Aurora: Method and Means For A Bimodal Auditory/Lingual-Haptic Music Experiment

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We present a contribution to the field of human computer interaction in the form of hardware and software, and a proposal for an experiment backed by a novel theory of perception expressed in the language of cybernetics. In doing so, we hope to launch the field of study of bimodal audio and lingual-haptic media: music accompanied by timed gentle electrical pulses on the tongue. This is an ongoing music technology research project for musicians by musicians. The tools contributed construct a claimable quantity of capabilities knowledge.

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1 Introduction

We have built a prototype of a system for enhancing music by playing timed gentle electrical pulses to the tongue in precise timing with audio, or "lingual haptics". The idea came from the several existing uses of this tongue stimulation technology in the medical field [1–5]. The plan is to attempt to train a generative model to create this haptic media automatically. A means and method is disclosed for how to go about using the biosignal of gait in order to search for stimulation parameters for a new wearable device. Gait is chosen because when a person walks around listening to music, their gait often changes in response to the music they're listening to, and the gait signal is in the same frequency range as beats in music [6–8].

The hypothesis motivating the creation of this multimodal human computer interface is that there is a deep, meaning-laden relationship between the part of the brain that processes signals from the trigeminal nerve in the tongue, the part of the brain that processes audio, and the part of the brain that processes input from body movements like the sensations felt in the body while dancing [5, 9]. In this work we introduce a means and method to attempt to invalidate the null hypothesis that lingual haptic stimulation has no potential for enhancing music. Convincingly invalidating this null hypothesis provides a quantifiable knowledge step towards lingual haptics.

The system we've designed includes the following: a listener dons a pair of open-ear headphones and two foot-mounted inertial measurement units. Their footfalls and gait is recorded with low latency, measured precisely with the timing of the music. Secondly, the listener wears an intraoral tongue stimulation device that stimulates the tongue with gentle biphasic alternating electric current. The device is either off or on.

We develop a system to measure changes in gait while listening to music with and without tongue stimulation. In doing so, we hope to gain data and insight in a future study using human participants into the potential for a programmable wearable tongue stimulator to be a significant asset to the field of music [10].

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2 Background and Applicable Science

It has been established in prior research that there is a strong relationship between tongue stimulation, audio, and body movement. Most of these findings have appeared in a medical or wellness context through developing methods to heal and train the body and mind. The Djogger research project was the first to explore footfall tracking in order to help enhance exercise in 2006 [12]. Two in the 2010s, Weav and Rock My Run also launched similar systems for augmenting running workouts by changing the speed of songs played to match running pace [13, 14]. Most recently, in the 2020s, the Medrhythms startup, in a partnership with Universal Music Group, has obtained FDA approval for its InTandem music therapy technology. The InTandem system gently speeds up a song in order to encourage a person recovering from a movement disorder to exercise faster and more vigorously [11].

Perhaps surprisingly, another method has also shown itself to be effective for the same movement disorder therapy: neuromodulation via stimulation the tongue with gentle, but perceptible electric current. Specifically, the PONS bimodal tongue stimulation device has been proven to help patients recover from neurological-rooted movement disorders. Stimulating the tongue with electric current appears to activate brain circuits that are involved in learning coordination and physical motion. The PONS device received FDA approval for the treatment of multiple sclerosis [1].

Tongue stimulation has also been shown to be effective in soothing tinnitus, the phantom ringing in the ears caused by hearing damage. The mechanism behind the phantom noise in tinnitus has been linked to somatosensory (trigeminal) inputs converging with auditory input in the dorsal cochlear nucleus [5, 9]. Large randomized trials of bimodal neuromodulation (Lenire) reported clinically meaningful improvements, and the device received FDA De Novo classification in 2023 [2–4, 15].

There is likely a strong, deep connection between signals from the trigeminal nerve, audio signals, and corporeal signals involved in movement. There is a large gap in hardware and software that can be used to explore these fundamental features of human perception. Our study fills that gap.

3 Interface Design Rationale

In creating a system for studying how to augment music, we made decisions about which body signals to focus on and why.

