Hearing Research 474 (2026) 109576

Contents lists available at ScienceDirect

Hearing Research

journal homepage: www.elsevier.com/locate/heares

Review Article

Using non-invasive brain stimulation to promote auditory neuroplasticity in the setting of hearing intervention: A scoping review

Joshua M. Wright [a], Lawrence Gregory Appelbaum [b], Sherri L. Smith [a], Tobias Overath [d], Samantha Kaplan [c], Matthew Cooper [a], Ofri Ronen [a], Tamar Tobi [e], Angel V. Peterchev [f,1], Howard W. Francis [a,1,*]

[a] Department of Head and Neck Surgery & Communication Sciences, Duke University School of Medicine, Durham, NC, USA
[b] Department of Psychiatry, University of California, San Diego, CA, USA
[c] Duke University Medical Center Library & Archives, Duke University School of Medicine, Durham, NC, USA
[d] Department of Psychology and Neuroscience, Duke University, Durham, NC, USA
[e] Tzafon Medical Center, affiliated with Azrieli Faculty of Medicine, Bar Ilan University, Israel
[f] Department of Psychiatry & Behavioral Sciences, Duke University, Durham, NC, USA

ARTICLE INFO

Keywords:
Auditory neuroplasticity
Non-invasive brain stimulation
Auditory rehabilitation
Cochlear implants

ABSTRACT

Cochlear implants (CI) have revolutionized our ability to treat severe sensorineural hearing loss (HL), yet there is substantial variability in speech perception outcomes. This may be due, in part, to the central nervous system's (CNS) response to HL, which is variable in extent and reversibility. Compensatory responses to HL mediated by neuroplasticity within the auditory CNS and other functional regions may interfere with perceptual, integrative and/or cognitive processes required to develop new listening skills with a CI. Non-invasive brain stimulation (NIBS) approaches offer a means to modulate the excitability of the brain and associated Hebbian processes that promote neuroplasticity. NIBS may therefore provide a means to increase gains in listening and communication function for individuals undergoing hearing rehabilitation. A narrative review is first performed to synthesize current evidence on CNS neuroplasticity associated with HL and intervention, and explores the conceptual rationale for applying NIBS to enhancing rehabilitation outcomes using contemporary hearing technology and auditory training. A formal scoping review was then done to identify studies that look at the use of NIBS in hearing rehabilitation in those with HL. Currently, clinical data for NIBS in patients with HL remain scarce. At present, conclusions regarding NIBS efficacy for improving hearing outcomes are premature; however, emerging findings provide a promising direction for future translational research. Limitations include the lack of standardized stimulation protocols and insufficient longitudinal data. Addressing these gaps will be essential to determine whether NIBS can safely and effectively enhance relevant neuroplasticity that improves rehabilitation outcomes for individuals with HL

1. Introduction

The development of cochlear implants (CIs) has transformed the treatment of severe to profound sensorineural hearing loss by enabling direct electrical stimulation of cochlear nerves (Macherey and Carlyon, 2014). However, speech perception outcomes among CI users vary widely, even though most achieve near-normal hearing thresholds. Current models explain less than 25% of this variability (Goudey et al., 2021; Zhao et al., 2020), and performance often declines further in noisy environments. As Wilson et al. noted, the key to understanding this variability may lie in the brain (Wilson et al., 2011).

Central nervous system (CNS) changes in response to hearing loss may impact how speech is subsequently processed with hearing aids or CIs (Roth, 2015). These neural adaptations begin early in the course of hearing loss (Allman et al., 2009; Fan et al., 2015; Sandmann et al., 2015), and may influence neurocognitive processes necessary for successful auditory rehabilitation. Evidence suggests that in general targeted interventions can enhance beneficial neuroplasticity and may

---

* Corresponding author.
E-mail address: howard.francis@duke.edu (H.W. Francis).
[1] These authors contributed equally as senior authors.

https://doi.org/10.1016/j.heares.2026.109576
Received 10 July 2025; Received in revised form 11 January 2026; Accepted 17 February 2026

provide enhanced rehabilitation outcomes. This review explores evidence for translating these benefits to the auditory system.

2. Methods

First, a narrative review was performed. A narrative review aims to synthesize existing research to provide a broad, in-depth overview of a topic, highlighting its historical context, theoretical frameworks and key findings (Sukhera, 2022). This was conducted to highlight key concepts related to CNS remodeling and compensatory changes related to hearing loss and subsequent rehabilitation (Sections 3-4). Then the historical background, mechanisms, and various modalities of Non-Invasive Brain Stimulation (NIBS) were summarized (Section 5). Finally, we highlighted findings from the auditory neuroplasticity literature that appear to provide key insights into how NIBS might be used to improve speech perception and verbal communication (Section 6.1). This review was performed with the aim of mapping and synthesizing current concepts and evidence in an emerging and interdisciplinary field. Relevant studies were identified through targeted searches of major biomedical and engineering databases including Medline via Pubmed, Embase (Elsevier) and Web of Science Core Collection (Clarivate) supplemented by manual searches of reference lists. Inclusion was based on relevance to the topic, and no formal exclusion criteria were applied.

In Section 6.2, a more structured scoping review was performed in search of literature relevant to the implementation of NIBS in the context of hearing loss and hearing rehabilitation. Relevant studies were identified through targeted searches of Medline via Pubmed, Embase (Elsevier) and Web of Science Core Collection (Clarivate). Databases were searched from inception to November 13, 2025. The inclusion criteria included studies of subjects with known hearing loss and the use of any form of NIBS with the goal of auditory rehabilitation. Exclusion criteria included studies not in English. See search strategy report in Supplemental Materials Table 1. 1929 titles and abstracts were initially screened by one reviewer. This identified 93 articles for full text review. The 93 articles were fully reviewed by two reviewers. At this stage, the same two reviewers then met to resolve any conflicts. Through this, 8

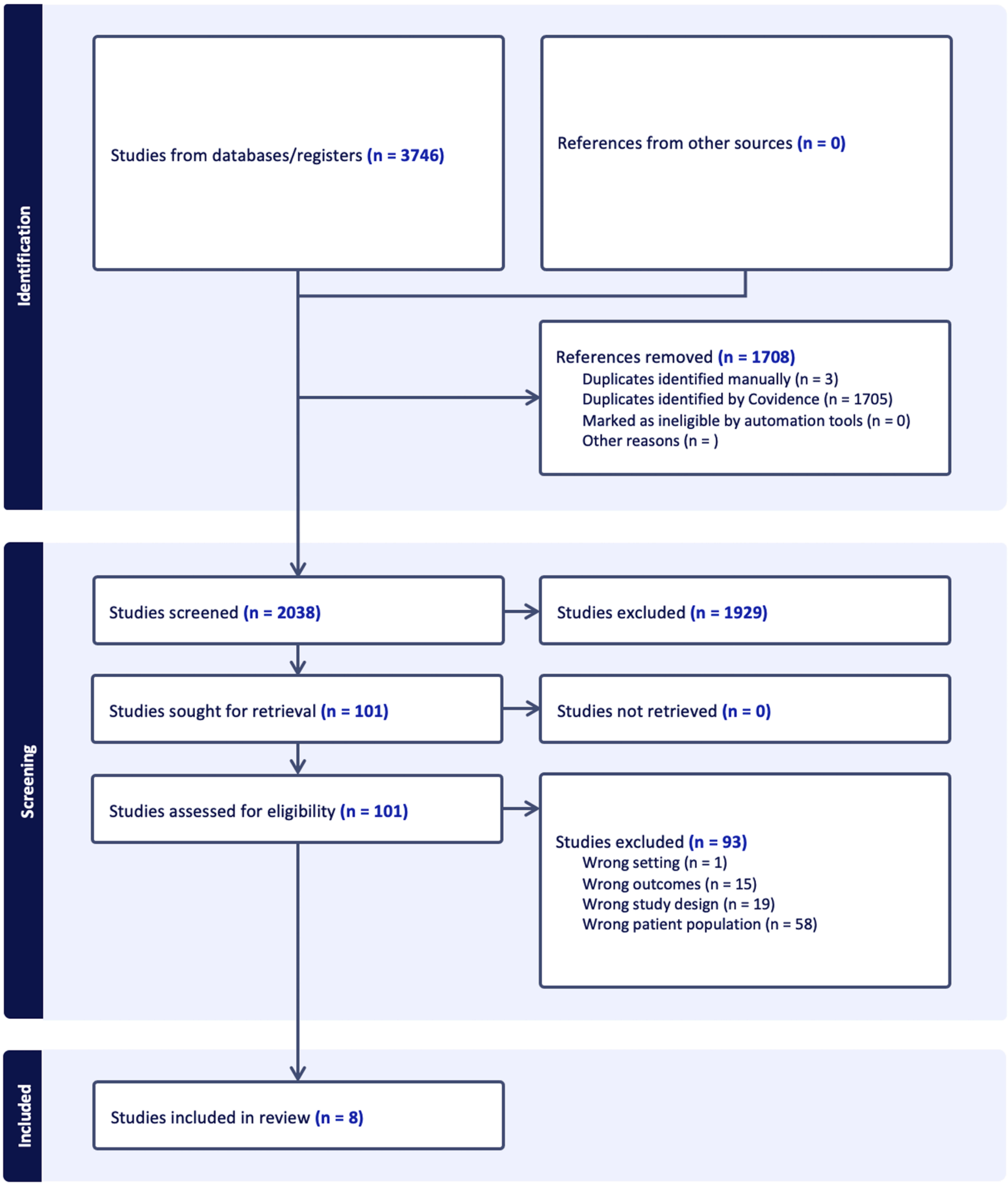

Fig. 1. Flow diagram for the selection process for scoping review looking at the use of NIBS for auditory rehabilitation in patients with hearing loss.

articles were identified to be included in the final review (Please review Fig. 1 for flow diagram of the screening process). As this was a scoping review, and the studies identified were heterogenous in methodology, a risk of bias was not performed (Arksey and O'Malley, 2005).

3. Cortical organization in normal and disordered hearing

3.1. Healthy auditory system

Early CNS development of the auditory system is characterized by high synaptic densities during the critical period of plasticity. Early sound exposure and natural pruning shape neural connections within the first few years of life (Hensch, 2004; Kral and Eggermont, 2007). Previously, auditory system development was thought to end in early childhood because the Auditory Brainstem Response (ABR) remains stable from about two years of age into adulthood (Skoe et al., 2015). However, later studies show additional developmental phases during childhood and adulthood, suggesting continuing plasticity throughout life (Chu, 1985; Jerger and Hall, 1980; Otto and McCandless, 1982; Rosenhall et al., 1985; Skoe et al., 2015; Stockard et al., 1979; Thivierge and Côté, 1990). Cortical responses such as N1 and P2 event-related potentials (ERP) emerge around age 5–6 y and mature by age 10–12 y, highlighting ongoing refinement of auditory function (Kraus et al., 1993; Pang and Taylor, 2000; Ponton et al., 2000).

As the auditory cortex matures, processing gradually shifts from bottom-up processing to more cognitively driven, top-down modulation (Chandrasekaran et al., 2014; Kral and Eggermont, 2007). This later phase supports speech perception and comprehension and may be critical for effective hearing interventions in young children. The application of peripheral stimulation outside of a critical window, however, will likely fail to reorganize appropriate higher order cortical networks that are required for top-down modulation of salient speech perception and language development.

