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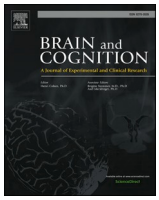

Theoretical Notes

Disturbing the sound of silence: Bilateral temporal cortex stimulation and auditory mental imagery

Benedetta Rollo, Gianluca Malatesta *, Anita D'Anselmo, Chiara Lucafò, Luca Tommasi

Department of Psychology – University "G. d'Annunzio" of Chieti-Pescara, Via dei Vestini, 31, 66100 Chieti, Italy

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ABSTRACT

Auditory imagery depends on temporal–cortical mechanisms that generate and sustain internal sound representations. If these mechanisms are causally involved, externally perturbing temporal cortex should alter the quality of imagery. We tested whether bilateral high-frequency transcranial random noise stimulation (hf-tRNS) over temporal cortex alters the vividness and control of auditory imagery. Forty-nine healthy adults completed two sessions on separate days, receiving Active hf-tRNS in one session and Sham in the other (order counterbalanced). The Bucknell Auditory Imagery Scale (BAIS; Vividness and Control subscales) was administered as two parallel half-forms to avoid item repetition; across the two sessions each participant completed the full BAIS, and the half-form paired with the Active session was counterbalanced across participants. Results showed reduced Control ratings under Active hf-tRNS compared with Sham, while Vividness showed a similar but weaker pattern. The effect was independent of which half was completed during Active hf-tRNS, the day-to-half mapping, the stimulation order, or prior musical training. These findings indicate that bilateral hf-tRNS can transiently disrupt the volitional control of internally generated auditory representations, plausibly by perturbing temporal-cortical dynamics that support auditory imagery.

1. Introduction

The term mental imagery refers to the capacity to generate perceptual-like experiences in the absence of corresponding external stimuli (Pearson et al., 2015). These internally generated representations are not limited to the recall of past events or objects but can also arise from novel recombination of perceptual elements previously encoded in memory (Kosslyn et al., 2001). Beyond the mere retrieval of stored sensory information, mental imagery plays a crucial role in several domains of cognition, including learning and reasoning (Boccaccio et al., 2024; Talamini et al., 2023). Owing to their perceptual origin, mental images can be visual, auditory, olfactory, tactile, or motor/kinesthetic in nature. Importantly, their generation may occur both consciously and unconsciously—much like perception itself, which is typically triggered by the presence of an external sensory stimulus (Kosslyn et al., 2001; Nanay, 2020).

Although early work on mental imagery was centered on the visual modality (Galton, 1880; Kosslyn et al., 2001; Marks, 1973; Pearson et al., 2015), subsequent research has extended the focus to auditory imagery, a heterogeneous phenomenon encompassing musical, verbal and inner speech, and environmental sounds (Halpern, 2015; Hubbard, 2010). In line with this diversity, measurement approaches have included self-report questionnaires, behavioral tasks, and neurophysiological assays (Halpern, 2015; Halpern et al., 2004; Zatorre & Halpern, 2005). Clinically, case work first documented loss of imagery (Zeman et al., 2010) and later introduced the term *aphantasia* to denote the marked reduction or absence of voluntary imagery (Zeman et al., 2015); more recently, the auditory-specific counterpart, *anauralia*, has been proposed (Hinwar & Lambert, 2021; see also Monzel et al., 2022 for multisensory variants).

Converging neuroimaging and behavioral evidence indicates that auditory imagery engages superior/middle temporal regions that also support perception, consistent with a *quasi*-perceptual account (Samson & Zatorre, 1994; Zatorre et al., 1996). Complementary behavioral evidence from language processing further supports this view: studies employing dichotic listening tasks have shown that the typical right-ear/left-hemisphere advantage persists even in the absence of external auditory input, suggesting that lateralized patterns of perceptual processing in the linguistic domain extend to internally generated auditory experiences (Marzoli et al., 2022; Prete, D'Anselmo, Brancucci, et al.,

* Corresponding author at: Via dei Vestini, 31, c/o Blocco A Psicologia, 66100 Chieti, Italy.
E-mail address: gianluca.malatesta@unich.it (G. Malatesta).

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2018; Prete, D'Anselmo, Tommasi, et al., 2018; Prete et al., 2024).

