An Inexpensive Bimodal Neuromodulator for Tinnitus

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Introduction

A new treatment that reduces tinnitus symptoms is a "bimodal neuromodulator" by Lenire [1]. Their device delivers simple sounds via headphones correlated with electrical stimulation from an electrode array placed on the tongue. Participants who used the device for two 30 min sessions per day for 12 weeks reported moderate improvements on the Tinnitus Handicap Inventory [2] that persisted after a 12-month follow-up [3]. Significant evidence of efficacy is the high compliance rate ~84%, measured from the device log [4], and replicated in a larger study ([5], by the same authors and sponsor).

We rationalize the mechanism of action based on two neuroscience principles. 1) Pavlovian or classical conditioning [6]. The brain always seeks patterns, co-relations, to learn to make more accurate predictions. This device's bimodal stimulation creates a novel correlation, just as Pavlov did by ringing a bell correlated with feeding his dogs. Repeating the correlation rewires brain circuits – "neurons that fire together wire together". 2) Sensory systems perform two distinct abstract operations: a) predict the input and *subtract* expectation from actual sensory input. The resulting (usually small) difference is b) amplified or *multiplied*, hence small *novel* stimuli produce large behavioral responses. Consider how our clothes constantly stimulate sensitive parts of our bodies without generating any response or even awareness, yet we have high gain to novelty such as an unexpected feather touching our neck.

Our auditory system operates near the noise threshold [7], and colleagues who study electric fish have long understood that cerebellar circuits, including the cerebellar-like dorsal cochlear nucleus (DCN) [8] and electrosensory lateral line lobe (ELL) generate and null expectation from sensory inputs. Hearing and hair cell loss reduces or removes the expected background input to the DCN [9], which continues to mix the (now absent) sensory input with expectation, resulting in a phantom signal perceived as tinnitus.

Of course, tinnitus isn't a single condition with a single cause as just described. Everything regarding the human brain is complicated. E.g., to achieve high gain and sensitivity, the inner ear is also a driven oscillator. Electronic engineers know that the difference between an amplifier and an oscillator can simply be accumulated phase lag in a feedback loop turning negative (stabilizing) feedback into positive (oscillating) feedback. This is part of the story behind how our ears *produce* sound – a phenomena called "otoacoustic emissions" [10].

Putting these ideas together, our working hypothesis is that hearing loss results in the brain amplifying a sensory expectation that no longer cancels auditory input. Novel bimodal neuromodulation activates latent synaptic plasticity in the affected circuits, so they learn to predict the bimodal correlation. Concurrently, the auditory system also learns or adapts to the absent or reduced high frequency auditory input, changing the expectation signal and reducing the perceived ringing. This suggests the precise nature of the bimodal neuromodulation isn't critical. If it is correlated, the nervous system recognizes a conditioning "opportunity", and reactivates latent neuroplasticity. Evidence from various stimulus regimens is consistent with this hypothesis – the effect is robust to single frequency sound, white noise, etc. And likewise, lingual electrical stimulation is likely not a critical choice as the co-modality.

The Lenire stimulator is expensive (~$4000), not readily available, nor covered by insurance. We have developed a radically inexpensive (<$25) alternative, using a commercial transcutaneous electrical nerve stimulator (TENS) interfaced to a speaker or earphone via a $1 isolation transformer and $1 audio amplifier (Fig. 1).

Methods

The transformer couples AC signal to the audio amplifier proportional to current flowing through the electrodes (and body). Nothing can be heard until the electrodes are connected to the body or each other. The TENS stimulator produces a high voltage (which we didn't attempt to measure but is likely >100V unloaded) with a large series (Thevenin) resistance – making it a current source – and hence the 600Ω:600Ω transformer isn't a significant series load. A speaker was chosen as the auditory output, but headphones/earphones would work just as well.

