Transcranial electrical brain stimulation modulates the vestibular system

Ilkka Laakso[1,2,*], Janita Nissi[1], Otto Kangasmaa[1],

September 13, 2024

[1]Department of Electrical Engineering and Automation, Aalto University, Espoo 02150, Finland
[2]Lead Contact
[*]Correspondence: ilkka.laakso@aalto.fi

Abstract

Transcranial electrical stimulation (tES) techniques are widely used to modulate brain excitability, though their mechanisms remain unclear. This study demonstrates that tES can directly activate the vestibular system, which may contribute to its observed effects. Using computational modelling, we showed that tES with a C3-Fp2 montage generates electric fields in the vestibular system, with strengths similar to those generated by electrical vestibular stimulation (EVS). Experiments in three participants with 4 Hz alternating current revealed that C3-Fp2 tES induces body sway at 4 Hz, comparable to the effect of EVS. A 2 mA tES produced a sway response equivalent to 1 mA EVS, suggesting both activate the vestibular system. These findings indicate that direct activation of the vestibular system may interfere with the interpretation of tES studies. The effect is likely to exist for wide range of typical tES frequencies and current intensities.

Transcranial electrical stimulation (tES) and its variants with direct and alternating currents (tDCS and tACS) are popular techniques for modulating the excitability of the brain. However, the mechanisms of these techniques are still unclear. Here, we show that tES directly activates the vestibular system in addition to its potential effects on the brain, which may contribute to the observed effects of tES.

The vestibular system is sensitive to electric currents, causing postural changes and eye movements[1]. A direct current (DC) applied through electrodes attached behind the ears makes the subject lean to one side, and an alternating current (AC) makes them sway from side to side. In the latter case, the response is easily observable using a force platform or by analysing movements from a video recording of the subject.

Whereas electrical vestibular stimulation (EVS) can produce postural changes for currents in the range of a few hundred µA, tES typically uses stronger currents in the range of 1–2 mA[2]. Even though tES electrodes are not typically placed over the inner ear, the spread of the current through the head tissues to

the vestibular organ might still be sufficiently strong to produce vestibular responses. Indeed, computational modelling indicates that 1 mA current applied with the C3–Fp2 montage, commonly used for stimulation of the somatomotor cortices, produces an electric field strength of 70–131 mV/m in the vestibular systems (Fig. 1A), while the same current with a typical bilateral EVS montage produces 143–204 mV/m (Fig. 1B). Therefore, we hypothesized that tES with the C3-Fp2 montage could directly affect the vestibular system. If yes, tES should produce an EVS-like body sway when the stimulation current intensity is roughly doubled from that of EVS.

To test our hypothesis, we performed experiments in three healthy participants (2 male, 1 female, 28-41 years, ethical approval: D/1219/03.04/2022, Aalto University Research Ethics Committee). The experiments were performed in a green room to aid video analysis. The participant stood on a 1.5 cm thick plastic foam mattress placed on a force platform (not active) with eyes closed, arms crossed, shoes off, and feet together. The participant faced a smartphone (Samsung Galaxy s23+) fixed to a tripod, which recorded a video (Android 14 Camera, 1920x824, 120 frames per second) of the participant's movements.

The stimulus was an AC sine wave at 4 Hz, lasting 120 s with 3 s ramp-up and 3 s ramp-down. This frequency is convenient, as the response to EVS is observable as a clear peak in the spectrum of the sway signal[3]. The AC stimulus was applied using a Starstim 20 stimulator (Neuroelectrics, Barcelona, Spain) with 25 cm^2 round saline-soaked electrodes. Six conditions were applied in the following order (Fig. 1C): no stimulus as a negative control, tES with 1.0, 1.5, and 2.0 mA given through electrodes at C3 and Fp2 of the 10-20 System; another negative control; and EVS as a positive control with 1.0 mA applied through electrodes attached to the bilateral mastoid processes. There was no blinding, as the outcome (body sway at 4 Hz) is very difficult if not impossible to produce except as a direct effect of stimulation.

We analysed the videos by segmenting the participant's silhouette from the video data using MATLAB (The Mathworks, Inc) and calculating its centre of gravity (CoG) in 12 regions of interest (Fig. 1D). Finally, we calculated the power spectrum of the CoG signal over 110 s, trimming away the start and end of the video.