Footfalls were chosen for this outing because the motion of the feet has been shown to be strongly correlated with entrainment to audio [6–8]. The act of walking around listening to music is also not necessarily an intentional action like dancing: it doesn't require conscious effort on the part of listeners to walk normally and to allow their gait to change naturally.

The intuition behind choosing footfalls is that because people might change their gait without noticing they're doing so, based on the rhythm of the song they hear, the gait signal a good candidate for investigating what the music is doing to the listener in a bottom-up neuroscience paradigm. That said, other signals are also attractive candidates, such as respiration and skin conductance to measure aesthetic chills: these may be explored in future work.

Further, this work expands on previous work by our team in creating interactive music that changes in response to footfall timing [16]. Adding a closed loop between the footfalls and the music could help strengthen the insights about what the tongue stimulation is doing under the hood.

We postulate that actuating the tongue of a walking listener may have an amplification effect on groove entrainment, measured by how gait changes. This is based on a review of the hypothesized mechanism for how tongue stimulation affects neural circuits involved in movement and audition, and on related work demonstrating haptic enhancement of musical engagement [5, 10].

4 Hardware And Software Prototype

In order to do the trimodal data science work to build our generative music enhancement system, we designed and built prototypes for custom hardware and software. First, we used two MbientLab inertial measurement units (MetaMotionS), one for each foot, streaming data over Bluetooth to a BLU J8L Android mobile phone [17, 18]. We made the footfall signal available in real time to the music playing entity on the android phone using the established methodology for accomplishing this engineering task, documented in prior work [16]. We separated the music player into a control and rendering modularity, where the control thread uses footfalls to send playback decisions to the rendering thread.

We detect footfalls using a bi-lstm and ZUPT, including real real-time detection on the android app.) [16, 19–22].

We also designed and built a custom tongue stimulator to deliver constant biphasic alternating current stimulation at 5000 Hz that can be turned off and on at the rate of IMU data collection. The tongue stimulator connects to the Android app over a USB cable. The point of this research is to create a wearable device to enhance the experience of listening to music. Our current version of the tongue stimulator is engineered similarly to the tools like developed for medical use, with comfort improvements. The tongue stimulation signal and comfortable hardware delivery of that meaningful signal will continue to be the focus of the next round of building hardware.

The sampling rate for the IMU data and the tongue stimulation is set at 200 Hz for collecting data, and this rate can be increased with a higher bandwidth networking protocol. The inaccuracies in the recorded timing for signal collection are limited to a few tens of milliseconds. The Mbient IMU we chose does not emit a timestamp for when the reading was made so we use the timestamp from the Android device clock.

Here follow a series of labeled photographs of the current iteration of custom-built hardware for this system

Fig. 1. Inertial measurement units for footfall detection.