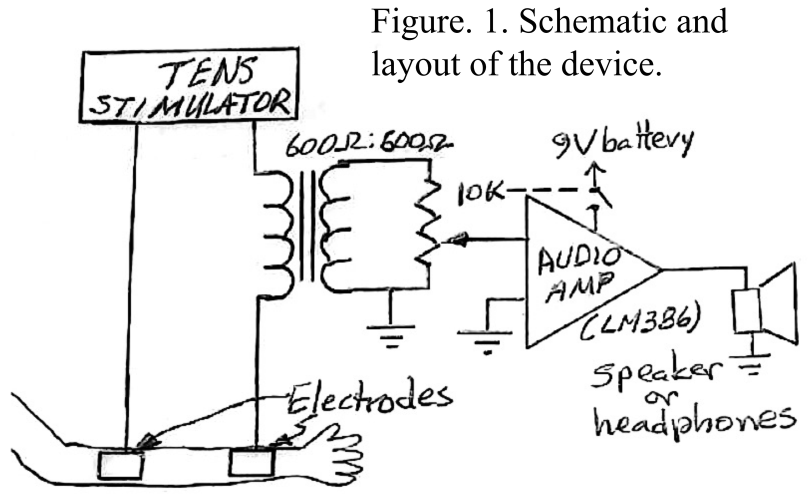
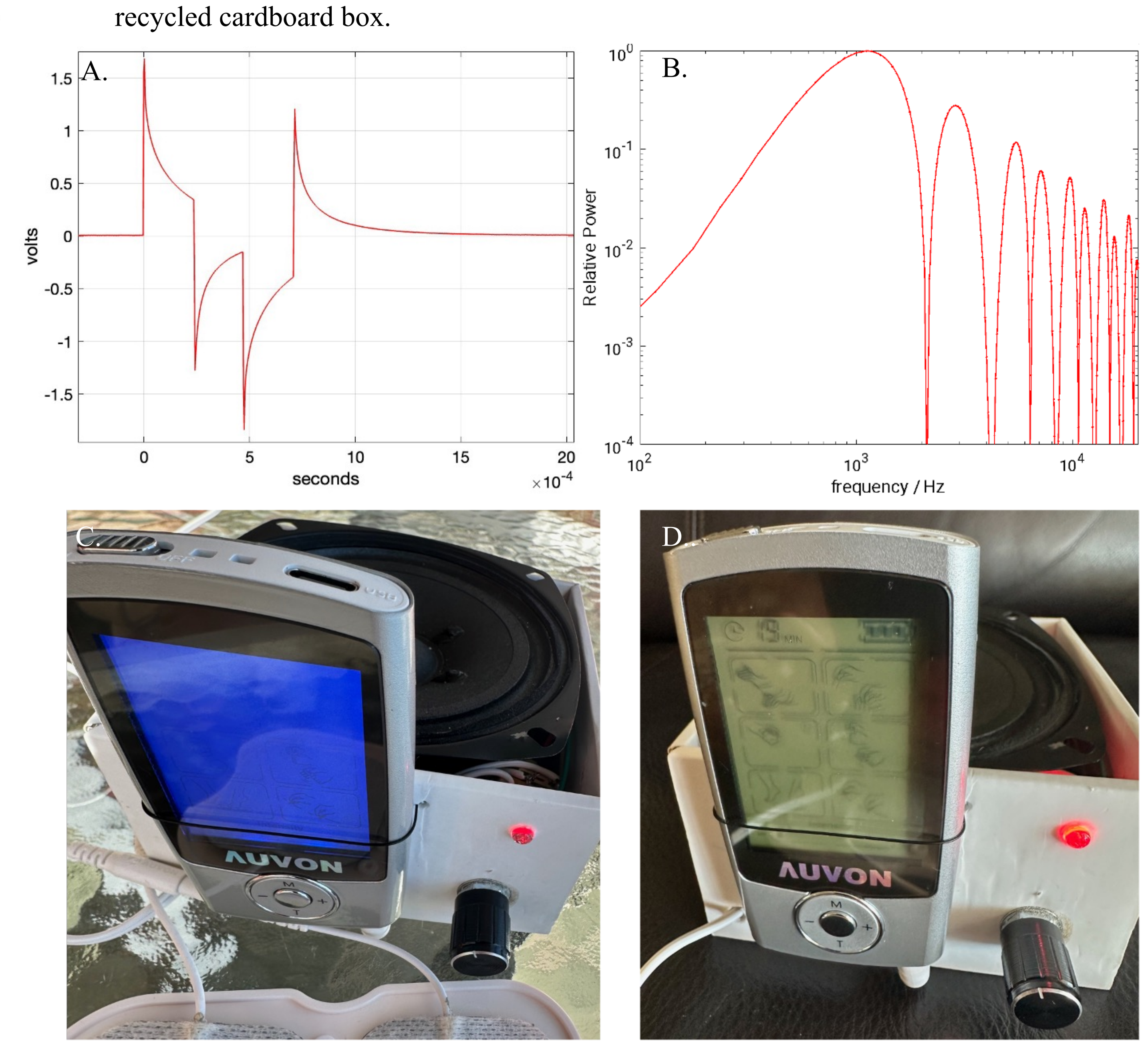


Figure. 1. Schematic and layout of the device.