Speech recognition primarily involves the left temporal cortex, which processes phonetic and phonological cues (Hickok and Poeppel, 2007; Obleser et al., 2008; Turkeltaub and Branch Coslett, 2010). Speech is then processed in the CNS by utilizing several higher-order processes including perceptual grouping, perceptual learning, categorical perception, and lexical segmentation (Davis and Johnsrude, 2007). Further processing of speech then combines various neural circuits including motor, short and long-term memory, emotional, and visual areas to fully achieve language comprehension and production (Price, 2012). There is evidence of functional connectivity between auditory centers and various non-auditory areas including the cingulo-insular cortex, mediotemporal limbic lobe, basal ganglia, and posterior orbitofrontal cortex during passive hearing (Langers and Melcher, 2011). Listening and speech understanding also requires the coordination of bilateral superior temporal cortices, which work together to

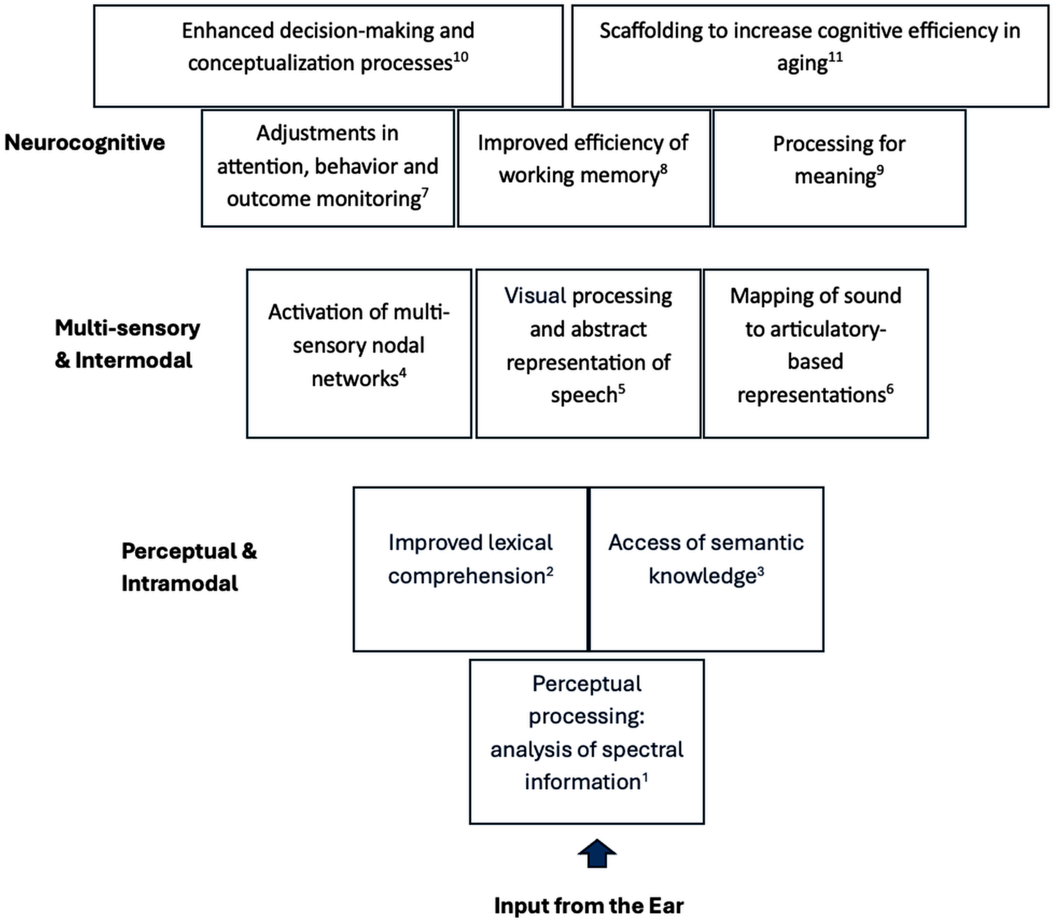

Fig. 2. Hierarchy of adaptive responses to hearing loss and hearing therapy: Potential targets for NIBS in conjunction with rehabilitation. [1]Heschl's gyrus (Smalt et al., 2013). [2]Anterior and posterior middle temporal gyrus (Smalt et al., 2013). [3]Wernicke's area (Smalt et al., 2013). [4]Including superior temporal gyrus (STG), superior temporal sulcus (STS) and right angular gyrus (H. J. Lee et al., 2007) (Alfandari et al., 2018). [5](Giraud et al., 2001; Kang et al., 2004). [6]Dorsal speech processing stream (Smalt et al., 2013) (Hickok and Poeppel, 2004). [7]Including cingulo-opercular network in the frontal cortex (Vaden et al., 2016, 2020, 2022; Vaden, Teubner-Rhodes, et al., 2017) and prefrontal and premotor cortex (Kral et al., 2016; Obleser et al., 2007; Peelle, 2010, 2018). [8]Insular region (Smalt et al., 2013). [9]Cingulate gyrus (Giraud et al., 2001; Kang et al., 2004). [10]Ventral speech processing stream (Smalt et al., 2013) (Hickok and Poeppel, 2004). [11](Park and Reuter-Lorenz, 2009; Goh and Park, 2009).

differentiate speech from non-speech signals (Turkeltaub and Branch Coslett, 2010). There is therefore a hierarchical organization of the auditory system's response to hearing loss in which distinct pathways are activated to address perceptual, cognitive and emotional demands of listening (Fig. 2).

3.2. Neuroplasticity mechanisms

Neuroplasticity is the process by which the brain reorganizes and forms new neural connections. It includes structural, functional, and molecular processes that maintain functional stability through compensation or adaptation to changes caused by aging or disease (Smith, 2013). Intra-modal reorganization occurs within local sensory circuits through mechanisms such as axonal sprouting, the unmasking of silent synapses, and altered modulation from lateral or thalamic connections (Bavelier and Neville, 2002). Inter-modal reorganization, by contrast, arises from pre-existing developmental pathways and occurs especially after early sensory loss. These processes may involve both cortical–cortical and subcortical–cortical interactions. At the macro level, neuroplasticity is linked to structural changes in grey and white matter that reflect new axonal growth and synapse formation to support learning or compensate for sensory deficits (Draganski and May 2008).

3.3. Neuroplasticity in response to Auditory Deprivation: (Supplemental Material Table 2)

3.3.1. Introduction

Hearing loss affects not only the cochlea but also the central nervous system. In mice, noise-induced hearing loss reduces cell density throughout the auditory pathway, including the primary auditory cortex (Gröschel et al., 2010; Su et al., 2017). Synaptopathy at the auditory nerve-inner hair cell interface can occur at noise exposure levels that do not cause measurable sensory cell loss or permanent threshold shifts, nevertheless resulting in notable changes in CNS organization and function (Kujawa and Liberman, 2015; Resnik and Polley, 2021). Additionally, noise-related damage to supporting cells may lead to altered excitability within the central auditory system, contributing to conditions such as tinnitus (Nguyen et al., 2017).

Neuroplasticity in response to hearing loss seems to arise from adaptive pressures to maintain communication and safety. These adaptations recruit sensory, perceptual, and cognitive systems to compensate for altered auditory input (Fig. 2). The extent and pattern of cortical reorganization differ depending on whether hearing loss is congenital or acquired. Mechanisms include changes in synaptic strength and axonal sprouting (Bavelier and Neville, 2002). Such changes may occur quickly or persist long-term, driven by both bottom-up and top-down processes (Irvine, 2018). For example, in polymodal association areas (e.g., visual-auditory-somatosensory regions), sensory competition often favors intact modalities over deficient ones (Bavelier and Neville, 2002; Nagappan-Chettiar et al., 2023). When bottom-up auditory input weakens, top-down systems increasingly help decode speech cues (Lesicko and Llano, 2017; Moberly et al., 2021).

Not all plasticity is beneficial, however. Some forms appear to be maladaptive and may hinder rehabilitation after cochlear implantation (Bengoetxea et al., 2012). This is better understood outside the auditory system, such as the overrepresentation of fingers in the somatosensory cortex which can cause dystonia, a maladaptive form of plasticity treatable with repetitive transcranial magnetic stimulation (TMS) (Siebner et al., 2009). The role of maladaptive plasticity in response to hearing loss is poorly understood yet demands consideration for improving hearing recovery strategies.

3.3.2. Alterations of cortical structure in response to hearing loss

A growing literature reports observations that reflect adaptations by the CNS to altered afferent input from the peripheral auditory system (summarized in Supplemental Material Table 2). Hearing loss has been associated with a smaller volume of grey matter in the primary auditory cortex, independent of age (Eckert et al., 2012; Qian et al., 2017; Schneider et al., 2009). Longitudinal data show faster decline of cortical volume in individuals with hearing loss (Eckert et al., 2019; Lin et al., 2014). Other affected regions include the frontal gyrus, occipital lobe, hypothalamus, and cingulate cortex (Boyen et al., 2013; Ren et al., 2018).

With unilateral hearing loss, significant volume reductions were noted in primary auditory cortex and visual cortex, accompanied by volume changes at other contralateral and ipsilateral sites. Volume loss in the auditory cortex correlates with hearing severity and duration (X. Wang et al., 2016). In sudden hearing loss, grey matter volume reduction can appear within weeks, particularly in contralateral temporal regions (Fan et al., 2015).

Interestingly, some regions show hypertrophy, such as the superior temporal and angular gyri (Alfandari et al., 2018; Boyen et al., 2013). The volume increase at the right angular gyrus is associated with learning a new skill that involves the integration and transfer of information from different modalities. These sites may serve as markers of neurocognitive adaptation and are potential targets for therapy (X. Wang et al., 2016).

3.3.3. Cross-modal recruitment

Cross modal plasticity is an adaptive change where neurons in a sensory-deprived system, such as the auditory cortex in cases of hearing loss, begin to respond to inputs from other, non-deprived sensory systems (Kral and Sharma, 2023). In animals, most auditory neurons can respond to visual stimuli within months of deafness (Allman et al., 2009). In humans, similar changes appear even in mild hearing loss and may reverse with hearing restoration (Campbell and Sharma, 2014; Kral and Sharma, 2023).

This reorganization mainly affects higher-order auditory areas, such as the dorsal and posterior auditory fields, rather than the primary auditory cortex (Glick and Sharma, 2017; Kral and Sharma, 2012; Land et al., 2016; Lomber et al., 2010). For example, in deaf cats, these regions support enhanced peripheral vision (Lomber et al., 2010). In acquired hearing loss, cortico-cortical neuroplasticity is likely to engage pre-existing poly-sensory networks; these multimodal cortical areas form the basis for compensatory processing (Kral and Sharma, 2023).

Brain imaging and non-invasive cortical electrophysiological studies in humans offer valuable insights into these compensatory processes and may guide their manipulation for improved outcomes (Stropahl et al., 2017). For example, functional magnetic resonance imaging (fMRI) show that in late-onset deafness, visual speech reading activates multisensory circuits in the superior temporal gyrus (H. J. Lee et al., 2007). Stronger activation of these regions is linked to better phonological access, suggesting that neuromodulator therapy targeting these pathways may facilitate rehabilitation.

3.3.4. Expanded cortical connectivity and cognitive demand in response to hearing loss

Hearing loss can have significant effects on cognitive processes that support speech comprehension, particularly in the presence of background noise (Roth, 2015). A degraded auditory signal recruits additional executive resources to preserve comprehension (Obleser et al., 2007; Peelle and Wingfield, 2016; Rudner and Lunner, 2014). As hearing continues to decline, these processes are engaged even in quiet settings, making all listening effortful (Cardin, 2016; Pichora-Fuller et al., 2016). Greater frontal activity is often observed in mild hearing loss, particularly in challenging listening conditions, indicating reliance on higher-order networks (Glick and Sharma, 2017).

It has been hypothesized that degraded peripheral auditory input and recruitment of other domains may lead to downregulation within the auditory cortex which might be responsible for grey matter volume loss (Peelle et al., 2011;Glick and Sharma, 2017). While this compensatory activation can improve perception, it also elevates cognitive demand and may deplete cognitive reserve (Kral et al., 2016; Obleser et al., 2007; Peelle, 2010, 2018;Mishra et al., 2013; Rönnberg et al., 2013). Activation of the cingulo-opercular network is associated with enhanced speech perception performance in noise, an effect that is attributed to adjustments in attention, behavior and outcome monitoring (Vaden et al., 2016, 2020; Vaden, Teubner-Rhodes, et al., 2017). Understanding these dynamics may inform strategies to reduce listening effort in rehabilitation.