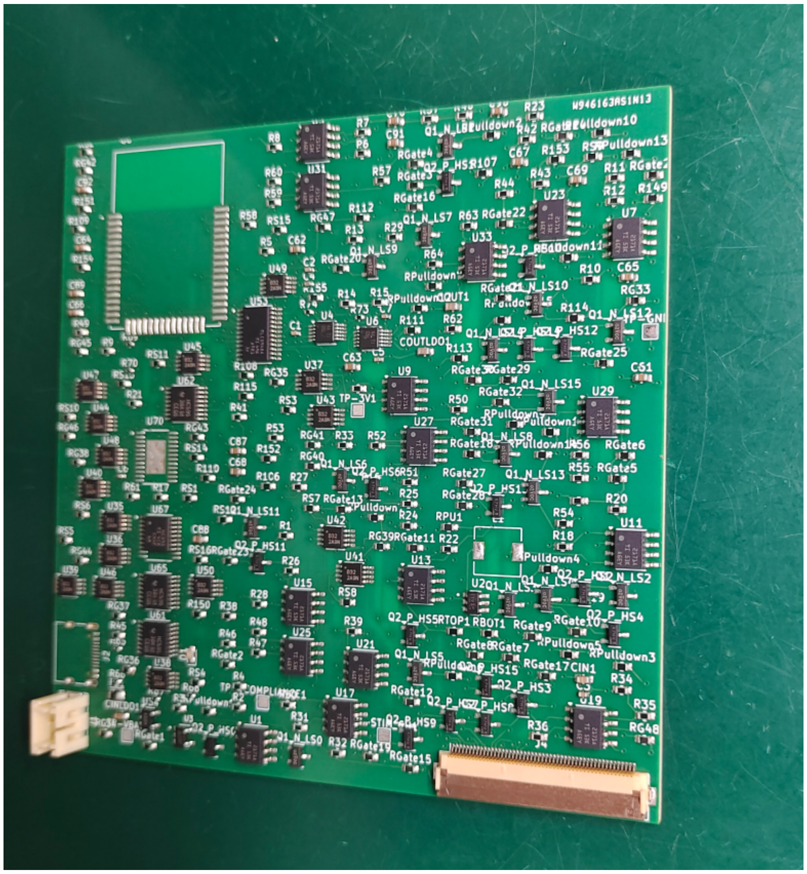


Fig. 2. Amplifier for delivering controlled biphasic current to the tongue strip.

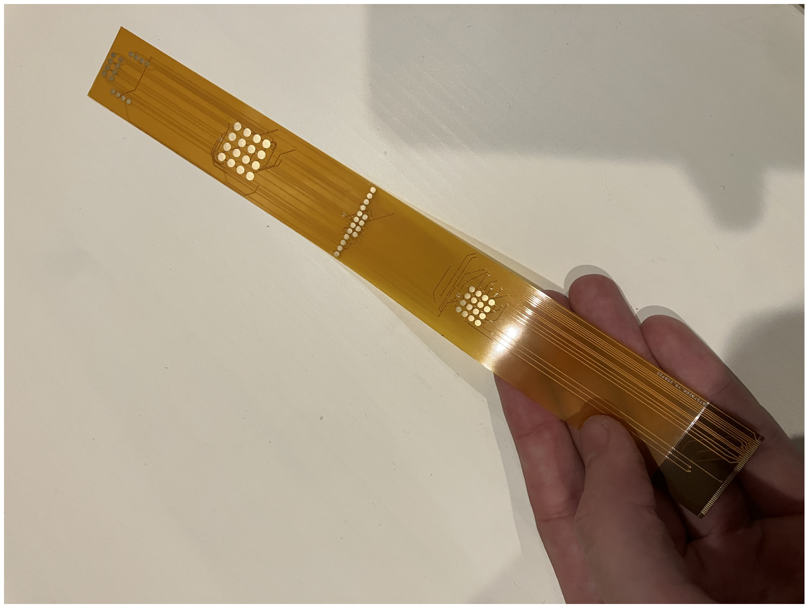


Fig. 3. Tongue stimulation tab with electrode array.