Auditory imagery reliably engages temporal cortex and, in tandem, recruits inferior prefrontal regions (memory retrieval/selection) and the supplementary motor area (internal sequencing), a pattern reported across musical imagery and inner speech tasks (Halpern et al., 2004; Halpern & Zatorre, 1999; Lotze et al., 1999; Zatorre et al., 1996). In inner speech, Shergill and colleagues (2001) observed a left-lateralized fronto–temporo–parietal network with SMA and right cerebellum; imagined speech elicited bilateral activity including precentral and superior temporal gyri. Crucially, auditory regions activate without acoustic input—as during musical imagery—underscoring their central role and their coupling with motor systems, particularly in trained musicians (Zatorre & Halpern, 2005).

While neuroimaging consistently links temporal cortex to auditory imagery, a key next step is to test whether this activity plays a causal role. To address this causal gap, we asked whether high-frequency transcranial random noise stimulation (hereafter hf-tRNS) over temporal cortex alters the subjective ratings of auditory imagery. hf-tRNS delivers broadband alternating currents (100–640 Hz) that can interact with ongoing activity in a state-dependent, sometimes nonlinear manner (Miniussi et al., 2013; Terney et al., 2008). Mechanistically, effects have been linked to stochastic resonance—noise-assisted amplification of weak signals (McDonnell & Ward, 2011)—and to changes in sodium-channel dynamics or network-level signal-to-noise (Chaieb et al., 2015; Paulus et al., 2016; Schoen & Fromherz, 2008). Behaviorally, facilitation has been reported in visual/parietal cortices (Cappelletti et al., 2013; Fertonani et al., 2011; Fertonani & Miniussi, 2017) and interference when targeting right dorsolateral prefrontal cortex (Ambrus et al., 2011). In audition, where temporal precision is critical, effects appear regime-dependent—improvements near threshold but possible disruption at supra-threshold timing (van der Groen and Wenderoth, 2016; Pavan et al., 2019; Rufener et al., 2017)—with reports in auditory-imagery contexts using bilateral temporal montages (e.g., Prete et al., 2017).

We assessed imagery with the Bucknell Auditory Imagery Scale (BAIS; Halpern, 2015), a standardized instrument comprising two subscales: Vividness (clarity/intensity of the imagined sound) and Control (capacity to voluntarily modify or replace it). The prompts span musical, verbal, and environmental content and have been used in healthy and clinical samples (Bacon et al., 2020; Halpern et al., 2004; Prete, D'Anselmo, Brancucci, et al., 2018; Regev et al., 2021). We chose the BAIS because it samples multiple auditory domains with parallel prompts, offers separable, psychometrically supported dimensions, and is sensitive to individual differences (and, plausibly, to subtle state-related changes), while remaining brief and standardized for repeated administration.

Given that auditory imagery relies on finely tuned temporal–cortical dynamics and predictive regimes, we reasoned that adding broadband neural noise to bilateral temporal cortex in this suprathreshold, self-generated imagery task would be more likely to disrupt the temporal precision and excitability balance that support internally generated sounds. This expectation is consistent with reports that auditory tRNS can interfere with supra-threshold temporal processing while sometimes facilitating detection of near-threshold stimuli through stochastic resonance (van der Groen and Wenderoth, 2016; Pavan et al., 2019; Rufener et al., 2017). Accordingly, we predicted that bilateral hf-tRNS, compared with Sham, would reduce BAIS ratings of both Vividness and Control across musical, verbal, and environmental prompts.

2. Method

2.1. Participants

Participants were recruited on a voluntary basis from the local university campus. Each participant took part in two experimental sessions, scheduled on separate days with a minimum interval of 24 h. A total of 54 individuals initially agreed to participate; however, five did not complete both sessions and were excluded from the final analysis. The final sample consisted of 49 participants (25 females, $M_{age} = 22.4$ years, $SD = 1.73$; 24 males, $M_{age} = 22.04$ years, $SD = 2.07$; age range: 18–27 years). However, this sample is larger than what is typically found in comparable brain stimulation studies, addressing concerns about underpowered designs in cognitive neuroscience (Minarik et al., 2016; Szucs & Ioannidis, 2020), and particularly appropriate given the high effectiveness of tRNS in preserving participant blinding (Ambrus et al., 2010; Sheffield et al., 2022).

Handedness was assessed using the Edinburgh Handedness Inventory (Oldfield, 1971; Salmaso & Longoni, 1985), which provides a laterality quotient (LQ) ranging from –1 (strongly left-handed) to + 1 (strongly right-handed). Based on this measure, the sample included 6 left-handed ($M_{LQ} = -.657$, $SD = 0.432$) and 43 right-handed ($M_{LQ} = 0.756$, $SD = 0.252$) individuals.