These progressive shifts, from primary perceptual to multimodal and higher-order cognitive engagement, reflect a hierarchical organization of adaptive responses within the auditory system. As hearing loss worsens, cortical reorganization extends beyond the auditory cortex into multisensory and neurocognitive domains that support comprehension, attention, and decision-making. This conceptual progression is illustrated in Fig. 2, which summarizes the adaptive hierarchy spanning perceptual, multisensory/intermodal, and executive networks. This hierarchy highlights how distributed cortical systems coordinate to maintain communication despite degraded sensory input, and it provides a framework for considering therapeutic strategies to enhance beneficial plasticity.

3.3.5. *Age related hearing loss*

Age-related hearing loss (presbycusis) is linked to cochlear atrophy and cortical thinning in auditory regions (Ren et al., 2018; Vaden, Matthews, et al., 2017). Structural brain changes correlate with cognitive decline and reduced activity in the default mode network. These effects may reflect maladaptive cortical recruitment that worsens with age (Ren et al., 2018).

Older adults rely more heavily on visual and cognitive cues for language processing, but these compensations become less efficient with declining cognitive reserve (Kral and Sharma, 2023; Kuchinsky et al., 2012). Both aging and hearing loss independently impair speech comprehension, but together they have additive effects (Cardin, 2016; Kuchinsky et al., 2012; Mishra et al., 2014; Vaden et al., 2015). The recruitment of additional circuitry to support primary cortical circuits that are becoming more noisy or inefficient with age, a process known as scaffolding (Park and Reuter-Lorenz, 2009), may contribute to the added disability associated with age-related hearing loss, and the greater challenge of achieving hearing intervention benefits that are equivalent to younger adults (Clark et al., 2012; Francis et al., 2015).

4. Neuroplasticity associated with Hearing Intervention

The patterns of CNS neuroplasticity in response to hearing rehabilitation are highly variable, and findings across studies are sometimes contradictory (Supplemental Material Table 3). This inconsistency may stem from differences in study methodologies, hearing outcome measures, and variability in the patients' hearing history. Due to a lack of longitudinal studies, the sequence and timing of changes in cortical response and metabolic patterns in deaf individuals following cochlear implantation is poorly understood. As duration and severity of hearing impairment significantly influence the outcome of hearing intervention, there is also presumably an effect on cortical plasticity and reorganization processes. Cortical changes following CI intervention include changes within the auditory cortex, cross-modal plasticity involving other sensory systems, and adaptive plasticity with the recruitment of higher-order cortical regions (Glennon et al., 2020).

4.1. *Therapy-induced neuroplasticity within the auditory cortex*

Cochlear implantation produces rapid and measurable cortical changes. Within eight weeks, post-lingually deaf adults show increased amplitudes and shorter latencies of auditory evoked potentials, reflecting central plasticity (F. Zhang et al., 2010). Stronger mismatch negativity and better adaptation to repeated stimuli correlate with improved speech perception. (Fujiki et al., 2004; Giraud et al., 2001; Naito et al., 2000; Roland et al., 2001). During the first year of CI use, neural responses become more defined and efficient, suggesting a return to typical auditory processing and reduced dependence on other sensory modalities (Sandmann et al., 2015).

Imaging studies also demonstrate heightened auditory cortex activity after implantation (Han et al., 2019; Pantev et al., 2006). For example, hypometabolism in auditory cortices reverses as auditory evoked potentials normalize (Ito et al., 1993). Strelnikov et al. (Strelnikov et al., 2015) observed greater activation in associative auditory regions, which correlated with perceptual gains. More recent work shows increased cortical thickness and activity in both auditory and language systems, extending to multimodal cortices, following cochlear implantation (Y. J. Lee et al., 2024). Together, these findings indicate that CI intervention promotes functional and structural reorganization within the auditory cortex that parallels perceptual improvement.

4.2. *Cortical reorganization*

4.2.1. *Cortical adaptation beyond the auditory cortex*

Studies of normal-hearing individuals adapting to degraded speech provide insights into cortical mechanisms relevant to auditory rehabilitation in CI users. In one fMRI study, improved sentence perception following two weeks of exposure to degraded speech was accompanied by altered cortical activation patterns (Smalt et al., 2013). Improved auditory perception was correlated with activity in both primary and secondary auditory regions, the ventral and dorsal speech processing streams, and additional non-auditory regions (Table 1).

Increased activation near the right Heschl’s gyrus suggested enhanced spectral analysis, while engagement of Wernicke’s area likely reflected greater access to semantic knowledge (Smalt et al., 2013). Bilateral activity in the middle temporal gyrus was linked to better lexical comprehension, and changes in the insular region suggested more effective use of working memory.

Similar activation patterns appear in CI users. PET studies reveal recruitment of the cuneus and cingulate gyrus (Giraud et al., 2001; Kang et al., 2004). The cuneus likely supports visual association or abstract speech representation, while cingulate activation reflects increased semantic processing.

Smalt et al. (Smalt et al., 2013) proposed that improved speech perception stems not only from auditory processing changes but also from enhanced mapping between sound and articulation (via the dorsal stream) and enhanced decision-making and conceptual processing (via the ventral stream). These findings align with models suggesting that speech perception depends on coordinated interactions between perceptual, conceptual, and motor systems (Hickok and Poeppel, 2004).

Table 1
Speech perception gains after two weeks of chronic exposure to degraded speech are correlated with the following activation changes on Functional Magnetic Resonance Imaging (Smalt et al., 2013).

Area:	Changes:
Primary and secondary auditory cortex	• Changes in activation in both the left and right superior temporal gyrus and sulcus • Greater activation in right hemisphere near Heschl’s gyrus • Strong activation noted in Wernicke's area (Brodmann area 22)
Ventral speech processing stream	• Strong activation changes in bilateral anterior and posterior middle temporal gyrus (Brodmann areas 21–22) • Left Hemisphere activation was slightly dominant in this stream
Dorsal speech processing stream	• Increased activation in the insula and left inferior frontal cortex (Brodmann area 47)
Outside auditory and speech processing areas	• Other areas of activation include the cuneus, and the cingulate gyrus

4.2.2. Cross-Modal reorganization

Cross-modal activation patterns before implantation can predict CI outcomes. Individuals with greater preoperative activation in the visual pathway often perform worse after implantation (Hyo et al., 2005), whereas those with stronger left prefrontal activation and decreased activity in Heschl's gyrus and the posterior superior temporal sulcus on the right side tend to do better (H. J. Lee et al., 2007).

Cross-modal plasticity can also reverse with successful auditory rehabilitation. In a pediatric single-sided deafness case, somatosensory-driven auditory activation disappeared within 27 months of CI use (Glick and Sharma, 2017). Somatosensory cross-modal effects appear more reversible than visual ones, and reversibility is greater in adult-onset than congenital deafness (Kral and Sharma, 2023).

Nevertheless, some degree of cross-modal integration often persists. CI users frequently benefit from congruent visual input, such as lip reading, which enhances speech understanding (Stevenson et al., 2017). Visual cortex activation can even predict better listening performance (Strelnikov et al., 2013, 2015). For instance, activation of the right cuneus within the visual cortex correlates with improved lip reading, suggesting that mental imagery aids communication (Giraud et al., 2001; Strelnikov et al., 2015). However, incongruent visual input may hinder performance under some circumstances (Song et al., 2015; Stevenson et al., 2017; Strelnikov et al., 2013).

Studies also show mixed results regarding whether cross-modal recruitment predicts better or worse auditory outcomes. Whereas some report that stronger visual activation relative to auditory activation benefits speech perception (L. C. Chen et al., 2016), others find it to be detrimental (Doucet et al., 2006). Overall, persistent visual activation of auditory regions tends to correlate with poorer CI speech perception outcomes (Han et al., 2019; Jae et al., 2003), even though it may still support lip reading. These discrepancies may result from differences in study populations, speech discrimination assessment methods, and whether communication was evaluated with or without lip reading. Currently, it remains unclear whether a better-developed visual response to auditory stimulation is a cause or a consequence of poorer speech perception.

4.3. Cortical changes following cochlear implantation in congenital deafness

Cochlear implantation in congenital deafness produces distinct reorganization patterns. In these cases, the auditory cortex undergoes extensive multisensory reorganization, but normal auditory development is not fully restored (Bavelier and Neville, 2002; Kral and Sharma, 2023). Poorer CI outcomes in pre-lingually deaf individuals may relate to the incomplete maturation of language areas such as Broca's region (Boisvert et al., 2020; Petersen et al., 2013).

Pre-lingual cross-modal plasticity is often more extensive than that seen in adults. Visual or somatosensory activation within auditory areas correlates with poorer CI outcomes (Bertrand et al., 2012; Campbell and Sharma, 2014, 2016; Gilley et al., 2008; Glick and Sharma, 2017; Hyo et al., 2005). Despite this, audiovisual cues can still enhance communication, as performance in combined tasks typically exceeds auditory-only tasks (Bergeson et al., 2005). Cross-modal plasticity is also evident in the somatosensory cortex, which is activated in response to CI stimulation in late-implanted congenitally deaf children (Gilley et al., 2008).

In congenital deaf cats, auditory regions recruited for visual processing continue to respond to both visual and CI-driven auditory input, although they appear to lose their coordinated bimodal interactions and function independently (Land et al., 2016). The visual system may thus serve as an alternative reference for interpreting new auditory signals. These findings support the idea that early multimodal experience during critical developmental windows is essential for successful multisensory integration and speech development (Kral and Sharma, 2023).

4.4. Next steps

Neuroplasticity remains active beyond traditional critical periods, providing opportunities for neurosensory modulation and even restoration. A key question is whether compensatory mechanisms can be intentionally engaged to improve real-world communication (Kral and Sharma, 2023). Post-implantation plasticity does not restore a pre-deprivation state but proceeds through multiple stages of cortical reorganization across auditory, visual, and cognitive networks. Understanding the hierarchical and temporal features of this process may inform the development of adjunctive therapeutic and rehabilitation strategies.

There is some early evidence that pharmacological strategies may facilitate neuroplasticity associated with stroke recovery (Viale et al., 2018; Walker-Batson, 2000). A randomized double-blind study of the impact of D-amphetamine on speech tracking scores was conducted in adults using CI while receiving auditory rehabilitation (Tobey et al., 2005). There was a clinically significant improvement in speech tracking in the experimental group compared to controls in the auditory-only condition.

As discussed, not all cortical reorganization following hearing intervention is beneficial, and some patients exhibit maladaptive plasticity, where compensatory cortical changes may hinder optimal auditory recovery. The reasons for these divergent outcomes remain incompletely understood, but likely involve individual variability in cortical reserve, timing of intervention, duration of deafness, and genetic or neurochemical factors influencing synaptic plasticity. Current evidence is insufficient to identify predictive markers that distinguish who will respond most favorably to auditory rehabilitation, and the field lacks longitudinal multimodal studies linking measures of cortical plasticity to behavioral outcomes.

Future research may help reduce this variability by leveraging interventions that modulate neuroplasticity directly and selectively. In this context, non-invasive brain stimulation (NIBS) may offer a more targeted approach. Used alongside auditory rehabilitation, NIBS could be directed at strengthening beneficial adaptive plasticity, while suppressing maladaptive processes. NIBS could potentially reduce interindividual differences in rehabilitation outcomes, thereby addressing one of the key challenges in auditory recovery. The following sections review current NIBS modalities, their applications, and how they could complement standard interventions for acquired sensorineural hearing loss. These strategies are informed by a proposed hierarchy of adaptive cortical responses to hearing loss and hearing therapy, which are illustrated in Fig. 2. While NIBS holds considerable promise as an adjunct to auditory rehabilitation, the absence of validated protocols or cost-effectiveness data underscores the need for further preclinical and clinical research before it can be translated into standard care.

5. Non-Invasive Brain Stimulation (NIBS): (Table 2)

5.1. Introduction and background to NIBS

NIBS techniques have become increasingly popular for their ability to modulate motor and cognitive functions (Wassermann et al., 2024). These methods deliver energy across the scalp—electrical or magnetic fields, ultrasound, or light—to alter neural activity. The brain responds via membrane polarization, ion-channel mechanics, and metabolic shifts, which change behavior (Bhattacharya et al., 2022; B. Wang et al., 2021; Wassermann et al., 2024). Depending on parameters and network state, NIBS can raise or lower excitability and connectivity in targeted circuits (R. Chen et al., 1997; Dayan et al., 2013; Galea et al., 2009; Legon et al., 2018; Sandrini et al., 2011; Silvanto et al., 2008; Silvanto and Pascual-Leone, 2008; Woods et al., 2016; Yaakub et al., 2023).

