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Decomposing the effects of α-tACS on brain oscillations and aperiodic 1/f activity

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Dear Editor,

Transcranial alternating current stimulation (tACS) has become a popular tool in neuroscience to non-invasively interfere with oscillations in the human brain [1]. This non-invasive brain stimulation technique works via the application of sinusoidal currents between at least two electrodes placed on the scalp and is based on the core assumption that it modulates brain oscillations in a frequency-specific manner. Interventional studies using tACS are attractive as they allow to establish causal relationships between oscillations within particular frequency bands and their associated cognitive functions [2]. Many studies have previously shown that tACS can induce aftereffects on oscillatory activity that outlast stimulation for several minutes or few hours [3,4].

In recent years, a growing body of research has emphasized the importance of accounting for the aperiodic component in electrophysiological power spectra when studying brain oscillations. This component follows a 1/f-like distribution, and will for simplicity in the following be referred to as *1/f-brain activity*. It can be represented as a line when depicted in a double logarithmic plot and is characterized by the line's *slope* (synonymous with the term 'exponent') and *intercept* (synonymous with the term 'offset'), respectively. While previous studies regarded 1/f-brain activity as pure noise, recent advances have put forward the notion that it is in fact functionally relevant [5–7].

Given the evidence for a functional role of 1/f-brain activity in cognitive processing and the resulting necessity of isolating this component from oscillatory activities, the question arises whether tACS only modulates oscillatory amplitudes or whether it may modulate 1/f-brain activity as well. It also has to be confirmed that established tACS aftereffects in magneto-/electroencephalography (M/EEG) [3,4] are still observable once aperiodic 1/f-brain activity is accounted for. To address these issues, we reanalyzed an existing dataset of tACS aftereffects on α-oscillations. We dissociated tACS effects on oscillations from those on aperiodic 1/f-brain activity by separately parameterizing the different components of the frequency spectrum [5].

Full details on the dataset and processing can be found in previous publications 8,9 and in the Supplementary Information. In short, the data consist of 10-min MEG recordings obtained before and after administration of 20-min parieto-occipital tACS or sham stimulation at individual α-frequency. After cleaning recordings from artifacts using spatiotemporal-signal-space-separation, independent component analysis and threshold-based artifact rejection, we performed frequency analyses on magnetometer data using non-overlapping, 2-sec segments (FFT, zero-padding to 4-sec, Hanning window). Power spectra were decomposed into oscillatory and 1/f-brain activity using the FOOOF algorithm [5] (https://fooof-tools.github.io/fooof/). The algorithm was fitted over a frequency range of 1 Hz–30 Hz of the average spectrum per channel and block of each participant. The intercept and the slope parameter of the aperiodic fit were extracted from the data. The aperiodic component was then subtracted from the full reconstructed spectrum in linear space to obtain a 1/f corrected spectrum.

We first replicated previous effects of tACS on α-oscillations in the data [8,9] in the uncorrected power spectrum. Cluster-based permutation analysis yielded a significant increase in α-power from pre-to post-tACS ($p_{cluster} < 0.001$; Fig. 1a and b). The effect was absent in the sham condition ($p_{cluster} = .25$, Fig. 1c and d). When directly comparing α-power changes between tACS and sham, the analysis revealed a significantly larger α-power increase after tACS as compared to sham ($p_{cluster} = .007$, Fig. 1e and f). This reflects the expected interaction of factors time and stimulation.

After removing 1/f-brain activity from individual spectra, we observed nearly the same results as in the uncorrected data (Fig. 1g–l). α-power increased significantly stronger after tACS as compared to sham ($p_{cluster} < 0.011$), reflecting the expected interaction of factors time and stimulation. While there was a significant increase in α-power from pre-to post-stimulation in the tACS group ($p_{cluster} = .015$), this effect was absent in the sham group ($p_{cluster} = .56$).

With respect to aperiodic components of the spectrum, we observed a significant increase of the 1/f slope parameter from pre-to post in the tACS condition ($p_{cluster} = .003$, Fig. 1m), but not in the sham condition ($p_{cluster} > 0.23$, Fig. 1o). However, a direct comparison of these differences between tACS and sham (i.e, the interaction effect) did not differ significantly ($p_{cluster} = 1$, Fig. 1n). There is thus no clear evidence for an effect of tACS on the aperiodic slope, nor a consistent time-on-task effect.

For the intercept of the aperiodic fit, we observed a significant increase from pre-to post-stimulation in both the tACS ($p_{cluster} < 0.001$, Fig. 1p) and the sham group ($p_{cluster} < 0.001$, Fig. 1r). The change of the intercepts did not differ between conditions ($p_{cluster} = 1$, Fig. 1q), which