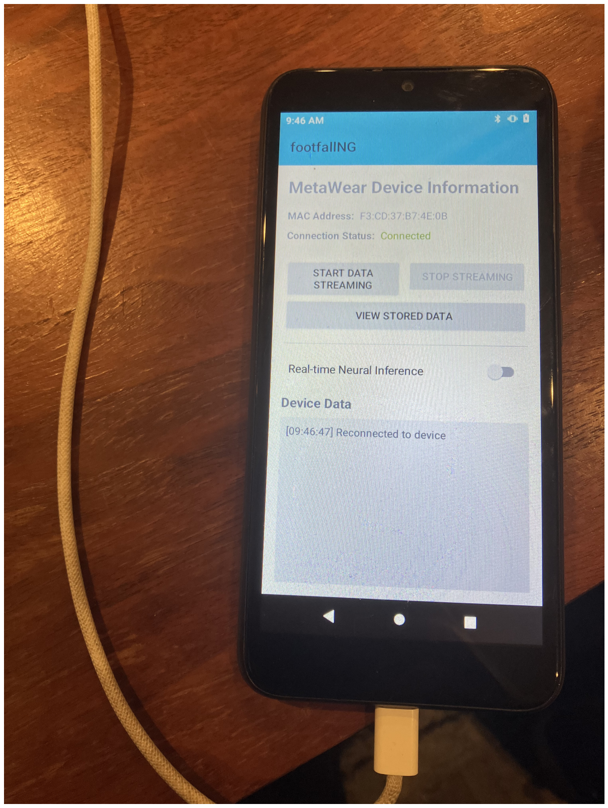
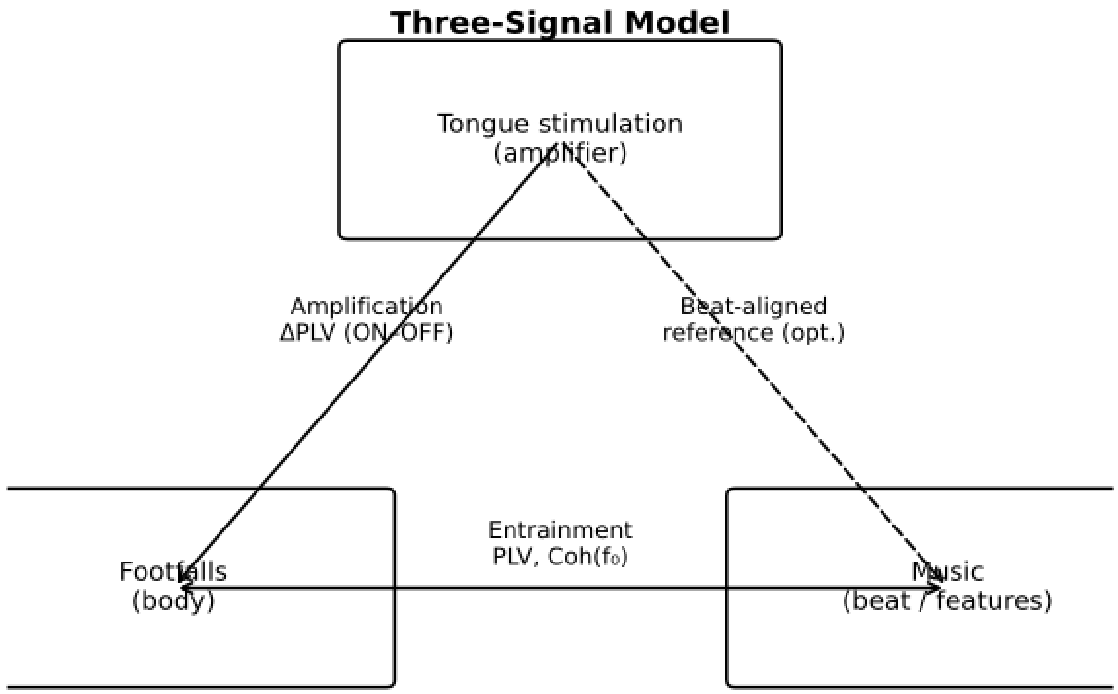


Fig. 4. Android phone used to collect data and control hardware

5 Proposed Cybernetic Model of The System

Below is a representation of the proposed underlying cybernetic components of this system:[23].



Components:

- **Tongue stimulation (amplifier)** at the top node represents the lingual stimulation signal.
- **Footfalls (body)** at the lower-left node represents the listener's gait events measured by the foot-mounted IMUs.
- **Music (beat / features)** at the lower-right node represents beat instants and other features extracted from the music.

The edges denote relationships and analysis targets:

- **Music ↔ Footfalls (base edge): Entrainment.** This captures how walking synchronizes with music. Typical readouts include *phase-locking value (PLV)* and *coherence at* f_0 (Coh(f_0)); see, e.g., neuronal entrainment work [7].
- **Tongue stimulation → Footfalls (left edge): Amplification.** This tests whether stimulation strengthens entrainment; a practical summary statistic is ΔPLV between *ON* and *OFF* conditions, i.e., ΔPLV (ON−OFF).
- **Tongue stimulation $\dashrightarrow$ Music (right edge, dashed): Beat-aligned reference (optional).**

A sample data set created by this schema might look like the following:

Table 1. Raw sensing streams and axes in the preliminary data set.