The biological effects of the most established forms of NIBS are mediated by the introduction of an electric field into the body. The electric field is either injected via transcranial electrical stimulation

Table 2
Forms of NIBS. TMS = transcranial magnetic stimulation, tDCS = transcranial direct current stimulation; tACS = transcranial alternating current stimulation; tRNS = transcranial random noise stimulation; CES = Cranial electrotherapy stimulation.

Category	Details
tES (transcranial electrical stimulation)	**Mechanisms:** Delivers low-intensity electrical currents via scalp electrodes which modulates neuronal polarization and cortical excitability. **Types:** - **tDCS:** Direct current stimulation modulating excitability. - **tACS**: Alternating current stimulation entraining brain oscillations. - **tRNS**: Random noise stimulation enhancing or disrupting activity. - **CES:** Cranial electrotherapy stimulation cleared for anxiety and/or insomnia **Uses:** - Enhancing motor learning, cognition, and neurorehabilitation; treating depression, chronic pain, and auditory processing disorders. **Pros:** - Portable, inexpensive, and easy to apply; can be used at home. **Cons:** - Low focal specificity; discomfort at high intensities
TMS (transcranial magnetic stimulation)	**Mechanisms**: Uses magnetic fields to induce an electric field, which can depolarize neurons and modulate cortical excitability/connectivity. **Types**: - **Single-pulse & paired-pulse TMS**: Used for cortical mapping and excitability assessment. - **Repetitive TMS (rTMS)**: Modulates excitability, with inhibitory or excitatory effects. - **LFMS & kTMP**: Subthreshold TMS with minimal scalp sensation. **Uses:** - FDA-approved for depression, anxiety, obsessive-compulsive disorder, tobacco use disorder, migraine, brain mapping; studied for cognitive enhancement and motor rehabilitation. **Pros:** - Well-established clinically, approved for several conditions, focal stimulation with controlled intensity. **Cons:** - Expensive, requires clinical setting, limited to superficial brain regions, can cause scalp discomfort, compatibility issues with cochlear implants.
tFUS (transcranial focused ultrasound stimulation)	**Mechanisms**: Uses acoustic waves to perturb ion channels via mechanical effects. **Uses:** - Research in neurostimulation, cognitive modulation, and neuropsychiatric treatment. **Pros:** - Superior spatial resolution, can reach deep brain structures non-invasively. **Cons:** - Not FDA-approved for neuromodulation, expensive, requires clinical setting, potential for tissue heating

(tES) or induced via transcranial magnetic stimulation (TMS) (Peterchev et al., 2012). Depending on the field strength, transcranial stimulation methods can be categorized into subthreshold and suprathreshold stimulation. Subthreshold methods, such as transcranial direct current stimulation (tDCS), transcranial alternating current stimulation (tACS), transcranial random noise stimulation (tRNS), cranial electrotherapy stimulation (CES), low-field magnetic stimulation (LFMS), and kilohertz transcranial magnetic perturbation (kTMP), use relatively low electric field strengths to modulate neural activity and network oscillations. In contrast, suprathreshold methods, such as TMS or suprathreshold forms of tES, use higher field strengths sufficient to directly elicit action potentials. Effects depend on field strength and pattern, head anatomy, neuron morphology, and the timing of stimulation relative to intrinsic activity.

Transcranial ultrasound is another form of NIBS that is showing promise. For instance, there is a growing literature reporting the effects of transcranial ultrasound in healthy participants and on clinical outcomes in patients with a variety of neurological disorders (K. Lee et al., 2024; Matt et al., 2024; Savelon et al., 2024). Interest in targeting auditory circuits with NIBS is increasing. Overall, NIBS offers flexible tools for auditory rehabilitation and other clinical applications.

5.2. *Transcranial electrical stimulation (tES)*

5.2.1. *Historical background*

Electrical stimulation of the nervous system dates to Galvani and Volta (Zaghi et al., 2010). The invention and development of CIs as a form of invasive, though peripheral, tonotopic electrical stimulation of the auditory nerve in the cochlea bypassing the organ of Corti, drew its inspiration from those same 18th century electrical stimulation experiments such as described by Volta who also experimented upon himself: "…at the moment when the circuit was completed, I received a shock in the head, and some moments after I began to hear a sound, or rather noise in the ears…" ("XVII. On the Electricity Excited by the Mere Contact of Conducting Substances of Different Kinds. In a Letter from Mr. Alexander Volta, F. R. S. Professor of Natural Philosophy in the University of Pavia, to the Rt. Hon. Sir Joseph Banks, Bart. K.B. P. R. S," 1800; Zeng, 2004). Electroconvulsive therapy emerged in the 1930s for severe psychiatric illness (HARMS, 1955). Suprathreshold tES pulses in awake humans were shown in 1980 (Merton and Morton, 1980). Modern subthreshold tES studies began in 2000 (Nitsche and Paulus, 2000), and the tES umbrella now covers multiple techniques (Bikson et al., 2019).

5.2.2. *tES mechanisms of action*

tES involves the application of electrical potentials to the scalp, creating a flow of current. A fraction of the applied current enters the brain and shifts membrane polarization. High-intensity tES can be painful due to skull impedance, so clinical suprathreshold tES is largely limited to anesthesia settings (e.g., Electroconvulsive Therapy). This has led to the development of more tolerable subthreshold techniques (Paulus et al., 2013). tES requires a small amount of current to generate a given intracranial field, enabling compact, battery-powered devices suitable for at-home therapy (Heimrath et al., 2016; Koponen and Peterchev, 2020; Pilloni et al., 2022; Reed and Cohen Kadosh, 2018).

5.2.3. *Forms of tES*

tDCS: tDCS is the most prevalent investigational subthreshold tES technique, applying a constant low-intensity direct current via scalp electrodes to modulate cortical excitability. Low-intensity direct current (1–2.5 mA for 10–40 min) shifts excitability; anodal tends to increase and cathodal to decrease, with exceptions (Bikson et al., 2019). The effects of tDCS are not limited to modulations of cortical excitability during stimulation (online effect) but outlast the stimulation period by several minutes or hours. This aftereffect or offline effect is due to long-term synaptic changes associated with long-term potentiation (LTP) and long-term depression (LTD) (Heimrath et al., 2016). Applications span motor learning, cognition, and memory (Antal et al., 2017; Buch et al., 2017).

tACS: tACS involves applying sinusoidal currents at specific frequencies to interact with brain oscillations. Conventional intensities for tACS are usually limited to 1–2 mA. The primary parameters influencing tACS effects are the frequency, amplitude, and duration of stimulation (Bikson et al., 2019; Paulus et al., 2013). Generally, tACS synchronizes cortical oscillations by inducing distinct frequency patterns. tACS directly entrains underlying brain oscillations causing a temporal alignment of intrinsic brain activity to the externally applied alternating current (Heimrath et al., 2016; W. A. Huang et al., 2021). Aftereffects has been related to synaptic changes via spike-timing dependent plasticity (Heimrath et al., 2016; Veniero et al., 2015).

tRNS: tRNS delivers electrical stimulation at random frequencies, creating a stochastic resonance effect that can enhance the perception of near-threshold stimuli or disrupt pathological rhythms. This method has been applied using frequency spectrums between 0.1 Hz and 640 Hz. This approach is frequency-unspecific and can adapt to individual oscillatory differences (Bikson et al., 2019; Heimrath et al., 2016; Paulus et al., 2013).

Cranial Electrotherapy Stimulation (CES): CES devices generate complex subthreshold current waveforms, akin to tRNS. They are typically applied either with scalp electrodes or electrodes clipped to the earlobes. Several devices hold FDA clearance for anxiety/insomnia; evidence suggests safety with modest benefit in anxiety with depression (Department of Heath and Human Services and Food and Drug Administration, 2019; Shekelle et al., 2018).

5.3. Transcranial magnetic stimulation (TMS)

5.3.1. Historical background

The concept of manipulating the brain's electrical activity via magnetic fields dates back to the late 19th century when d'Arsonval reported the induction of magnetophosphenes—perceived flashes of light in participants exposed to magnetic fields generated by wire coils (Geddes, 1991). This early experiment provided the first evidence that magnetic pulses could non-invasively evoke neural activity (Adank et al., 2017). Barker and colleagues in 1985 introduced modern TMS, which stimulates cortex painlessly with pulsed magnetic fields(Barker et al., 1985).

TMS now has FDA clearance for several psychiatric and neurological conditions and has broad research use in cognition and motor learning (Benster et al., 2023; Beynel et al., 2020; Buch et al., 2017; Cox et al., 2020; Fröhlich et al., 2014; Kan et al., 2020; Neacsiu, Beynel, Powers, et al., 2022; Polanía et al., 2018; Regenold et al., 2022). Few studies have applied TMS with hearing aid patients; however, a recent study has showed that 5 days of repetitive TMS in such patients had sustained improvement in the perception of complex sentences and pure- tone reception (Neri et al., 2024).

5.3.2. TMS mechanisms of action

A changing magnetic field induces an intracranial electric field (Faraday's law). During TMS, a rapidly changing magnetic field is applied to the superficial layers of the cerebral cortex, generating an electric field therein. Suprathreshold pulses depolarize neurons; repetitive trains (rTMS) modulate excitability and connectivity beyond the stimulation period, with behavioral and therapeutic effects. This process does not require direct current to pass through the skull, thereby avoiding the discomfort associated with TES (Rossi et al., 2009).

5.3.3. Forms of TMS

TMS can be single-pulse, paired-pulse, or rTMS. Frequency, intensity, train duration, and task timing determine inhibitory or excitatory outcomes and behavioral impact (Adank et al., 2017). (Adank et al., 2017). Subthreshold variants—LFMS and kTMP—produce weaker, kilohertz-range fields with minimal scalp sensation and sound, which may aid blinding and tolerability (Dubin et al., 2019; Labruna et al., 2024; Rohan et al., 2014).

5.4. Transcranial focused ultrasound stimulation (tFUS)

5.4.1. Historical background

Ultrasound uses acoustic waves above 20 kHz. Its neural effects have been noted for a century (Pauly et al., 2021). tFUS now offers millimeter-scale focality, including deep targets, with electronically steerable foci (Yaakub et al., 2023). High-intensity focused ultrasound is FDA-approved for ablative treatment of tremor and Parkinson's disease; neuromodulatory tFUS remains investigational but is rapidly advancing and can modulate sensory cortex (Matt et al., 2024; Yoo et al., 2022).

5.4.2. tFUS mechanisms of action

The carrier wave frequency used for tFUS in humans is in the range of several hundred kilohertz to over one megahertz. The mechanism of neuromodulation by ultrasound is not entirely established. Leading models propose mechanical perturbation of membranes and ion channels, altering ionic flux and cell state.

5.5. NIBS properties and applications

5.5.1. Spatial effects: (Fig. 3)

Spatial effects refer to the distribution of the electric, magnetic, or ultrasound field delivered to the brain, which is determined by the configuration of the field transducers (electrodes, coils, or ultrasound elements) and their placement on the scalp (Peterchev et al., 2012). TMS and tES preferentially affect superficial cortex; larger TMS coils reach deeper but less focally, while smaller coils are more focal (Deng et al., 2013b). Likewise, Smaller/closer tES electrodes increase focality (Deng et al., 2013a). Optimization algorithms can tailor electrode placement and currents for focality or depth (Dmochowski et al., 2011; Truong et al., 2021) tFUS provides the most flexible, deep, and focal targeting by leveraging wave phenomena such as constructive interference between multiple ultrasound transducers (Atkinson-Clement and Kaiser, 2024).

5.5.2. Temporal effects

NIBS can be administered in two distinct paradigms: "online" and "offline". Online stimulation coincides with task performance and can transiently alter processing in targeted cortex, enabling causal inference (Hartwigsen, 2015; Siebner et al., 2009; Walsh and Cowey, 2000).