The signals thus processed showed a clear 4 Hz sway response compared with no stimulation for both tES (C3-Fp2) and EVS at multiple heights, with the largest response in the lower legs (Fig. 1D). The characteristic peak at the stimulation frequency was present in all three participants (Fig. 1E), and tES with 1 mA was sufficient to produce a slight body sway at 4 Hz. When the current intensity increased, the sway response increased, such that 2 mA tES produced roughly the same 4 Hz sway magnitude as 1 mA EVS, as predicted by modelling (Fig. 1A,B). Likewise, distributions of the sway response across body segments were similar for 2.0 mA tES and 1.0 mA EVS (Fig. 1D). Similarity of the responses confirms that both EVS and tES (C3-Fp2) activate the same structure: the vestibular system.

The effective frequency range of EVS overlaps with common tES frequencies. The vestibular system is highly sensitive to DC, leading to postural changes and sensations of illusory movements[1,4]. Postural sway can be observed at least up to 10 Hz[3], and eye movements can be produced at up to 20 Hz[5]. Therefore, we expect that the vestibular effects demonstrated here at 4 Hz are present in a wide frequency range covering both tDCS and tACS.

EVS slightly activates variety of muscles throughout the body. The cerebral cortex is likely not involved in the immediate effects, as the earliest EVS responses are measured in lower leg muscles at latencies as short as 50 ms[6,7]. It remains to be studied whether the vestibulospinal mechanisms causing muscle activations could alter corticospinal excitability, which has been the main outcome of motor cortical tDCS studies[8]. Vestibular effects can also interfere with the measurement of tremor during tACS[9–11].

In conclusion, direct modulation of the vestibular system may interfere with the interpretation of tES studies. The effect is likely to exist for typical tES frequencies and current intensities as well as for multiple commonly used tES montages.

Author contributions

Ilkka Laakso: Conceptualization, Methodology, Investigation, Formal analysis, Writing – Original Draft, Visualization, Supervision.
Janita Nissi: Methodology, Investigation, Formal analysis, Writing – Review & Editing, Visualization.
Otto Kangasmaa: Methodology, Investigation, Writing – Review & Editing.

Declaration of interests

The authors declare no competing interests.

References

[1] Dlugaiczyk, J., Gensberger, K. D. and Straka, H. (2019). Galvanic vestibular stimulation: from basic concepts to clinical applications. Journal of Neurophysiology 121, 2237–2255. https://doi.org/10.1152/jn.00035.2019.

[2] Woods, A. J. et al. (2016). A technical guide to tDCS, and related non-invasive brain stimulation tools. Clin. Neurophysiol. 127, 1031–1048. https://doi.org/10.1016/j.clinph.2015.11.012.

[3] Nissi, J., Kangasmaa, O., Kataja, J., Bouisset, N. and Laakso, I. (2024). In vivo and dosimetric investigation on electrical vestibular stimulation with frequency- and amplitude-modulated currents. Journal of Neural Engineering 21, 046038. https://doi.org/10.1088/1741-2552/ad658f.

[4] Fitzpatrick, R. C. and Day, B. L. (2004). Probing the human vestibular system with galvanic stimulation. J Appl Physiol 96, 2301–16. https://doi.org/10.1152/japplphysiol.00008.2004. https://doi.org/http://jap.physiology.org/content/96/6/2301.full.pdf+html.

[5] Mackenzie, S. W. and Reynolds, R. F. (2018). Ocular torsion responses to sinusoidal electrical vestibular stimulation. Journal of Neuroscience Methods 294, 116–121. https://doi.org/10.1016/j.jneumeth.2017.11.012.

[6] Fitzpatrick, R., Burke, D. and Gandevia, S. C. (1994). Task-dependent reflex responses and movement illusions evoked by galvanic vestibular stimulation in standing humans. J Physiol (Lond) 478, 363–372. https://doi.org/10.1113/jphysiol.1994.sp020257.

[7] Rosengren, S. and Colebatch, J. (2002). Differential effect of current rise time on short and medium latency vestibulospinal reflexes. Clin Neurophysiol 113, 1265–1272. https://doi.org/10.1016/s1388-2457(02)00121-9.

[8] Nitsche, M. A. et al. (2008). Transcranial direct current stimulation: State of the art 2008. Brain Stimul. 1, 206–23. https://doi.org/10.1016/j.brs.2008.06.004.