2.1.1. Musical background

Participants completed a brief custom self-report questionnaire comprising three 5-point Likert-scale items assessing their musical background and habits: i) enjoyment of music, ii) daily listening frequency, and iii) prior musical training. Most participants (71.4 %) reported liking music "a lot," 22.4 % "enough," and 6.1 % gave neutral or negative responses. Regarding listening habits, 53.1 % reported 1–2 h of music per day, 20.4 % for 3–4 h, 6.1 % for more than 4 h, 18.4 % for less than 1 h, and 2.0 % reported not listening to music at all. Based on prior training, participants were classified as *Non-Musicians* (n = 25; no instruction in music or singing) and *Trained Musicians* (n = 24; with at least some instruction). Among the latter, 75.0 % reported 1–3 years of training, 12.5 % less than 1 year, and 12.5 % between 4–5 years.

2.2. Materials

2.2.1. Bucknell auditory imagery scale (BAIS)

The main measure used in this study was the Bucknell Auditory Imagery Scale (BAIS; Halpern, 2015), a validated self-report questionnaire designed to assess the subjective vividness and controllability of internally generated auditory experiences. Accordingly, it comprises two parallel subscales: Vividness (BAIS-V), which captures the clarity and intensity of imagined sounds, and Control (BAIS-C), which assesses the ability to intentionally transform one auditory image into another. Each subscale includes 14 items covering three domains of auditory imagery: musical, verbal, and environmental sounds. Importantly, the items in BAIS-V and BAIS-C are structurally parallel: for every vividness item that prompts the participant to generate a specific auditory image, there is a corresponding control item that asks the participant to imagine changing that image to another sound within the same context (e.g., imagining a trumpet and then switching to a violin playing the same melody). Participants were instructed to read each prompt, form the requested auditory image as vividly as possible, and then provide an immediate, intuitive rating for each item. For Control items, they were explicitly asked to imagine replacing the initial sound with the alternative one and to rate how easily they could perform this transformation, rather than how much they liked the sounds. Responses were given on a 7-point Likert scale (1–7), with higher scores reflecting greater vividness on BAIS-V and greater ease of control on BAIS-C. Accordingly, total scores on each subscale can range from 14 to 98, with higher scores reflecting either greater clarity and intensity of auditory imagery (BAIS-V) or greater voluntary control over imagined sounds (BAIS-C). Overall, participants reported a mean total score of 65.35 ($SD = 13.93$) on the BAIS-V and 72.00 ($SD = 13.56$) on the BAIS-C, with observed scores ranging from 32 to 98 across both scales. No additional general imagery questionnaires were administered, as the BAIS was selected as a modality-specific, psychometrically validated measure of auditory imagery vividness and control.

2.2.2. BAIS scores by prior musical training

Notably, musical training did not affect BAIS performance in our sample: Trained Musicians scored slightly higher on BAIS-V ($M = 67.96$, $SD = 14.32$) than Non-Musicians ($M = 62.84$, $SD = 13.35$), but this was not significant ($t_{(47)} = 1.295$, $p = 0.203$); the same held for BAIS-C (Trained Musicians: $M = 73.63$, SD = 12.92; Non-Musicians: $M = 70.44$, SD = 14.25; $t_{(47)} = 0.819$, $p = 0.417$). Given the absence of baseline BAIS differences between Trained Musicians and Non-Musicians, prior musical training was not included as a factor in subsequent analyses.

2.2.3. BAIS split-half item-sets

To prevent repeated exposure to identical prompts across sessions (which could lead to practice effects or memory-based biases; e.g., Bartels et al., 2010), the full BAIS was divided into two parallel half-forms: Block A contained the odd-numbered BAIS-V items (1, 3, 5, 7, 9, 11, 13) and their one-to-one BAIS-C controls, and Block B the even-numbered items (2, 4, 6, 8, 10, 12, 14) with matches. Each participant completed one half in one session and the complementary half in the other. The pairing preserved the vividness–control correspondence and kept a balanced mix of musical, verbal, and environmental prompts in both halves. We refer to these two half-forms as Odd and Even item-sets.

2.2.4. Counterbalancing across days and stimulation order

Block fixed the day-to-half mapping (Block A: Day 1 = Odd, Day 2 = Even; Block B: Day 1 = Even, Day 2 = Odd). Order specified the sequence of stimulation (Active-then-Sham *vs* Sham-then-Active). For brevity, hereafter we refer to the hf-tRNS session as "Active" and to the placebo session as "Sham." Combining Block with Order yields, for each participant, the Active Half (Odd *vs* Even), that is, which BAIS half was administered during the Active stimulation session (the complementary half necessarily occurring under Sham). Participant assignment to Block A or Block B was counterbalanced across the sample. Within each participant, the day-to-half mapping was fixed (i.e., not re-randomized across sessions), so that each BAIS half was administered once under Active and once under Sham at the group level. This mapping (see Table 1) underlies the within-subject Active − Sham (AmS) contrast used in the analyses.