Conversely, offline stimulation is applied before or after a task, resulting in prolonged effects on behavior that persist beyond the stimulation period. Repetitive or prolonged NIBS protocols can induce lasting modulation of cortical excitability or connectivity, enhancing the potential for long-term rehabilitation gains (Adank et al., 2017; Bikson et al., 2019; B. Wang et al., 2021).

5.5.3. Integrating with rehabilitation

There are several domains in which the pairing of NIBS with rehabilitation therapy has been explored leading to emerging therapeutic protocols. In stroke patients, tDCS combined with constraint-induced movement therapy is under study (e.g., TRANSPORT2; NCT03826030) and meta-analyses suggest enhanced upper-limb function (Chhatbar et al., 2017). Trials in traumatic brain injury target memory, attention, and motor systems (Calderone et al., 2024). tDCS has also been shown to enhance surgical skill acquisition in healthy participants (Ashcroft et al., 2020; Cox et al., 2020). In movement disorders and cerebral palsy, neuromodulation may reduce spasticity and improve engagement in physical therapy (Hastings et al., 2022). Psychiatry increasingly pairs TMS with behavioral interventions, such as cue-provocation during smoking-cessation TMS (Zangen et al., 2021) or adjunctive cognitive behavioral therapies (Neacsiu, Beynel, Graner, et al., 2022). Together, stimulation plus active training may boost Hebbian learning and functional outcomes.

5.6. Evaluation of efficacy

Assessing NIBS requires behavioral, physiological, and imaging measures. One of the challenges in assessing the efficacy of NIBS is the considerable interindividual variability in response to stimulation. This variability arises due to differences in skull and scalp thickness, cortical folding, tissue properties, and other biological factors, as well as age, sex, hormones, cognitive state, and medications (Boucher et al., 2021; Chagas et al., 2018; Hinder et al., 2014; Peterchev et al., 2012).

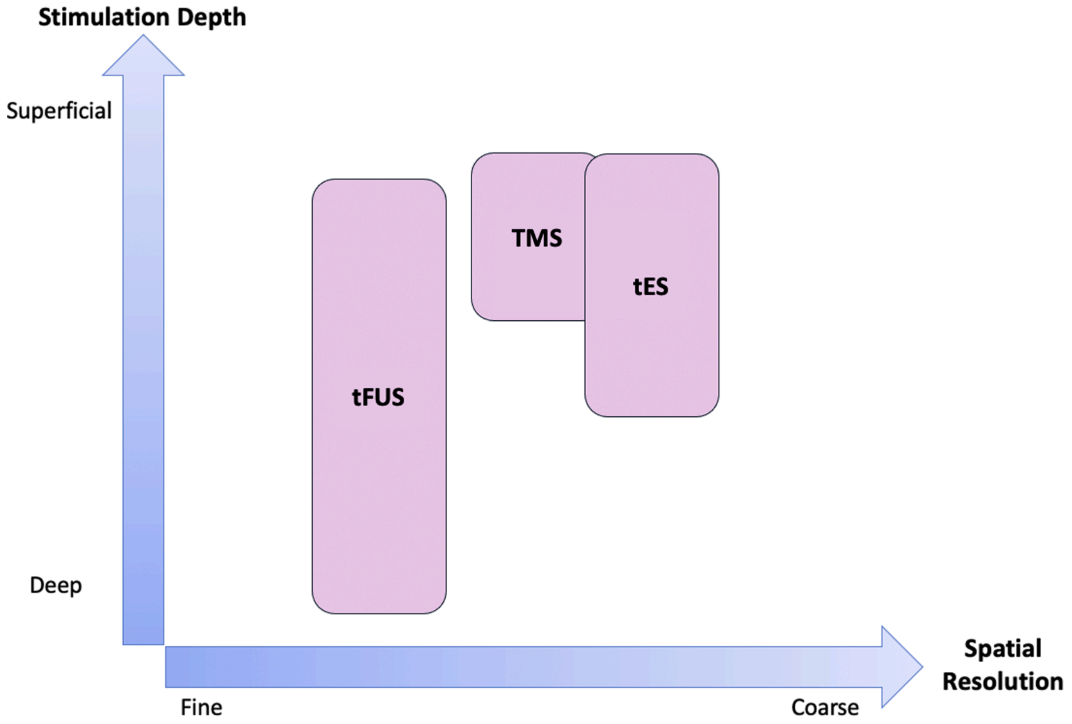

Fig. 3. Comparison of spatial resolution and stimulation depth between NIBS techniques. This schematic illustrates the relative spatial precision and penetration depth of three principal NIBS techniques: transcranial electrical stimulation (tES), transcranial magnetic stimulation (TMS), and transcranial focused ultrasound stimulation (tFUS). The horizontal axis represents spatial resolution (fine to coarse), while the vertical axis depicts stimulation depth (superficial to deep). tES—including tDCS, tACS, and tRNS—acts primarily on superficial cortical regions with broad electric fields and limited focality. TMS also acts on superficial cortical regions, but is capable of modulating both superficial and moderately deep cortical targets depending on coil geometry and field strength. In contrast, tFUS achieves the greatest focal precision and the deepest penetration, allowing selective activation or inhibition of subcortical and deep cortical structures. These properties inform the choice of stimulation modality depending on therapeutic goals, target depth, and desired spatial specificity. This is a modification of a figure previously published by Matt et al. (Matt, E., Radjenovic, S., Mitterwallner, M., & Beisteiner, R. (2024). Current state of clinical ultrasound neuromodulation. *Frontiers in Neuroscience*, 18. https://doi.org/10.3389/fnins.2024.1420255). Their article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

Sham-controlled designs are essential to separate true effects from placebo. Sham stimulation mimics the procedural aspects of active stimulation without delivering significant fields to the brain, helping to maintain blinding and ensuring that any observed behavioral or physiological changes can be attributed to the active intervention (Bikson et al., 2019). The inclusion of appropriate control sites and tasks is also crucial to ensure that any observed effects are specific to the targeted brain regions and not due to nonspecific factors such as auditory masking or cutaneous sensations (Adank et al., 2017).

Moreover, studies that combine behavioral assessments with neuroimaging and neurochemical measurements add value. For example, research has shown that tDCS can modulate neurotransmitter levels, such as glutamate and myo-inositol (Marquardt et al., 2021). However, the findings are not always consistent. More comprehensive, multimodal studies are needed to refine mechanisms and optimize protocols for applications such as hearing loss.

6. Could NIBS increase the effectiveness of hearing intervention and rehabilitation?

6.1. Narrative review of the effect of NIBS on audiologic parameters

6.1.1. Introduction

We suggest that speech perception performance during auditory rehabilitation in patients using hearing aids and CIs could be enhanced by NIBS. This section outlines early published data and theories that informed our inquiry into the potential role of NIBS as an adjunct of CI and auditory rehabilitation. Our objective is to map the current landscape, identify disparate strands of research, and highlight opportunities for future investigation. This is a narrative review of studies regarding NIBS in the hearing domain with emphasis on tES given the relative contraindication of TMS in the setting of implantable electronic devices. It is recognized that the studies discussed may have mixed or contradictory findings on the effect of NIBS on outcomes. There are several possible explanations for this, including their small and heterogenous study populations, and varying methodologies and parameters being tested.

Published applications of NIBS to influence central auditory processing and speech perception are summarized and presented in Table 3. It should be noted that the majority of the studies presented address online effects of tES in normal hearing subjects. To enhance the benefits of auditory intervention and potentiate the effects of auditory rehabilitation we would be most interested in offline and sustained effects from NIBS. This review excludes tFUS as to date there are no published studies of its use in this context.

6.1.2. tDCS

tDCS studies on the auditory cortex are mainly limited to participants with normal hearing. Findings include modulation of mismatch negativity, improved temporal resolution, and enhanced phonetic categorization and pitch discrimination (Heimrath et al., 2016). Results for the right-ear advantage in dichotic listening remain mixed (Marquardt et al., 2021). Giustolisi et al. and Vergallito et al. (Giustolisi et al., 2018; Vergallito et al., 2020) explored whether tDCS could enhance sentence comprehension in healthy individuals. They found that outcomes depend on stimulation site: targeting the left inferior frontal gyrus

Table 3

Summary of published studies assessing the effect of tES on central auditory processing and speech perception. tFUS = transcranial focused ultrasound stimulation; TMS = transcranial magnetic stimulation, tES = transcranial electrical stimulation, tDCS = transcranial direct current stimulation; tACS = transcranial alternating current stimulation; tRNS = transcranial random noise stimulation.

Reference tDCS	Stimulation Type	Design (Within, Between, Crossover)	Control Condition (Sham, Anode vs. Cathode)	Study Population	Stimulation Electrode Position/ Brain Target	Intensity	Duration	Auditory Variable Tested	Online/ Offline Effect	Main Results (Negative or Positive Result)
Giustolisi et al., 2018	tDCS	Between	Sham	44 – Subjects with normal hearing	Left inferior frontal gyrus (F5)	0.75 mA	30 minutes	Natural auditory language comprehension	Online	tDCS over the Left inferior frontal gyrus lead to improvement in language comprehension – **Positive Result**
Marquardt et al., 2021	tDCS	Crossover	Sham	32 - Subjects with normal hearing	Left temporo-parietal cortex (CP5)	2 mA	20 minutes	Dichotic listening	Online	tDCS had little to no effect on dichotic listening – **Negative Result**
Vergallito et al., 2020	tDCS	Between	Sham	66 - Subjects with normal hearing	Left inferior parietal cortex (P3)	0.75 mA	30 minutes	Natural auditory language comprehension	Online	tDCS over the Left inferior parietal cortex decreased language comprehension. Applying tDCS over different hubs of the same neural network can lead to opposite behavioral results – **Negative Result**

tACS

Reference	Stimulation Type	Design	Control Condition	Study Population	Stimulation Electrode Position/ Brain Target	Intensity	Duration	Auditory Paradigm Tested	Online/Offline Effect	Main Results (Negative or Positive Result)
Riecke, 2016	tACS	Crossover	Sham	25 - Subjects with normal hearing	Bilateral Auditory Cortices (T7/T8)	4 Hz	10 minutes	Detection of near-threshold auditory stimuli	Online	tACS may amplify/attenuate sounds that are temporally coherent/ anticoherent with tACS-entrained cortical oscillations – **Positive Result**
Rufener et al., 2016	tACS	Between	Control group without sham stimulation	18 - Subjects with normal hearing	Bilateral Auditory Cortices (T7/T8)	6 Hz & 40 Hz	18 minutes	Repetition-induced improvement in phoneme categorization	Offline (Immediately after stimulation)	40 Hz tACS selectively attenuated repetition-induced improvement in phoneme categorization. Causally confirming the functional relevance of 40 Hz oscillations in phoneme processing – **Positive Result**
Riecke et al., 2018	tACS	Crossover	Sham	22 - Subjects with normal hearing	Bilateral Auditory Cortices (T7/T8)	4 Hz	36 minutes	Speech recognition performance	Online	Demonstrated a causal role of speech-brain entrainment in speech intelligibility. They suggested that transcranial speech envelope shaped currents can be utilized to modulate speech comprehension in impaired listening conditions – **Positive Result**
Wilsch et al., 2018	tACS - envelope	Crossover	Sham	19 - Subjects with normal hearing	Bilateral Auditory Cortices (T7/T8)	5.12 Hz (average)	20 minutes each day for 2 days	Speech comprehension during noise – Oldenburg sentence test	Online	Envelope-tACS modulates intelligibility of speech in noise at or near the peak frequency of the speech envelope – **Positive Result**
Rufener et al., 2019	tACS	Crossover	Sham	34 - Children, Adolescents and Adults with developmental dyslexia but normal hearing	Bilateral Auditory Cortices (T7/T8)	40 Hz	20 minutes	Auditory phoneme processing acuity – phoneme-categorization task	Online	tACS improved phoneme categorization in children, adolescents and adults with developmental dyslexia – **Positive Result**