Results

The transformer coupled signal (Fig. 2) appeared constant across TENS settings, except for variable amplitude and interpulse interval. Amplitudes to 40Vp-p were measured. The TENS spectrum conveniently has peak energy in the middle of the auditory spectrum, and the combined sound is not unpleasant, hence no filtering was applied. Keeping it simple! 'Everything should be made as simple as possible, but not simpler,' paraphrasing from a 1933 lecture by Einstein.

Figure 2. A. Oscilloscope trace of the transformer-coupled TENS signal, and B. its power spectrum confirms rich harmonic content. C.,D. Images of a unit mounted in a recycled cardboard box.



Discussion

Using it

From our reading of the literature, where the electrodes are placed shouldn't matter as long as they generate a perceptible sensation. The inner arm below the elbow and on the wrist is convenient and produces a dynamic sensation in my fingers as stimulus program #2 ramps up the amplitude and inter-pulse frequency. The sound is also dynamic and not unpleasant. We suggest setting the stimulus to a perceptible and comfortable level, and then adjust the volume to a comfortable (background) level. The goal is bimodal stimulation, not pain nor discomfort!

Take detailed notes about what parameters you are trying, and how your tinnitus responds. There's more about the brain that we don't know than what we know – so empirical testing is key. What works well initially perhaps is due to its novelty, and may become habituated, so changing parameters is likely a more effective ingredient of the optimal recipe. Moving the electrodes around your body, switching TENS programs, and co-varying concurrent activities, are probably all beneficial (and *changing* programs maybe more important and relevant than which programs you use). The flexibility of a TENS system could make it more effective than Lenire's.

Risks and Dangers

There is always a risk of electrocution when connecting any wall-powered appliance to you with low impedance electrodes on your skin. The $1 audio transformer provides significant isolation, but we strongly recommend using a battery to power the audio amplifier rather than a line-powered AC adapter. Likewise, don't use a TENS device while it is connected to a charger. As designed, this device is not *more* dangerous than the commercial TENS stimulator – which if misused can incur serious health risks. Educate yourself, consult with trusted health care providers, always use caution, and don't try this alone initially – have someone nearby who knows how to turn off the TENS stimulator.

References

[1] https://www.lenire.com/clinical-trials/
[2] https://ata.org/wp-content/uploads/2022/08/Tinnitus_Handicap_Inventory.pdf
[3] Conlon B et al. (2019) Noninvasive Bimodal Neuromodulation for the Treatment of Tinnitus: Protocol for a Second Large-Scale Double-Blind Randomized Clinical Trial to Optimize Stimulation Parameters. DOI: 10.2196/13176 . https://pubmed.ncbi.nlm.nih.gov/31573942/
[4] Conlon B et al. (2022) Different bimodal neuromodulation settings reduce tinnitus symptoms in a large randomized trial. Sci Rep. Jun 30;12(1):10845. doi: 10.1038/s41598-022-13875-x. https://pubmed.ncbi.nlm.nih.gov/35773272/
[5] Langguth B (2020) Non-Invasive Neuromodulation for Tinnitus. J Audiol Otol. Jul;24(3):113-118. doi: 10.7874/jao.2020.00052. (Review) https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7364190/
[6] https://en.wikipedia.org/wiki/Classical_conditioning
[7] https://en.wikipedia.org/wiki/Absolute_threshold_of_hearing
[8] https://en.wikipedia.org/wiki/Dorsal_cochlear_nucleus
[9] Baizer JS et al. (2012). Understanding tinnitus: the dorsal cochlear nucleus, organization and plasticity. Brain Res. 1485:40-53. doi:10.1016/j.brainres.2012.03.044.
[10] https://en.wikipedia.org/wiki/Otoacoustic_emission

Parts list

1. https://www.amazon.com/AUVON-Channel-Stimulator-Machine-Electrode/dp/B07D58V8LD/
2. https://www.amazon.com/HiLetgo-LM386-Audio-Amplifier-Module/dp/B00LNACGTY
3. https://www.amazon.com/BOJACK-EI-14-Efficiency-Isolation-Transformers/dp/B07Q6RSWYC
4. https://www.amazon.com/dp/B08ZL1C8CS

Further Reading

- Searchfield GD & Zhang J (eds.) 2021. The Behavioral Neuroscience of Tinnitus. Springer. https://link-springer-com.ezproxy.csuci.edu/book/10.1007/978-3-030-85503-1
- Rasnow B (2014) Electricity, eels and evolution. Review of Turkel, W. Spark from the Deep. Physics World 27(7):44-5. http://www.rasnowpeak.com/brian/pub/PWJul14reviews-rasnow.pdf

[Actual functioning device mounted here]