2.3. Stimulation protocol

hf-tRNS was delivered by a battery-driven constant-current stimulator (DC-Stimulator, NeuroConn GmbH, Germany) using two 5 × 5 cm saline-soaked sponge electrodes placed bilaterally at T3/T4 according to the international 10–20 EEG system, targeting the overlying temporal cortex. Stimulation intensity was 1.5 mA (zero offset) with randomized high-frequency noise (100–640 Hz). Active stimulation lasted 20 min with 15-s fade-in/out; in the Sham condition, current was applied for 15 s only (Fig. 1). Participants were not informed which session involved Active versus Sham stimulation and were told that stimulation parameters could vary across sessions. At the end of each session, they indicated whether they believed the stimulation had been Active or Sham, or reported being unsure. Correct identification was low (Session 1: 34 %; Session 2: 43 %), indicating that participants could not reliably distinguish Active from Sham. The brief 15-s stimulation in the Sham condition, combined with identical electrode placement and fade-in/fade-out timing, was chosen to mimic the cutaneous sensations of Active hf-tRNS and support participant blinding, in line with prior work showing that tRNS is generally well tolerated and difficult to distinguish from sham at 1.5 mA (Ambrus et al., 2010; Sheffield et al., 2022).

2.4. General procedure

Each participant completed two sessions on different days (≥ 24 h apart) to limit carryover (including residual cortical excitability). At the first session, participants provided informed consent and completed preliminary self-report measures for handedness and musical background. Electrodes were fitted before each session; stimulation followed the protocol as in section 2.3. Ten minutes after stimulation onset, the BAIS questionnaire (one half-form per session; duration: 8–10 min; see section 2.2.3) was administered via Qualtrics on a desktop computer. The 10-minute delay between stimulation onset and BAIS administration was chosen to ensure that task performance occurred during the plateau phase of hf-tRNS-induced excitability changes, in line with standard tRNS protocols in perception and cognition (Fertonani et al., 2011; Terney et al., 2008). Given the 8–10 min duration of the questionnaire, the entire BAIS half-form was thus completed while stimulation was ongoing in this steady-state window. At baseline, 27 participants started with Block A and 22 with Block B. Assignment of the Active Half (Odd/Even) and stimulation Order was counterbalanced across participants (see section 2.2.4; Table 1). The remaining half-form was completed in the second session. Groups were approximately balanced by sex and by Order to minimize order-related biases. All procedures were approved by the local Institutional Review Board of Psychology (see the Ethics Statement) and conducted in accordance with the Declaration of Helsinki.

2.5. Statistical analysis

For BAIS-V and BAIS-C we computed, for each participant, a within-subject Active − Sham (Active-*minus*-Sham; hereafter AmS) contrast determined from session order (Active at Day 1 *vs* at Day 2). Testing whether mean AmS ≠ 0 (two-tailed one-sample *t* with 95 % CI) yields the stimulation effect for split-half crossovers. We then ran an ANOVA (GLM) on AmS including three between-subject factors: Active Half (Odd *vs* Even), Block (A *vs* B), and Order (Active-then-Sham *vs* Sham-then-Active). As a convergent analysis, we modelled Δ = Day 2 − Day 1 and compared the two levels of Order in a GLM including Block (difference-in-differences; hereafter DiD). We defined the Order contrast as (Sham-then-Active) − (Active-then-Sham); under this parameterization, the Order contrast = 2 × AmS, therefore the implied AmS estimate is (Order contrast) / 2 (sign preserved).

Table 1
Mapping from Block × Order to the BAIS half administered during the Active session ("Active Half"). The complementary half necessarily occurred under Sham. "Day of Active session" indicates whether Active occurred on Day 1 or Day 2. Cell values report the Active Half (Odd/Even) and n per cell.