Stream	Axes	Symbol(s)	Unit	Rate	Notes
Foot IMU (accelerometer)	x, y, z	a_x, a_y, a_z	g	200 Hz	Shoe/body frame; used to estimate linear acceleration and vertical ("up") component.
Foot IMU (gyroscope)	x, y, z	$\omega_x, \omega_y, \omega_z$	deg/s	200 Hz	Angular velocity; used for stance/quiet detection and motion segmentation.
Audio beat instants	–	$\{\tau_k^{\text{beat}}\}$	s	events	Beat times from the detector (44.1 kHz front-end); mapped to grid as B_t (see Eq. (E1)).
Control index	–	$t \in \{1, \ldots, T\}$	bins	200 Hz	Control bins on the common clock ($t\Delta t$ is bin time).
Stim command	–	S_t	$\{0, 1\}$	200 Hz	Tongue stim on/off on the grid (can generalize to $[0, 1]$ amplitude).

Tables 1–3 summarize the streams, axes, grid-aligned variables, and the CSV schema used in the preliminary data set. Streams are aligned to a 200 Hz control grid (bin width $\Delta t = 1/200$ s). The audio is sampled at 44.1 kHz only to detect beat instants, which are then mapped to the 200 Hz grid. Beats are detected using the "beat this" library. [24]

Beat–Grid Mapping and Interpolations

Let the control grid have bin width $\Delta t = 1/200$ s and let $\{\tau_k^{\text{beat}}\}$ be beat instants from the audio front-end (44.1 kHz domain). For grid index $t \in \{1, \ldots, T\}$ with grid time $s_t = t\,\Delta t$:

Beat flag on grid. Each beat time τ_k^{beat} is assigned to its nearest grid bin

$$t_k \;=\; \arg\min_t \left| t\,\Delta t - \tau_k^{\text{beat}} \right|.$$

We then define the binary beat flag B_t as

$$B_t \;=\; \begin{cases} 1, & \text{if } t \in \{t_k\}_k, \\ 0, & \text{otherwise.} \end{cases} \tag{E1}$$

(If two beats would fall in the same bin—rare at musical tempi—keep B_t=1.)

Beat phase on grid. Define $k(t) = \max\{k : \tau_k^{\text{beat}} \le s_t\}$ (the most recent beat before s_t). The instantaneous musical-beat phase at grid time s_t is the linear interpolation between consecutive beats:

$$\phi_t \;=\; \operatorname{wrap}\!\left(2\pi\,\frac{s_t - \tau_{k(t)}^{\text{beat}}}{\tau_{k(t)+1}^{\text{beat}} - \tau_{k(t)}^{\text{beat}}}\right) \;\in [-\pi, \pi), \tag{E2}$$

where $\operatorname{wrap}(\cdot)$ maps angles to $[-\pi, \pi)$. For footfall events, let $\mathcal{I} = \{t : F_t{=}1\}$ be event bins and take $\{\phi_i\}_{i\in\mathcal{I}}$ when computing block-level PLV.

Table 2. Grid-aligned variables, derived features, and labels.

Variable	Definition	Range/Unit	Rate	Description
B_t	Beat flag on grid (see Eq. (E1))	$\{0, 1\}$	200 Hz	1 if a beat falls in bin t; can be extended to salience in $[0, 1]$.
ϕ_t	Beat phase on grid (see Eq. (E2))	$[-\pi, \pi)$	200 Hz	Unwrapped/wrapped phase of the musical beat at bin t.
F_t	Footfall event label	$\{0, 1\}$	200 Hz	1 if a footfall occurs in bin t (from detector/annotation).
S_t	Stim command	$\{0, 1\}$	200 Hz	On/off command; later extendable to continuous amplitude.
$\hat{\mathbf{g}}_t$	Unit gravity direction	unit vector	200 Hz	Estimated via causal low-pass of accelerometer.
$\mathbf{a}_t^{\text{lin}}$	$\mathbf{a}_t - \mathbf{g}_t$	g	200 Hz	Linear acceleration (gravity removed).
upAcc_t	$\mathbf{a}_t^{\text{lin}} \cdot \hat{\mathbf{g}}_t$	g	200 Hz	Linear acceleration projected onto gravity (vertical).
$\lVert\omega_t\rVert$	$\sqrt{\omega_x^2 + \omega_y^2 + \omega_z^2}$	deg/s	200 Hz	Gyro magnitude; used for stance/quiet gating.

