evidence for pain perception in presence of suppression of alpha oscillations for phasic pain^{23,36,38,45}. Likewise, longer-lasting tonic pain, which may represent a precursor to chronic pain, suppressed alpha oscillations^{13,24,40,52}. In addition, pain severity and alpha oscillations were negatively correlated^{40,52}. These studies are correlational in nature but a recent tACS study with behavioral outcome measures provided the first evidence for a causal role of alpha oscillation in pain processing⁴ albeit no confirmatory neurophysiological measurements were performed. Our study differed in scope and question since we examined target engagement of tACS by EEG and examined the causal role of alpha oscillations in the context of chronic pain. Such a target-specific approach with EEG may provide a new insight to understand mechanisms of chronic pain.

As any scientific study, our study has several limitations. First, we found a significant reduction for DVRPS only on exploratory analysis and none for ODI. One possible reason for this is that post-stimulation ODI was measured two days after each session since we hypothesized that a single session of tACS may not change disability. It is of note that our study was designed as a target engagement study with physiological changes including the alpha oscillation as primary outcome rather than treating chronic pain by a single session of tACS. The study was not designed or powered to detect meaningful clinical difference. Importantly, a treatment protocol would consist of repeated application of 10Hz-tACS as in our recent treatment clinical trial for auditory hallucinations in schizophrenia³⁷. In a follow-up study, we plan to investigate the treatment effect with larger sample size and more refined target engagement strategies such as individual alpha frequency^{27,54,59}. Second, even though brain stimulation approaches have been used widely to modulate cortical excitability and treat patients, inter- and intra-individual variability for effects still exist^{10,35}. Individualizing stimulation parameters with precise modeling of electric current density may be one approach to minimize variability. In our study, likewise, we fixed stimulation intensity and montage across all participants without individualization. In a follow-up study, individualization of stimulation parameters should be considered as well as multi-session stimulation.

In summary, we report on the first study of target identification and engagement with high-density EEG and tACS for patients with CLBP. Our findings suggest a causal role of alpha oscillations in CLBP. Targeting and modulating neuronal oscillations represents a promising strategy to understand the interaction between pain symptoms and brain oscillations. Potentially, such a target-specific approach to modulate pathologically impaired oscillations with tACS may provide therapeutic benefit for other disorders associated with brain network pathologies.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

Disclosures

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Highlights

- Target identification of alpha oscillations by EEG in chronic low back pain.
- Target engagement of alpha oscillations by 10Hz-tACS.
- Target validation of enhanced alpha oscillations linked to clinical improvement.

Figure 1. Stimulation montage, waveforms, and distributions of electric field in the brain. (A) Electrodes E1 and E2 delivered in-phase 10Hz-tACS with 1mA amplitude (zero-to-peak). Electrode E3 was used as the return electrode. (B) Normalized electric field distribution (V/m) by bifrontal 10Hz-tACS (top-view and left-top-view) in grey and white matter.

Figure 2.

Correlations between baseline alpha oscillations and clinical assessments (DVPRS and ODI). (A) Topographical distribution for DVPRS and ODI. Small black dots represent EEG channels with statistical significance ($p < 0.05$, FDR corrected). (B) Scatter plot for correlated ODI and DVPRS ($\rho = 0.6375$, $p = 0.0025$).

Figure 3.

Averaged topographical distribution of changes in spatially-normalized alpha oscillations for tACS (left), sham (middle), and the difference (right). Individual alpha frequency was used ($\text{IAF} \pm 1\text{Hz}$) and small black dots represent EEG channels with statistical significance ($p < 0.05$, FDR corrected).

Figure 4. Topographical distribution of correlations between enhanced alpha oscillations and pain symptom changes. Small black dot represent EEG channels with statistical significance ($p < 0.05$, FDR corrected).

Figure 5. Changes in pain assessments (DVPRS and ODI) under stimulation conditions (tACS and sham). Statistical significance was assessed with the non-parametric Wilcoxon sign-rank test (*: $p < 0.05$). Red symbol indicates an outlier.

Table 1.

Demographic information. DVPRS: Defense and Veterans Pain Rating Scale, ODI: Oswestry Disability Index. Data reported as mean $\pm$ std.

	Participants (n=20)
Gender (M/F)	8/12
BMI	25.9 $\pm$ 4.3
Duration of chronic back pain (months)	84.8 $\pm$ 70
DVPRS (baseline)	4.4 $\pm$ 1.0
ODI (baseline)	22.7 $\pm$ 11.2
Race (Caucasian/African Caucasian)	18/2
Ethnicity (Hispanic/Not Hispanic)	1/19
Education level	
Bachelor's degree or less	12
Master's degree	6
Doctorate degree	2