Order	Day of Active session	Block A	Block B	Total *n*
Active–then–Sham	1	Active Half = Odd (n = 14)	Active Half = Even (n = 10)	24
Sham–then–Active	2	Active Half = Even (n = 13)	Active Half = Odd (n = 12)	25
Total *n*		27	22	N = 49

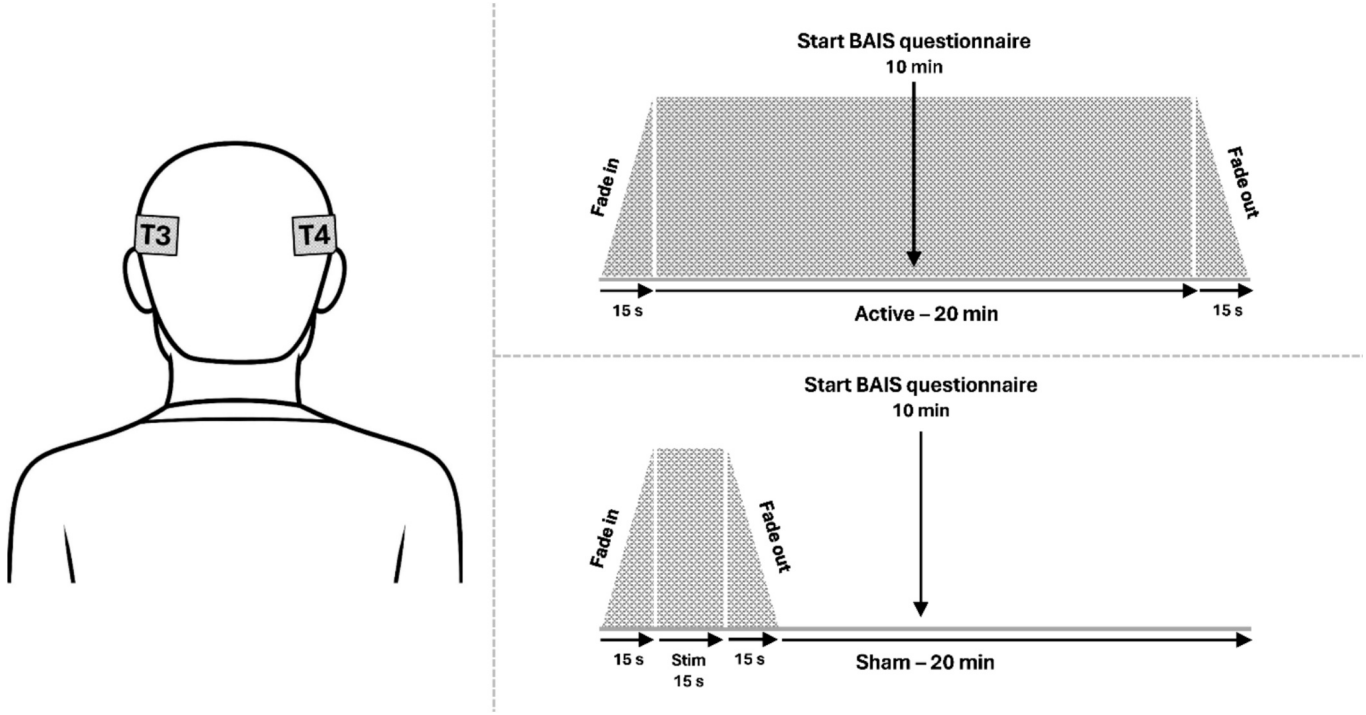

Fig. 1. (**Left**) Electrode montage for bilateral hf-tRNS over T3/T4. (**Top right**) Active profile: 20 min stimulation with 15-s fade-in/out; the task began 10 min after onset. (**Bottom right**) Sham profile: 15 s stimulation (plus 15-s fade-in/out); the task began at the same time as in (Top right). Schematic only; profiles are not on scale.

Two endpoints (Vividness, Control) were prespecified; we controlled family-wise error rate (FWER) at 0.05 using Bonferroni by testing each endpoint at $\alpha = 0.025$ (two-tailed); reported *p*-values are uncorrected. We report means, standard deviations (SDs), 95 % confidence intervals (CIs), *t*/*F*, *p*, Cohen's *dz* for AmS and partial η^2 for models. Analyses were performed in SPSS v20. A post-hoc sensitivity analysis (G*Power 3.1) indicated that, with N = 49 and $\alpha = 0.025$ (two-tailed), our repeated-measures design had 80 % power to detect within-subject effects of approximately Cohen's $dz \geq 0.40$; smaller effects may have gone undetected.

3. Results

3.1. Primary within-subject stimulation effect (AmS)

The AmS contrast showed a significant reduction in Control (BAIS-C: $M_{(AmS)} = -2.16$, $SD = 4.85$, 95 % CI [−3.56, −0.77], $t_{(48)} = -3.12$, $p = 0.003$, Cohen's $dz = 0.45$). Vividness showed a convergent, non-significant decrease (BAIS-V: $M_{(AmS)} = -1.67$, $SD = 5.95$, 95 % CI [−3.38, 0.03], $t_{(48)} = -1.97$, $p = 0.055$, $dz = 0.28$; Fig. 2).