Table 3. CSV schema (per row) used for logging and interchange.

Column name	Symbol	Unit	Description
`timestamp`	t_{ms}	ms since epoch	Board/sensor timestamp (or validated system time).
`accelerationX`	a_x	g	Accelerometer x axis (shoe/body frame).
`accelerationY`	a_y	g	Accelerometer y axis.
`accelerationZ`	a_z	g	Accelerometer z axis.
`gyroscopeX`	ω_x	deg/s	Gyro x axis.
`gyroscopeY`	ω_y	deg/s	Gyro y axis.
`gyroscopeZ`	ω_z	deg/s	Gyro z axis.
`sequenceNumber`	n	—	Monotone sample index from device/session.
`eventType`	—	—	Categorical: `sample`, `footfall`, etc.

6 Preregistered Human-Participant Experiment Towards Cautiously Invalidating Null Hypothesis

In a proposed experiment, we aim to validate cautiously a bottom–up, physiological hypothesis: *tongue (trigeminal) stimulation, music (beats/phase), and gait are strongly intertwined independent of semantic context.* To avoid overclaiming, we preregister an *experimental method* chosen intentionally to minimize analytic flexibility and to include active controls for common artifacts. [25, 26]. We report two distinct outcomes:

(1) **Group-level effect (existence).** Does tonic stimulation change gait–beat entrainment on average?
(2) **Population prevalence in group of study participants.** What fraction of individuals show an effect above a smallest effect size of interest (SESOI)?

Primary objective and null (group-level). With music playing, **tonic** tongue stimulation does *not* change entrainment of gait to the beat relative to stimulation OFF.

Primary endpoint (per block). At each footfall, compute the musical-beat phase ϕ; per-block phase locking value (PLV):

$$\text{PLV}_{\text{block}} = \left| \frac{1}{N} \sum_{i=1}^{N} e^{j\phi_i} \right|.$$

Per participant, aggregate $\overline{\text{PLV}}_{\text{ON}}$ and $\overline{\text{PLV}}_{\text{OFF}}$ as the *median* across valid blocks. Define the contrast $\Delta\text{PLV} = \overline{\text{PLV}}_{\text{ON}} - \overline{\text{PLV}}_{\text{OFF}}$.

6.1 Design Overview (Within-Subject, Double-Blind, Active Controls)

Stimulation conditions (blockwise randomized, double-blind): (i) **ON**: continuous, biphasic alternating current, tonic within the block;; (ii) **SHAM**: active sham consisting of a brief ramp up (2–3 s) to a perceptible sensation followed by a ramp down (2–3 s) to near-zero current for the remainder of the block;; and (iii) **OFF**: no current for the entire block. *D*uty-cycling or gating is **not** used during experimental blocks (to remain consistent with a tonic hypothesis); Ramps are used only at block transitions for the purposes of comfort and blinding. Intensity is calibrated to be comfortable during a pre-block procedure.

Analytic control (beat scrambling). In analysis, we recompute PLV against *irrelevant* beat sequences (e.g., beats from another track of the same tempo, or the true beats circularly shifted by a random offset). If stimulation only increases general regularity, entrainment estimates would stay elevated; if the effect is truly music-specific, PLV relative to the mismatched beats should not appear.

Blocks and randomization. 30 s blocks; 12 Music blocks (balanced ON/SHAM/OFF) and 6 No-Music blocks (balanced ON/OFF) per participant; order Latin-square–counterbalanced and randomized. Rests (10–20 s) between blocks.