[9] Brittain, J.-S., Probert-Smith, P., Aziz, T. and Brown, P. (2013). Tremor suppression by rhythmic transcranial current stimulation. Curr Biol 23, 436–440. https://doi.org/10.1016/j.cub.2013.01.068.

[10] Mehta, A. R., Pogosyan, A., Brown, P. and Brittain, J.-S. (2015). Montage matters: the influence of transcranial alternating current stimulation on human physiological tremor. Brain Stimul. 8, 260–268. https://doi.org/10.1016/j.brs.2014.11.003.

[11] Schreglmann, S. R. et al. (2021). Non-invasive suppression of essential tremor via phase-locked disruption of its temporal coherence. Nat Commun 12. https://doi.org/10.1038/s41467-020-20581-7.

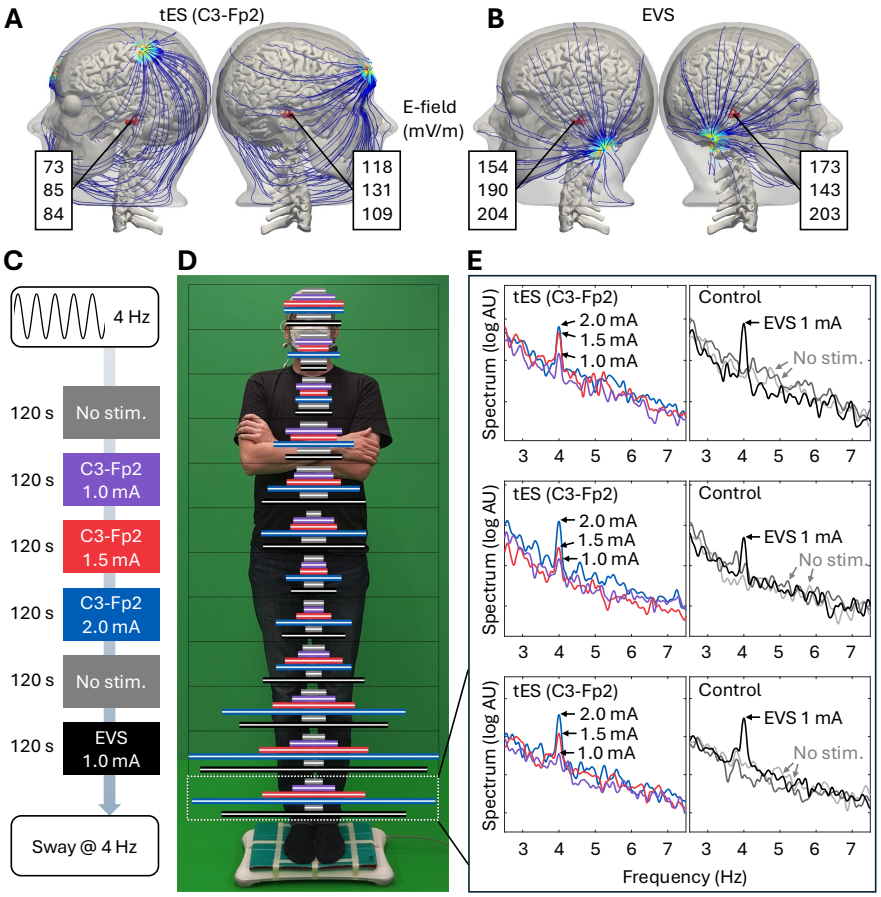

Figure 1: Current flow modelling and measurements of body sway responses for tES and EVS.

A and B. Modelled current streamlines for a current applied through C3-Fp2 (A) or through mastoid processes (B) obtained using MRI-based models of three participants. Numbers are the mean electric field strengths in the vestibular systems of each participant. The details of the modelling approach are identical to our earlier study[3].

C. Experimental conditions with a 4 Hz sine wave as the stimulus and the body sway as the outcome.

D. Horizontal bars indicate the magnitude of the 4 Hz spectral component (average over three participants) of the left-right sway signal in 12 body segments. The length of the bars is normalized, and their order and colour correspond to the conditions in C. One of the authors served as the model and gave consent for the publication of this picture in an online publication.

E. Power spectra of the sway signal (arbitrary units, AU) from the lower legs of three participants (rows).