3.2. Robustness to item-set assignment and order

ANOVAs on AmS including the between-subject factors Active Half (Odd *vs* Even), Block (A *vs* B), and Order (Active-then-Sham *vs* Sham-then-Active) confirmed the pattern: for BAIS-C, the stimulation (session) effect (AmS ≠ 0) was significant ($F_{(1,45)} = 8.68$, $p = 0.005$, partial $\eta^2 = 0.162$), with no main effects of Active Half, Block, or Order and no interactions; for BAIS-V, the stimulation effect was borderline ($F_{(1,45)} = 3.92$, $p = 0.054$), again with no main effects or interactions.

The DiD analysis on Δ = Day 2 − Day 1 replicated these estimates: for BAIS-V, the Order contrast was − 3.417 ($SE = 1.653$, $p = 0.044$), implying AmS = − 1.71; for BAIS-C, the Order contrast was − 4.228 ($SE = 1.383$, $p = 0.004$), implying AmS = − 2.11.

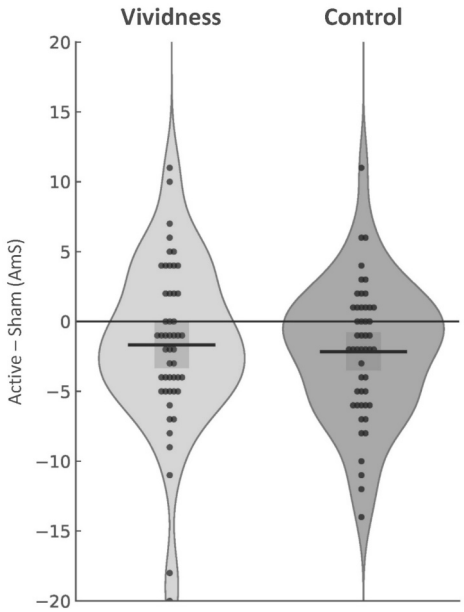

Fig. 2. Within-subject Active − Sham (AmS) contrasts for BAIS-Vividness (**left**) and BAIS-Control (**right**). Violin plots depict the score distributions; jittered dots show individual participant AmS scores. Thick horizontal line = mean; shaded band = 95 % CI. Both variables share a common y-axis for direct comparability. Negative values indicate lower scores under Active relative to Sham.

3.3. Raw BAIS scores by stimulation condition

For completeness, descriptive statistics for raw BAIS scores in the Active and Sham sessions (means and standard deviations for Vividness and Control) are reported in Table 2.

Table 2
Raw BAIS scores by stimulation condition. Means (M) and standard deviations (SD) of Vividness (BAIS-V) and Control (BAIS-C) total scores in the Active and Sham sessions (N = 49). Higher scores indicate greater vividness or greater voluntary control of auditory imagery.

BAIS subscale	Stimulation	*M*	*SD*
Vividness	**Active**	31.84	7.93
Vividness	**Sham**	33.51	7.2
Control	**Active**	34.92	7.6
Control	**Sham**	37.08	6.78

4. Discussion

The present findings indicate that Control ratings for auditory imagery were lower under Active than Sham (AmS < 0), with a parallel—but non-significant—trend for Vividness. Crucially, the effect was estimated within-subject using an Active − Sham (AmS) contrast in a counterbalanced split-half crossover and was convergent under a difference-in-differences (DiD) analysis across Order conditions; no moderation by Active Half, Block, or Order was detected. By contrasting sessions within the same participants and differencing out day-specific shifts (Δ = Day 2 − Day 1), these analyses isolate the stimulation effect from item-set assignment and session order.

This observation aligns with neuroimaging evidence implicating superior and middle temporal regions in both perceived and imagined auditory information (e.g., Goldenberg et al., 1991; McGuire et al., 1996; Zatorre et al., 1996). In line with these findings, previous studies have shown that auditory imagery recruits not only auditory association areas but also lateralized language-related regions (Halpern & Zatorre, 1999; Marzoli et al., 2022; Prete, D'Anselmo, Brancucci, et al., 2018), supporting the view that internally generated auditory content engages networks partially overlapping with those of perception.

Among non-invasive stimulation methods, tRNS differs mechanistically from tDCS (e.g., Sheffield et al., 2022), delivering random-frequency alternating currents that can alter cortical excitability and interact with plasticity-related processes (Terney et al., 2008). In the present context, the pattern of results is consistent with a transient disruption of internally generated auditory representations, plausibly via an impact on the ongoing oscillatory activity of temporal cortex during imagery generation.