Participants. Healthy adults (18–65), normal hearing, able to walk unaided ≥ 20 minutes. Exclusions (preregistered): oral lesions, implanted stimulators, neurological/vestibular disorders, pregnancy, or any contraindication to translingual stimulation.

6.2 Procedure

Consent → screening → stim titration → timing calibration → practice (1–2 blocks) → randomized blocks (Music and No-Music interleaved) → debrief. After each block: (i) comfort (Likert), (ii) perceived effort, (iii) blinding check (ON/SHAM/OFF forced choice). These are recorded for robustness; they do not alter assignment.

6.3 Analysis Plan

Preprocessing. IMU footfalls with preregistered detector; beats/phases with validated detector and quality guardrails. Block invalid if dropout or standstill >10%.

Primary group-level test. For each participant compute ΔPLV. Test $\mathbb{E}[\Delta\mathrm{PLV}] = 0$ via a *within-participant blockwise permutation test* (two-sided; $R \geq 10{,}000$) aggregated across participants by the median-of-means approach; report exact permutation p-value and 95% bootstrap CIs (blockwise resampling).

Music specificity (must-pass controls). (a) **No-Music (cadence regularity):** With no beat reference, PLV is undefined. We use the coefficient of variation of inter-step intervals ($\mathrm{CV}_{\mathrm{ISI}}$) per block as a generic arousal/regularity check. We define step event times $\{u_m\}$ from the detector; inter-step intervals are $\Delta u_m = u_{m+1} - u_m$. For each block, $\mathrm{CV}_{\mathrm{ISI}} = \frac{\mathrm{sd}(\{\Delta u_m\})}{\mathrm{mean}(\{\Delta u_m\})}$.(E3) We test $\Delta\mathrm{CV}_{\mathrm{ISI}} = \overline{\mathrm{CV}}_{\mathrm{ON}} - \overline{\mathrm{CV}}_{\mathrm{OFF}} \approx 0$ via the same within-participant permutation.; and (b) **Mismatched beat (scramble):** In Music blocks, recompute PLV against an irrelevant beat sequence (tempo-matched but phase-shifted or drawn from another track); here we expect $\Delta\mathrm{PLV} \approx 0$.

Expectancy control. Re-run the primary test after stratifying by *correct vs. incorrect* blinding guesses. We determine that a credible effect appears when guesses are wrong and is larger for ON vs. SHAM than SHAM vs. OFF.

Cadence covariate. Report stride time/variability per block; verify ΔPLV is not reducible to uniform cadence shifts (within-participant regression as robustness).

Table 4. Sample-size planning for a population-level claim (illustrative). Claim requires $\hat{p} \geq 2/3$ and the 95% Wilson lower bound > 0.5.

Observed responders $\hat{p}$	Participants n	Typical $L_{.95}(\hat{p})$
0.70	30	≈ 0.52
0.67	36	≈ 0.51
0.70	40	≈ 0.55

Equivalence if null. If the primary test is non-significant, perform TOST with SESOI $|\Delta\text{PLV}| < 0.03$ to claim a practically null effect.

6.4 Sample Size, Precision

We separate *existence* from *prevalence* and preregister both:

Stage A (existence, group-level). Aim: detect a small but meaningful average effect (SESOI $\approx$ 0.03–0.05 in ΔPLV). With 10–12 valid Music blocks per condition and a within-subject design, a cohort of n=20–24 typically affords 0.8 power in simulation for $\Delta\text{PLV} \approx 0.05$ (nonparametric permutation). Whereas stage A supports only a *group-level* conclusion.

Stage B (prevalence, generalization). We *operationalize* a general effect as: $\Pr\{\text{individual shows } \Delta\text{PLV} \geq \delta\} \geq 2/3$, where δ is the within-person SESOI (e.g., $\delta = 0.03$). An individual is a **responder** if their $\Delta\text{PLV} \geq \delta$ and a within-person permutation test (blockwise) is significant at α=0.05. Let $\hat{p} = k/n$ be the observed responder proportion.