(*continued on next page*)

Table 3 (*continued*)

tACS

Zoefel et al., 2019	tACS	Blocked	Sham	46 - Subjects with normal hearing	Unilateral (T7) & Bilateral Auditory Cortices (T7/T8)	3.15 Hz	30 minutes	Speech comprehension (rhythmic noise-vocoded speech)	Online	Showed evidence for a tACS-induced phasic modulation of speech perception but only if the stimulation was applied bilaterally using ring electrodes – **Positive Result**
Erkens et al., 2020	tACS - envelope	Crossover	Sham	32 - Subjects with normal hearing	FC5, FC6, P7, and P8 according to the international 10–20 system.	5 Hz	8 minutes	Speech comprehension during noise – Oldenburg sentence test	Online	No significant difference between the optimal stimulation time-lag condition and best sham condition – **Negative Result**
Kadir et al., 2020	tACS - envelope	Crossover	Sham + tDCS anodal and cathodal	17 - Subjects with normal hearing	Bilateral Auditory Cortices (T7/T8)	3 Hz	20 minutes each day for 2 days	Speech comprehension during noise – sentence reception threshold	Online	Phase and latency of neurostimulation have accordingly distinct influences on speech comprehension; tES in this study mostly resulted in worsening of speech comprehension – **Negative Result**
Keshavarzi et al., 2020	tACS - envelope	Crossover	Sham	18 - Subjects with normal hearing	Bilateral Auditory Cortices (T7/T8)	4–8 Hz (theta band) or 1–4 Hz (delta band)	Unspecified time	Speech comprehension during noise – sentence reception threshold	Online	tACS in the theta band (4–8 Hz) but not in the delta band (1–4 Hz) impacts speech comprehension, improving speech-in-noise comprehension – **Positive Result**
Ruhnau et al., 2020	Pulsed tDCS - brief (5 ms) direct current pulses at time points between syllables to simulate envelop tES	Within	Nil	20 - Subjects with normal hearing	Bilateral Auditory Cortices (T7/T8)	Brief direct current pulses (5 ms) at time points between syllables. Maximum current was 1.95 mA.	55 minutes	Speech comprehension during noise – Oldenburg sentence test	Online	Concluded that pulsed tDCS can aid cortical entrainment to speech input, which is especially relevant in noisy environment – **Positive Result**

tRNS

Reference	Stimulation Type	Design	Control Condition	Study Population	Stimulation Electrode Position/ Brain Target	Intensity	Duration	Auditory Paradigm Tested	Online/ Offline Effect	Main Results (Negative or Positive Result)
Van Doren et al., 2014	tRNS	Crossover	Sham	14 - Subjects with normal hearing	Bilateral Auditory Cortices (Cathode applied to T7/Anode applied to T8)	High frequency tRNS (100–640 Hz)	20 minutes	Auditory evoked activity by means of Auditory Steady State response	Offline – Immediately after	tRNS induces increased excitability in the auditory cortex – **Positive Result**
Rufener et al., 2017	tRNS	Crossover	Sham	20 – Subjects with normal hearing	Bilateral Auditory Cortices (T7/T8)	High frequency tRNS (100–640 Hz)	40 minutes	Temporal and spectral resolution ability – Gap detection and pitch discrimination tasks	Online	tRNS can improve acoustic perception of time critical auditory information – **Positive Result**
Rufener et al., 2019	tRNS	Crossover	Sham	34 - Children, Adolescents and Adults with developmental dyslexia but with normal hearing	Bilateral Auditory Cortices (T7/T8)	High frequency tRNS (100–640 Hz)	20 minutes	Auditory phoneme processing acuity – phoneme-categorization task	Online	tRNS improved phoneme categorization acuity in adults with developmental dyslexia – **Positive Result**

Table 4

Study characteristics from a scoping review of therapeutic use of NIBS as adjunct to hearing intervention and rehabilitation Abbreviations: AAT = auditory attention training; CI = Cochlear Implant; DLPFC = dorsolateral prefrontal cortex; HA = hearing aid; HBO = Hyperbaric Oxygen Therapy; HHIE-*S* = Hearing Handicap Inventory for the Elderly-Screening; ISSNHL = idiopathic sudden sensorineural hearing loss; MMSE = Mini-mental state examination; MoCA = Montreal Cognitive Assessment Scale; PTA = pure tone audiometry; rDLPFC = right DLPFC; SCT = Standard Corticosteroid Therapy; SRT = Speech Reception Threshold; tACS = transcranial alternating current stimulation; tDCS = transcranial direct current stimulation; rTMS = repetitive transcranial magnetic stimulation; SNHL = sensorineural hearing loss.

Reference	NIBS Modality	Study Design	Control Condition	Study Population	Stimulation Electrode Position/ Brain Target	Intensity	Duration	Auditory Variable Tested	Online/Offline Effect	Main Results (Negative or Positive Result)
Mori et al., 2016	tDCS	Within	Nil	1 subject; bilateral hearing impairment after brainstem encephalitis. No use of HA/CI.	Left auditory cortex	1 mA	10 min daily × 4 days	Speech discrimination (right ear)	Offline (assessed immediately after and 4 days after)	Speech discrimination improved after a single session; effect persisted 4 days after final session – **Positive Result**
Mansouri et al., 2025 (International Journal of Pediatric Otorhinolaryngol)	tDCS	Between: 3 arm randomized controlled trial	Sham tDCS + AAT; tDCS alone	24 children (8–11y); moderate to severe hearing loss. Subjects used bilateral HAs for at least 3 years prior to study.	Bipolar tDCS: Anode F3 (left DLPFC), Cathode F4 (right DLPFC)	1 mA first session then 1.5 mA subsequent sessions	20 min sessions; 10 sessions (3×/week); AAT started 5 min after tDCS onset and ran 15 min	Auditory attention, speech-in-noise, P300 latency	Offline (≤48 h post-intervention and 1 month follow-up)	Combined tDCS + AAT improved auditory attention and speech-in-noise more than sham+AAT and tDCS-only; effects stable at 1 month – **Positive Result**
Mansouri et al., 2025 (Auditory and Vestibular Research)	tDCS	Between: Randomized pilot	Sham tDCS + AAT	8 children (8–11y); moderate to severe hearing loss. Subjects used bilateral HAs for at least 3 years prior to study.	Bipolar tDCS: Anode F3 (left DLPFC), Cathode F4 (right DLPFC)	Not reported	20 min sessions; 10 sessions (3×/week); AAT started 5 min after tDCS onset and ran 15 min	Auditory attention, speech-in-noise, P300 latency	Offline (immediately after intervention and 1 month follow-up)	Active tDCS+AAT improved auditory attention and speech-in-noise measures; P300 latency decreased in both groups with larger reductions in active group; outcomes stable at 1 month – **Positive Result**
Zhou et al., 2025	tDCS	Between: Randomized controlled trial	Sham tDCS + routine auditory rehab training	100 Elderly patients ≥60 years old; bilateral progressive SNHL. Subjects used bilateral HAs for at least 6 months prior to study	Dual-site sequential stimulation: Right DLPFC (F4 anode; cathodes F2/F6/FC4/AF4) + Left temporal area (CP5 anode; cathodes C5/TP7/CP3/P5)	2 mA per site	15 min per site (30 min total); 3×/week for 1 month; order of sites randomized	Auditory Ability (PTA, HHIE-S), Cognitive Ability (MoCA, MMSE), Communication Performance, Fear of Communication and Quality of Life outcomes	Offline (assessed 1 month post intervention)	tDCS-assisted auditory rehabilitation training improved cognitive and auditory functions as well as quality of life – **Positive Result**
Erkens et al., 2021	tACS	Between: Non-randomized	Sham	40 older adults (Ages 49–79); 20 Hearing impaired participants vs 20 normal hearing controls. For the hearing impaired subjects, 18 had been using a HA for at least 1 year prior to study.	Electrodes placed at EEG positions FC5/P7 and FC6/P8 (10–20 system)	Stimulation was presented at 1 mA peak to peak. The stimulation signal corresponded to the envelope of the concurrent speech signal	~20 min total	Speech comprehension in noise	Online	Hearing-impaired participants improved more than normal hearing subjects with envelope-tACS stimulation) – **Positive Result**

(*continued on next page*)

Table 4 (*continued*)

Reference	NIBS Modality	Study Design	Control Condition	Study Population	Stimulation Electrode Position/ Brain Target	Intensity	Duration	Auditory Variable Tested	Online/Offline Effect	Main Results (Negative or Positive Result)
Neri et al., 2024	rTMS	Between: Randomized controlled trial)	Sham	27 adults (Ages 40–93); Bilateral Hearing aid users with SNHL. Subjects used bilateral HAs for at least 1 year prior to study.	Posterior left superior temporal sulcus (auditory association cortex; between BA22/ 42)	10 Hz	1800 pulses/ session. One session a day. 5 consecutive daily sessions;	Speech comprehension in noise; PTA	Offline (Immediately after and 1-week post intervention)	rTMS produced greater reductions in SRT and PTA vs sham immediately and at 1 week (beyond learning effects). – **Positive Result**
Zhang and Ma, 2015	rTMS	Between: Non-randomized	Standard Therapy Alone (SCT & HBO)	54 adults; ISSNHL patients failing primary therapy (SCT & HBO). No use of HA/CI.	Temporoparietal association cortex ipsilateral to affected ear (Left scalp: between T3 and the midpoint of the line joining C3/T5. Right scalp: between T4 and the midpoint of the line joining T6/C4)	1 Hz	1200 pulses/ session. One session a day. 20 sessions (Mon–Fri ×4 weeks)	PTA; tinnitus perception	Offline (~72 hrs post intervention)	rTMS group showed improved hearing thresholds and decreased tinnitus vs control. – **Positive Result**
Huang et al., 2025	rTMS	Between: Non-randomized	Standard therapy only (Ginkgo biloba extract, vitamin B1 and intravenous steroids)	339 adults; ISSNHL (onset $\leq$30 days). No use of HA/CI.	Temporoparietal junction ipsilateral to symptomatic ear	1 Hz	600 pulses/ session. One session a day. Sub grouped by $\leq$10 vs >10 sessions	PTA; tinnitus perception	Offline (on discharge and 6 month follow up)	rTMS administered in courses > 10 sessions, demonstrated both short-term and long-term beneficial effects in the ISSNHL – **Positive Result**

improved sentence comprehension, while stimulation of the left inferior parietal cortex reduced it. These studies suggest that targeted tDCS can modulate auditory processing.

6.1.3. *tACS*

Most of the recent literature regarding tES and speech understanding studies focus on tACS and have been mostly conducted in participants with normal pure-tone thresholds (Zoefel et al., 2019). Research using stereotactic EEG and fMRI has revealed that during speech perception, the auditory cortex shifts from a resting oscillatory state to a structured neural response that aligns with the speech envelope's spectro-temporal features (Giraud and Poeppel, 2012; Lalor and Foxe, 2010). This phenomenon, called neural entrainment, is often weaker as individuals age or in individuals with hearing loss (Henry et al., 2017). tACS operates by delivering a sinusoidal current at a specific frequency to synchronize and modulate cortical oscillations (Antal and Paulus, 2013), influencing both online and offline processing (Heimrath et al., 2016; Veniero et al., 2015). The effectiveness of this modulation can depend on various factors, including the phase and timing of stimulation in relation to the speech signal (Kadir et al., 2020). Notably, tACS in the theta band (4–8 Hz) improves speech comprehension, while delta band stimulation (1–4 Hz) supports syntactic and semantic encoding (Keshavarzi et al., 2020). Additionally, envelope-tACS, which aligns stimulation with the temporal envelope of speech, presents a promising avenue for enhancing speech perception and addressing auditory processing difficulties (Erkens et al., 2020).

Riecke (2016) showed that tACS can enhance or suppress speech perception depending on alignment with speech timing. Keshavarzi et al. (Keshavarzi et al., 2020) applied tACS to 18 individuals with normal hearing, using waveforms extracted from speech envelopes and filtered into delta and theta frequency ranges to modulate cortical entrainment. They found that theta-band tACS improved speech-in-noise comprehension, while delta-band did not.