In visual and motor domains, performance enhancements under tRNS have been interpreted as compatible with stochastic resonance accounts (e.g., van der Groen & Wenderoth, 2016; Pavan et al., 2019), with reports of improved sensitivity and learning (Fertonani & Miniussi, 2017; Terney et al., 2008). Over auditory regions, outcomes appear more contingent on stimulus regime. For instance, tRNS improved temporal resolution near threshold only (Rufener et al., 2017), consistent with a non-linear, domain-sensitive response possibly constrained by auditory gamma-band tuning.

More generally, behavioral effects of non-invasive stimulation depend on the functional architecture and current state of the targeted system (Miniussi et al., 2013). Reports of state- and stimulus-dependent facilitation or disruption—including findings modulated by stimulus dynamics or affective content (Malatesta et al., 2024)—underscore that the interaction between neural noise and signal processing is system-specific rather than uniformly enhancing. The interaction between neural noise and signal processing varies across domains, and in the case of the auditory cortex, increased noise may not uniformly enhance processing but could disrupt finely-tuned oscillatory regimes critical for temporal precision. Furthermore, individual differences in baseline excitability, age, brain state, and hormonal profile can modulate tRNS responsiveness (Krause & Cohen Kadosh, 2014), potentially explaining variability in results across domains and individuals. This variability is especially relevant in auditory tasks that rely on precise temporal encoding, possibly making the auditory system more susceptible to overstimulation or dysregulation under noisy input.

Interestingly, in the present study, Control decreased significantly under Active hf-tRNS (AmS < 0), whereas Vividness showed a parallel decrease that did not meet the prespecified family-wise threshold (α = 0.025). This partial dissociation aligns with prior neuroimaging evidence suggesting that vividness and control may rely on partially distinct neural substrates, particularly within the auditory association cortex and prefrontal areas (Halpern & Zatorre, 1999). Moreover, recent research has introduced the notion of anauralia, a condition characterized by impairments in auditory imagery vividness or controllability, further supporting the view that these two dimensions, while correlated, may reflect separable mechanisms with differential susceptibility to neuromodulatory interventions (Hinwar & Lambert, 2021).

An alternative interpretation could be that the reduced performance under hf-tRNS reflects general disruption of task-related attention or working memory processes (e.g., Ai et al., 2024), rather than a direct interference with auditory imagery per se. However, additional evidence supports the view that auditory imagery is tightly linked to anticipatory neural activity in language-related areas. The low task demands and the within-subject AmS/DiD estimators—which subtract session-level shifts—argue against a purely general-state account, although dedicated controls (e.g., non-imagery attention tasks) would adjudicate this more directly. For instance, Magrassi and colleagues (2015) demonstrated that electrocorticographic recordings from Broca's area and the dominant temporal cortex during awake neurosurgery show a close match between the electrical signal and the acoustic envelope of internally generated words, even in the absence of overt speech. These findings suggest that imagining a sound entails a predictive oscillatory process that simulates its acoustic features before articulation. From this perspective, hf-tRNS may disrupt imagery not by degrading the mental image itself, but by interfering with the fine-tuned temporal structure that normally underlies its generation. This interpretation aligns with models that emphasize the importance of internal forward models and temporal prediction in sensorimotor and cognitive domains. Notably, this view is further supported by evidence of stronger left-hemisphere engagement during inner speech and verbal imagery, especially in individuals with a pronounced right-ear advantage, suggesting that auditory imagery relies on lateralized predictive mechanisms within the speech perception network (Marzoli et al., 2022; Prete, D'Anselmo, Brancucci, et al., 2018; Prete et al., 2024). Nevertheless, future studies should consider including control tasks to disentangle imagery-specific effects from broader cognitive interference—such as attentional or working memory disruption—even though the present task was relatively undemanding.