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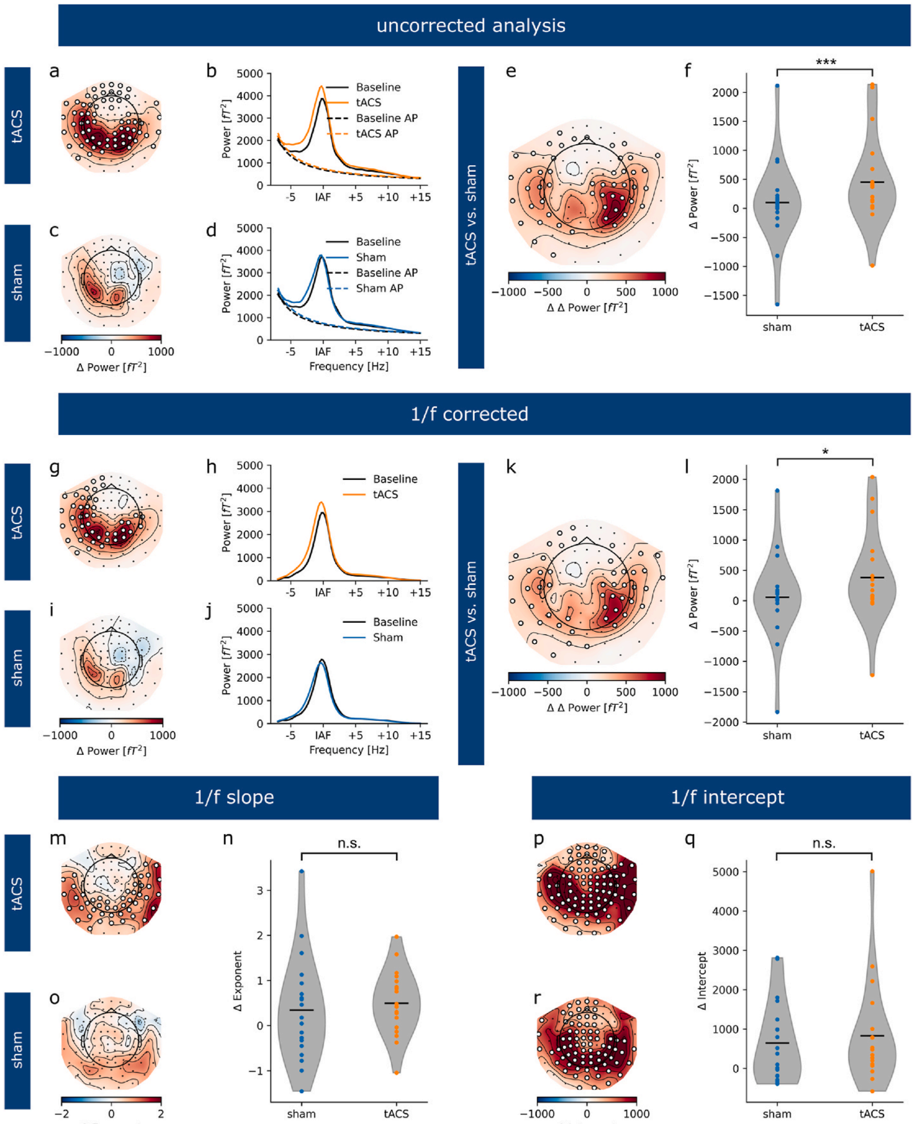

Fig. 1. tACS modulates power in the α-band but not 1/f parameters. a) Topography of difference in spectral power in the α-band from pre-to post-stimulation in the tACS group. White markers indicate sensors with significant power increase. **b)** Average uncorrected power-spectra overlaid with the 1/f aperiodic fit (AP) before and after tACS. **c, d)** Same as in a, b for sham condition. **e)** Topography of difference of the difference in α-power from pre-to post-stimulation between tACS and sham [(tACS - baseline) - (sham - baseline)]. **f)** Violin plots depict distribution of pre-/post-stimulation α-power difference across participants. Black bars represent sample average. **g-l)** same as a-f after removing 1/f components from individual spectra. **m)** Topography of difference in aperiodic slope from pre-to post-tACS. **n)** Distribution of the change in aperiodic slope between tACS and sham conditions. **o)** same as m for sham condition. **p)** Topography of change in intercept of the aperiodic fit from pre-to post-tACS. **q)** Distribution of the change in aperiodic intercept between tACS and sham conditions. **r)** Same as p for sham condition. Data shown in violin plots reflect averages per subject across significant sensors identified in permutation tests. Data was averaged across all sensors if no cluster was identified. Asterisks indicate significant differences in the respective cluster test (***$p < 0.001$, *$p < 0.05$, *n.s.* not significant).

reflects a main effect of the factor time (in absence of a main effect of the factor stimulation). This unspecific increase of 1/f-activity as a function of time may contribute to the established increase in α-power over time [3,10], which is assumed to correlate with longer reaction times and higher error rates.

The results of the present study demonstrate that aftereffects of tACS on α-amplitude in comparison to sham stimulation are in fact present, even when correcting for 1/f-brain activity. Spectral parametrization of the frequency spectrum into periodic and aperiodic components enables for a better characterization of tACS effects on oscillatory power. Conclusively, tACS seems to be frequency specific and does not affect the underlying aperiodic spectrum. However, this aperiodic component varies over time, signifying the importance of correcting for it when analyzing aftereffects of brain stimulation on brain oscillations.

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CRediT authorship contribution statement

Florian H. Kasten: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **René Lattmann:** Writing – review & editing, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Daniel Strüber:** Writing – review & editing, Writing – original draft, Conceptualization. **Christoph S. Herrmann:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: CSH holds a patent on brain stimulation. FHK, RL and DS, declare no competing interests.

Appendix ASupplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.brs.2024.05.015.

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