Wilsch et al. (2018) explored how tACS synchronized with the speech envelope at varying time lags (0–250 ms from sentence onset) influences speech intelligibility. They concluded that envelope tACS can influence speech perception in noise by modulating cortical entrainment to the speech envelope. Similarly, Riecke et al. (Riecke et al., 2018) provided evidence supporting the causal role of speech-brain entrainment in improving intelligibility. Additionally, Rufener et al. (Rufener et al., 2016) showed that 40 Hz tACS benefited older adults more than younger ones on a phoneme categorization task.

Ruhnau et al. (2020) investigated the effects of a pulsed tES. They administered brief 5 ms of direct current (DC) monophasic pulses between syllables. Their findings suggest that pulsed tES can enhance cortical entrainment with speech, improving perception in noise. They also explored the potential application of this approach in real-world scenarios, proposing a setup where a hearing aid could be integrated with a wearable electrical stimulation device.

Not all studies show benefits. Kadir et al. (2020) examined how tACS influences speech-in-noise perception by applying stimulation synchronized to the speech envelope but with phase shifts and temporal delays. Their findings revealed that the sentence reception threshold varied depending on the phase of stimulation. Notably, their results suggested that tACS generally led to a decline in speech perception. Similarly, Erkens et al. (Erkens et al., 2020) observed no improvement when comparing optimal tACS to sham. These findings highlight the importance of timing precision and individual variability in responsiveness.

6.1.3. *tRNS*

tRNS has been developed as an option that would potentially modulate many different types of neurons. tRNS applies randomly fluctuating currents that resemble white noise, modulating a wider range of cortical rhythms without prior knowledge on the specific frequency of the target resonator (Rufener et al., 2017; Van Doren et al., 2014). Stochastic resonance describes the phenomenon that the perception of a near threshold stimulus, like a sound signal, is boosted if noise is also present (Rufener et al., 2017). The effects of tRNS are dependent on stimulation intensity, spectrum, and task demands (Van Doren et al., 2014).

Van Doren et al. (2014) found tRNS increased 40 Hz auditory steady-state responses, suggesting heightened cortical excitability. Rufener et al. (Rufener et al., 2017) examined the impact of tRNS on the auditory cortex based on both behavioral and electrophysiological measures. They observed that tRNS improved the detection of near-threshold stimuli in the temporal domain (gap detection) but did not affect spectral discrimination (pitch perception). These behavioral effects were accompanied by a reduction in peak latencies of the P50 and N100 auditory event-related potentials, indicating that tRNS influences early sensory processing. Their findings suggest that tRNS may enhance the auditory system's endogenous resonance frequency, potentially improving the perception of temporally sensitive auditory information.

Rufener et al. (2019) studied the online effects of tACS and tRNS in normal hearing adolescents and adults with developmental dyslexia which is related to disordered auditory temporal resolution and impaired processing of information at the phonemic scale. In dyslexia, tRNS improved phoneme categorization in adults, while tACS worked better for children.

In summary, there is growing evidence that tES can enhance central auditory processing, with the preponderance of evidence linked to on-line effects during behavioral tasks in participants with normal hearing. There remains limited information about the impact of auditory training and other rehabilitation strategies on the quality and duration of benefit.

6.1.5. *NIBS used in Tinnitus*

Tinnitus, the perception of sound without external input, affects 66–86% of CI users (Peter and Kleinjung, 2019) (Quaranta et al., 2004). It reflects hyperactivity and maladaptive reorganization in auditory and non-auditory regions (Adjamian et al., 2009; Peter and Kleinjung, 2019).

NIBS techniques, transcutaneous vagus nerve stimulation, and bimodal auditory-somatosensory stimulation, have been explored for tinnitus treatment (De Ridder et al., 2021; Langguth, 2020; Peter and Kleinjung, 2019). Some rTMS and tDCS studies show temporary symptom relief, but repeated sessions rarely produce lasting benefits.

A meta-analysis found rTMS over the auditory cortex had the most consistent effect, especially in women, while tDCS showed no significant advantage over sham (Lefebvre-Demers et al., 2021). Some studies found rTMS reduced tinnitus severity (Barwood et al., 2013) and, in some cases, improved hearing perception (D. Zhang and Ma, 2015). When considering NIBS for CI patients, tinnitus assessment is essential.

6.2. *Scoping review of therapeutic use of NIBS as adjunct to hearing intervention and rehabilitation*

6.2.1. *Study characteristics*

This scoping review examined the therapeutic application of NIBS for hearing rehabilitation in individuals with hearing loss. Eight studies met inclusion criteria (Fig. 1 and Table 4). Study designs included randomized controlled trials, sham-controlled crossover studies, pilot trials, observational cohort studies, and case reports. There were generally small sample sizes and substantial methodological heterogeneity. Study populations included children, adults, and older adults with sensorineural, age-related, or idiopathic sudden sensorineural hearing loss. The search included all forms of NIBS but only 3 modalities were used in the identified articles: tDCS, tACS, and rTMS. Stimulation parameters, rehabilitation protocols, outcome measures, and follow-up durations varied widely across studies, precluding quantitative synthesis.

6.2.2. *tDCS*

tDCS was the most frequently studied modality and was predominantly applied over frontal (dorsolateral prefrontal cortex, DLPFC) (Mansouri, Javanbakht, et al., 2025; 2025; Y. Zhou et al., 2025) or auditory cortex (Mori et al., 2016). Across studies, tDCS was most effective when combined with structured auditory or auditory-attention training rather than delivered as a standalone intervention. In pediatric populations with moderate-to-severe hearing loss (Mansouri, Javanbakht, et al., 2025; 2025), repeated sessions of anodal tDCS over the DLPFC paired with auditory attention training led to improvements in selective and sustained auditory attention, speech-in-noise perception, and electrophysiological markers of auditory-cognitive processing (e.g., reduced P300 latency). These gains were generally stable at short-term follow-up (up to one month).

In older adults with age-related hearing impairment, high-definition tDCS combined with conventional auditory rehabilitation training was associated with improvements in self-reported communication ability and quality of life measures, with minimal adverse effects reported (Y. Zhou et al., 2025). Although improvements in auditory thresholds were modest, the consistent benefits observed in functional and cognitive-communication outcomes suggest that tDCS may primarily act by enhancing top-down cognitive control mechanisms that support listening under challenging conditions. However, methodological limitations were common among tDCS studies, including small sample sizes, pilot designs, and some concerns regarding randomization and blinding (Mansouri, Javanbakht, et al., 2025; 2025; Mori et al., 2016).

6.2.3. *tACS*

Only one included study directly examined tACS in hearing-impaired participants, using envelope-shaped stimulation synchronized to the speech signal (Erkens et al., 2021). This study demonstrated that individuals with hearing impairment showed greater improvement in speech-in-noise performance under envelope-tACS compared with normal-hearing controls. These findings support the hypothesis that tACS may enhance speech perception in noise by facilitating neural entrainment to the temporal envelope of speech (Erkens et al., 2021). Despite these promising results, the evidence base for tACS remains sparse, with limited reporting of stimulation parameters and small sample size.

6.2.4. *rTMS*

rTMS studies primarily focused on adults with sensorineural or idiopathic sudden sensorineural hearing loss and targeted temporal auditory association areas, such as the superior temporal sulcus or temporoparietal junction (C. Huang et al., 2025; Neri et al., 2024; D. Zhang and Ma, 2015). In a randomized sham-controlled trial, short courses of high-frequency rTMS were associated with significant off-line improvements in speech reception thresholds and pure tone averages compared with sham stimulation (Neri et al., 2024).

Observational and non-randomized studies further suggested that longer rTMS treatment courses (>10 sessions) may yield superior short- and long-term hearing recovery, although risk of relapse varied by audiometric configuration (C. Huang et al., 2025; D. Zhang and Ma, 2015). While these findings are clinically encouraging, the overall risk of bias for rTMS studies was higher than for randomized tDCS trials, primarily due to non-randomized designs, potential confounding, and allocation bias.

6.2.5. *Safety and Tolerability*

Across all modalities, NIBS was generally well tolerated. Reported adverse effects were mild and transient, most commonly including scalp tingling or mild headache, with no serious adverse events reported (Mansouri, Shaabani, et al., 2025; Mori et al., 2016; Y. Zhou et al., 2025). This favourable safety profile supports further investigation of NIBS as an adjunctive rehabilitation strategy in hearing-impaired populations.

6.2.6. *Strengths and limitations of the evidence*

This review benefits from inclusion of multiple NIBS modalities and diverse populations, providing a broad overview of current neuromodulation approaches in hearing rehabilitation. Several studies employed randomized or sham-controlled designs and incorporated objective auditory and neurophysiological outcomes, strengthening internal validity (Mansouri, Shaabani, et al., 2025; Neri et al., 2024).

However, the certainty of evidence remains limited by small sample sizes, pilot designs, and substantial heterogeneity in stimulation protocols, rehabilitation approaches, and outcome measures, which precluded meta-analysis (C. Huang et al., 2025; Y. Zhou et al., 2025). Limited long-term follow-up further constrains conclusions. These limitations necessitate cautious interpretation.

6.2.7. *Conclusions and future directions*

Overall, the findings suggest that NIBS—particularly when combined with behavioral auditory rehabilitation—can positively influence auditory and auditory-cognitive outcomes in individuals with hearing loss. tDCS appears most effective for enhancing top-down cognitive and attentional processes that support listening, whereas rTMS shows more direct effects on auditory thresholds and speech perception in specific clinical populations. tACS represents an appealing but underexplored approach, warranting further study.

Future research should include large-scale, well-controlled trials with standardized auditory outcomes in order to clarify the clinical utility of NIBS in hearing rehabilitation. Longer follow-up periods are needed to assess durability of treatment effects and to evaluate the need for booster stimulation sessions. Subgroup analyses examining age, etiology of hearing loss, and cognitive status are needed to identify populations most likely to benefit. Studies integrating neurophysiological and neuroimaging measures may further inform optimization of stimulation protocols

6.3. *Conceptual framework for NIBS in hearing rehabilitation (Fig. 4)*

6.3.1. *Introduction and rationale*

As stated by Kral et al. (Kral et al., 2016): "…central processing of sensory information, particularly if it is an impoverished representation of normal input, is key to the clinical success of neural prostheses". There is substantial variability in speech perception outcomes in CI users. Almost all CI patients improve dramatically after CI activation, but some patients will reach a plateau in their performance. Some patients might even grow reluctant to wear the external part of the implant if their outcomes are poor (Távora-Vieira et al., 2020). Poor speech understanding in noise is a common complaint of patients using both CIs and hearing aids. Therefore, there is an unmet need for approaches that can boost patients' speech perception performance even when receiving auditory rehabilitation (Goudey et al., 2021; Zhao et al., 2020). We also need to consider the safety of using different modalities of NIBS with CIs and HAs, which is discussed in a later section.

Intra-modal, intermodal and neurocognitive processes involved in this rehabilitation construct may benefit from relevant NIBS particularly if it would be possible to selectively enhance beneficial plasticity and suppress maladaptive plasticity (Fig. 2). Whereas a growing literature documents the impact of NIBS on neurocognitive processes relevant to receptive language in normal hearing subjects (Y. Wang et al., 2020; Zoefel and Davis, 2017) , there is very limited direct evidence of how NIBS may impact speech perception outcomes in those with hearing loss who use hearing devices. Reviewing the available literature, there seem to arise two general strategies for applying tES and other NIBS modalities to the remediation of hearing loss with a CI or hearing aid. These are reviewed in the next sections.

6.3.2. *Strategy 1 – online brain entrainment with NIBS*

Based on recent studies of tES and speech understanding, this strategy would uses online effects of tES to improve the neural representation of speech sound for better spatial and temporal resolution and enhanced perception in quiet and background noise (see Section 6.2). Published findings suggest that tACS or pulsed tES may enhance speech envelop features that are temporally coherent with tES-entrained cortical oscillations. This strategy would require that the tACS stimulation characteristics adapt in real time in response to changing speech sound signals. In addition to its online effects, this real-time use of tACS may also produce longer lasting off-line effects that need to be investigated.