Although our data are purely behavioral and were obtained in healthy participants, they may offer tentative clues for clinical phenomena involving internally generated auditory experiences, such as tinnitus or auditory hallucinations. Any translational implication, however, is speculative and would require explicit testing in clinical samples. In this regard, chronic non-pulsatile tinnitus is often framed as maladaptive plasticity with altered excitability and synchrony along auditory pathways (De Ridder et al., 2015; Kaltenbach, 2011; Haider et al., 2018). Several studies report symptom reductions with bilateral tRNS over auditory cortex (e.g., Vanneste et al., 2013), though findings are mixed across protocols (Joos et al., 2015; Kreuzer et al., 2019) and recent reviews stress substantial heterogeneity (Alashram, 2024). Within mechanistic frameworks such as thalamocortical dysrhythmia (De Ridder & Vanneste, 2014), our lower control scores under Active hf-tRNS are compatible with a noise-sensitive auditory representation, but this convergence is far from direct evidence of clinical efficacy and any extrapolation remains tentative. A similar caution applies to auditory hallucinations, where abnormal activation of auditory regions without external input is well documented, individual differences in inner-speech lateralization may relate to vulnerability (Prete et al., 2024), and tDCS/tRNS have produces variable effects on positive symptoms (Mondino et al., 2022; Moseley et al., 2016). Taken together, these

findings suggest that auditory cortical regions are not passive relays but active contributors to the construction and regulation of internally generated auditory phenomena—voluntary, as in imagery, and involuntary, as in hallucinations or tinnitus.

The observed sensitivity of the BAIS to neuromodulatory effects is consistent with prior work highlighting its ability to capture meaningful individual variability across both clinical and healthy populations (Bacon et al., 2020; Regev et al., 2021). This supports its use as a valid instrument not only for assessing stable traits but also for detecting state-dependent changes induced by external interventions such as tRNS. In our data, AmS-based within-subject shifts were detectable on BAIS-C, consistent with BAIS capturing state-level modulations in addition to stable individual differences.

5. Limitations

This study presents some limitations. Although the counterbalanced split-half design and within-subject estimators (Active − Sham; DiD) were intended to reduce session variability, the reduction in BAIS-V did not meet the prespecified family-wise threshold ($\alpha = 0.025$), so conclusions on Vividness are more cautious than for the robust Control effect; nonetheless, convergence across analyses and parallel trends support a genuine modulation to be clarified with larger samples. The two BAIS halves were treated as parallel forms, which, despite counterbalancing (Block, Order, Active session), cannot fully exclude item-specific influences; future work could address this with item-level randomization or mixed-effects/IRT approaches. Outcomes relied on self-report scores; pairing them with physiological markers of temporal-cortical dynamics (e.g., EEG/fMRI) would strengthen mechanistic inference. Residual session factors (fatigue, circadian/context) may persist despite counterbalancing—DiD mitigates but cannot remove them. Another limitation is that we targeted only bilateral temporal cortex and did not include an active control site (e.g., parietal or occipital stimulation). Although the montage was theory-driven and converges with prior temporal-cortex imagery work, we cannot fully rule out non-specific effects of hf-tRNS; future studies using additional active control sites will be needed to establish the spatial specificity of the present effects. Finally, the sample size afforded reasonable precision for Control but left Vividness borderline; larger preregistered studies are warranted to refine effects and test moderators (e.g., baseline imagery ability).

6. Conclusions

The present study shows that Active stimulation was associated with reduced Control ratings in auditory imagery, with a similar but non-significant trend for Vividness. These results suggest that hf-tRNS may disrupt the temporal dynamics or excitability of auditory cortex processes sustaining internally generated sounds. More broadly, the findings reinforce the view that auditory imagery relies on active, generative mechanisms grounded in perceptual systems but shaped by top-down influences (e.g., Barsalou, 1999).

Future work should examine whether these effects generalize across modalities and stimulation protocols, and whether repeated sessions may modulate imagery abilities in lasting ways. Exploring cross-modal interactions (auditory, visual, tactile) and integrating behavioral with physiological measures will be critical to clarify the neural bases of imagery and its susceptibility to neuromodulatory input.

Ethics Statement

All procedures were reviewed and approved by the Institutional Review Board of Psychology – Department of Psychology of the University "G. d'Annunzio" of Chieti–Pescara (approval number 24050, issued on 24 January 2025), and were conducted in accordance with the Declaration of Helsinki.

Author Contributions

Gianluca Malatesta and Benedetta Rollo conceived and designed the study, conducted the investigation, performed the analyses, and co-wrote the manuscript. Anita D'Anselmo contributed to conceptualization, data collection, and manuscript revision. Chiara Lucafò was involved in data collection and manuscript revision. Luca Tommasi supervised the project, contributed to its conceptual development, and revised the manuscript. All authors approved the final version of the manuscript for submission.

CRediT authorship contribution statement

Benedetta Rollo: Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gianluca Malatesta:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Anita D'Anselmo:** Writing – review & editing, Visualization, Validation, Software, Methodology, Investigation, Conceptualization. **Chiara Lucafò:** Writing – review & editing, Investigation, Data curation. **Luca Tommasi:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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