We **will only claim** a general effect if the one-sided 95% Wilson lower confidence bound $L_{.95}(\hat{p})$ exceeds 0.5 (i.e., more than half) *and* $\hat{p} \geq 2/3$. For planning, the binomial margin of error near prevalence p is $\approx z_{.975}\sqrt{p(1-p)/n}$. Thus, with $\hat{p} \approx 0.67$, observing $n \geq 36$ typically yields $L_{.95}(\hat{p}) \gtrsim 0.50$; with $\hat{p} \approx 0.70$, $n \geq 30$ suffices.[1] **Preregistered rule:** we do *not* make any claim unless $n \geq 36$ and the Wilson lower bound satisfies $L_{.95}(\hat{p}) > 0.5$.

Interpretation discipline. Stage A alone (e.g., n=20) **cannot support** a general claim—even if significant on average. Stage A can motivate Stage B. Only Stage B, with the proportion test and $n \geq 36$, would support such language.

6.5 Threats to Validity and Mitigations

- **Expectancy/demand:** Active SHAM + double-blind; blinding checks; ON vs. SHAM reported.
- **Generic arousal:** No-Music and mismatched-beat controls should yield $\Delta\text{PLV} \approx 0$.
- **Timing/beat errors:** Latency/jitter gating; beat-confidence guardrails; preregistered exclusions.
- **Detector/floor effects:** Validated footfall detection, controlled surface; block/session exclusion rules.

6.6 Decision Criteria Must Be Clear Pass/Fail at Each Stage

Stage A (existence). Reject the null *only if*:

(1) Primary ΔPLV permutation test is significant (two-sided $p < .05$); *and*
(2) No-Music control shows $\Delta\text{CV}_{\text{ISI}}$ not different from zero (two-sided); and mismatched-beat PLV control shows effects not different from zero;
(3) ON vs. SHAM > SHAM vs. OFF (descriptively with CIs).

[1]Exact bounds will be computed with Wilson intervals; these approximations guide preregistration.

Stage B general. In addition to Stage A criteria, *and* with $n \geq 36$: the 95% Wilson lower bound on $\hat{p}$ exceeds 0.5 and $\hat{p} \geq 2/3$. Otherwise, no general claim is made.

If Stage A fails, we refrain from claiming an average effect and proceed to TOST to assess equivalence. If Stage A passes but Stage B fails, we only report the estimated $\hat{p}$ and CIs.

6.7 Transparency and Safety

We will preregister protocol, analysis code, and synthetic reproductions (OSF). We will share de-identified per-block summaries (PLVs, cadence) and redacted raw logs subject to IRB guidance. Safety will be paramount throughout. [25, 26].

7 Contributions and Significance

To the field of human computer interaction we present a novel cybernetic model, concrete artifacts, and a testable falsifiable hypothesis that can be tested in an experiment in the real world. If the null hypothesis, that tongue stimulation has no effect on music-gait entrainment, is disproven convincingly, this opens a path for continuing research on the capabilities of lingual haptics for music.

Note that even if the null hypothesis turns out to be true, it is still very likely that the signal of lingual haptic stimulation can be engineered to enhance music even without collecting any data. A human expert may very well be able to come up with a way to program the device that works. But in the case that the described experiment does work, it's a very clear zero to one that might hopefully enable this subfield of music technology research to come to life.

8 Conclusions and Sociology and Ethics Implications

To be clear, the point of this research project is to encourage human thriving through music. Technology that successfully enables a more vibrant medium for musical expression could have far-ranging interpersonal implications, hopefully to be harnessed for good. Also note that a popular bioelectric toothbrush with the same biophysical risk profile is available over the counter for consumer use [27].

A dream is that our wearable device could be used to elevate the profession of writing, recording, and performing music. For this reason, if this project gets off the ground, we may need to take measures to try and guarantee that new capabilities lead to ethical sociological results.

We would strongly advocate that this project be viewed as an information-ethics-sensitive methodology to generate new knowledge, at least until more is known.

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