Another simpler option would be to use tRNS which has been shown to increase excitability in the auditory cortex and has positive effects on phoneme-categorization acuity and acoustic perception of time critical auditory information. tRNS allows for frequency non-specific application without prior knowledge of the specific frequency of the target resonator and therefore may be easier to implement for real-time listening.

A general conceptual drawback of the use of NIBS for chronic stimulation synchronized with speech perception is that the CI recipient will also have to wear surface electrodes and other NIBS gear whenever they are wearing the CI. Therefore, unless it is limited to a period of rehabilitation, this strategy may be impractical for daily use. Nonetheless, if the strategy of chronic synchronous CI and cortical stimulation works, it may justify the development of a minimally invasive cortical stimulator implant coupled to the CI device either internally or externally.

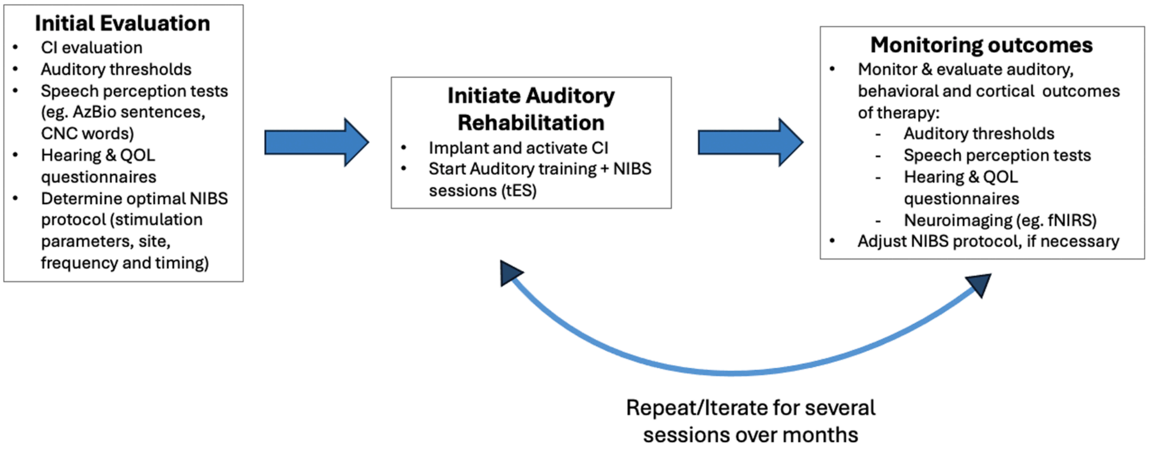

Fig. 4. Proposed NIBS Protocol. A schematic representation of a rehabilitation protocol that incorporates NIBS and auditory training following cochlear implantation in adult patients with post-lingual deafness. CI = Cochlear Implant, QOL = Quality of Life, NIBS = Non-invasive Brain Stimulation; tES = Transcranial Electrical Stimulation, fNIRS = Functional Near-Infrared Spectroscopy.

6.3.3. Strategy 2 – Offline NIBS to facilitate therapy

6.3.3.1. Correlating neuroplasticity patterns with auditory rehabilitation outcome. Several changes in cortical structure and activity patterns may represent the direct effects of auditory deprivation as reflected in the adaptive hierarchy outlined in Fig. 2. Early activation of pre-existing circuits, localized to the superior temporal gyrus (STG) and superior temporal sulcus (STS) are thought to involve multi-sensory cortical circuits that support speech reading in adult-onset hearing loss (H. J. Lee et al., 2007). The improved access to phonological representations during speech reading may therefore result from compensatory use of latent multi-modal circuits rather than cortical reorganization. Furthermore, grey matter hypertrophy at the right angular gyrus is correlated with severity of hearing loss and compensatory skill development associated with multi-modal integration (Alfandari et al., 2018).

Enhanced speech perception associated with activation of the cingulo-opercular network in the frontal cortex (Vaden et al., 2016, 2020, 2022; Vaden, Teubner-Rhodes, et al., 2017) and prefrontal and premotor cortices (Kral et al., 2016; Obleser et al., 2007; Peelle, 2010, 2018) is attributed to compensatory adjustments in attention, behavior and outcome monitoring. Can the use of NIBS enhance the capacity and/or efficiency with which this cognitive network is recruited to improve speech perception? There is however a tenuous balance between the benefits of activating these central compensatory networks and the accompanying cognitive load and processing demands, particularly in aging populations where reserve is limited (Park and Reuter-Lorenz, 2009). Nevertheless, the cingulo-opercular network may offer an opportunity to monitor or target neurocognitive processes that are central to auditory rehabilitation. Appropriately designed rehabilitation exercises may further enhance the efficiency of these cognitive adaptations.

Should these sites be considered as targets for NIBS to support better accommodation to imperfect auditory input? Could this, however, be counterproductive to the goal of better auditory perception? Is it best to target the primary auditory cortex with the goal of normalizing central auditory processes, higher order cortical networks to enhance compensatory processes, or both? Phonology-related neural activity in Wernicke’s area and the left supramarginal gyrus as well as increased prefrontal and parietal activity (H. J. Lee et al., 2007), may however be associated with reduced CI performance. Older adults with hearing loss experience diminished functional benefits from central compensatory mechanisms (Cardin, 2016; Kuchinsky et al., 2012; Mishra et al., 2014; Vaden et al., 2015). More detailed studies are therefore needed to set therapeutic boundaries and appropriate expectations for the role of NIBS in hearing rehabilitation.

6.3.3.2. Anticipating NIBS targets that may potentiate favorable cortical neuroplasticity in response to auditory rehabilitation (Table 5). Therapeutic strategies designed to leverage off-line effects of NIBS would likely be repetitive and timed to coincide with relevant auditory training

Table 5

Potential Targets for NIBS and Effect Monitoring: Key brain regions and neural changes linked to improved hearing and speech outcomes.

Site	NIBS Effect	*Citation*	Effect Monitoring: Changes with positive predictive value	*Citation*
Auditory cortex	Improved hearing threshold and speech comprehension	Mori et al., 2016	Auditory evoked potential with increasing amplitude and shorter latency Increasing metabolic activity Lower vision-evoked activity relative to auditory-evoked activity in visual cortex	F. Zhang et al., 2010; Sandmann et al., 2015 Ito et al., 1993 Chen et al., 2016
Superior temporal gyrus/ Superior temporal sulcus *(Auditory Associative Cortex)*	Improved speech reception thresholds and pure tone averages	H. J. Lee et al., 2007 Neri et al., 2024 C. Huang et al., 2025 D. Zhang and Ma, 2015	Increasing response to auditory versus visual stimuli Increasing activation of right Heschel’s gyrus (improved spectral analysis) Increasing activation of Wernicke’s area (access to semantic knowledge) Increasing contralateral cortical volume	Strelnikov et al., 2015 Smalt et al., 2013 Y. J. Lee et al., 2024
Right angular gyrus *(Auditory Associative Cortex)*	For potential investigation to promote multi-sensory integration and auditory learning		Cortical hypertrophy associated with adaptations to hearing impairment	Alfandari et al., 2018
Middle temporal gyrus	For potential investigation to promote lexical processing		Increased activation associated with improved sentence comprehension	Smalt et al., 2013
Cingulo-opercular network	For potential investigation to promote attention and outcome monitoring		Increased activation in response to noise and degraded speech	Vaden et al., 2016, 2020, 2022; Vaden, Teubner-Rhodes, et al., 2017
Left inferior frontal gyrus *(Prefrontal Cortex)*	Improves verbal short term memory and sentence comprehension	Giustolisi et al., 2018*;*	Increased activation with auditory training (representation of speech) Baseline activity associated with CI performance	Smalt et al., 2013 Strelnikov et al., 2013
Dorsolateral prefrontal cortex *(Prefrontal Cortex)*	Increased auditory attention and speech perception in noise with training Improved auditory and cognitive function associated with age-related hearing loss	Mansouri, Javanbakht, et al., 2025; 2025 Y. Zhou et al., 2025	Reduced P300 latency	Mansouri et al., 2025 *(Auditory and Vestibular Research)*
Insula	For potential investigation to promote working memory and decision making		Increased activation with auditory training	Smalt et al., 2013
Cuneus *(Occipital cortex)*	For potential investigation to promote abstract speech representation		Baseline activity Associated with CI performance Auditory stimulation of visual activity stronger than the reverse in CI users Increasing activity with auditory training	Strelnikov et al., 2013 Chen et al., 2016 Smalt et al., 2013
Cingulate Gyrus	For potential investigation to promote semantic processing		Increasing activity with auditory training and CI experience	Smalt et al., 2013; Giraud et al., 2001 *(Neuron)*; Kang et al., 2004

activities. The selected NIBS modality would need to be compatible with the hearing device that is in use and able to penetrate to the appropriate target depth. Neurophysiological or functional imaging effects that precede behavioral benefits may be monitored and used to inform therapeutic decisions (Fig. 4). However, activation patterns associated with favorable results do not necessarily inform which components of these networks should be targeted for NIBS. Indeed, Vergallito et al. (2020) have observed that “tES over different hubs of the same neural network can provide opposite results”.

6.3.3.2.1. Auditory cortex. Cochlear implant benefit is associated with increasingly normal physiological characteristics of the auditory cortex, yet these effects may represent a complex combination of processes within and outside the auditory cortex. NIBS may therefore need to be multi-focal at different stages of the rehabilitation process, targeting specific adaptive responses associated with the hierarchy presented in Fig. 2.

Increased activity in the auditory association cortex and not the primary auditory cortex is associated with improved perceptual performance following cochlear implantation (Strelnikov et al., 2015). This may represent the activation of higher order networks needed to integrate multi-sensory and cognitive inputs that support the development of new listening capabilities. Improved sentence perception associated with increased activity in the right hemisphere near Heschl’s gyrus may represent improved analysis of spectral information (Smalt et al., 2013). Improved performance was also associated with activation of Wernicke's area (BA 22 and BA 39) suggesting better access to long-term semantic knowledge. NIBS that targets these networks within the temporal lobe, may facilitate Hebbian learning that could be further facilitated by auditory training. Indeed, studies have shown that stimulation of the auditory association cortex with rTMS resulted in prolonged improvements of hearing threshold and speech comprehension in patients with hearing loss (C. Huang et al., 2025; Neri et al., 2024; D. Zhang and Ma, 2015).

6.3.3.2.2. Prefrontal cortex. The prefrontal cortex represents a promising target for NIBS in auditory rehabilitation because of its central role in top-down control of auditory perception and attention. Neuroimaging studies have shown that the dorsolateral prefrontal cortex (DLPFC) is engaged during tasks requiring selective attention (Mansouri, Shaabani, et al., 2025). This is critical for effective listening, particularly in individuals with hearing loss who must exert greater cognitive effort to decode degraded auditory input. Stimulation of the prefrontal cortex has the potential to improve the brain’s responsiveness to concurrent attention-based auditory training. Preliminary studies have shown that when targeting the DLPFC, tDCS in combination with auditory training leads to improved auditory attention, speech-in-noise comprehension, cognition and quality of life of patients with hearing loss (Mansouri, Javanbakht, et al., 2025; 2025; Y. Zhou et al., 2025). The inferior frontal gyrus is also a potential site for both treatment and effect monitoring based on improved language comprehension in normal hearing subjects following tDCS treatment (Giustolisi et al., 2018).

6.3.3.2.3. Ventral speech processing stream. This system mediates comprehension (Hickok and Poeppel, 2004). Adults with normal hearing and simulated CI listening through chronic exposure to degraded speech (Smalt et al., 2013), demonstrated improving speech perception that was proportionate to fMRI activity within bilateral anterior and posterior middle temporal gyrus (BA 21–22), which are foci within the ventral speech processing stream. It is, however, unclear if responses at these sites reflect increased intelligibility upstream or improved lexical processing at other sites. Whether or not direct stimulation of this site would be productive is subject to further investigation.

6.3.3.2.4. Dorsal speech processing stream. The Dorsal Speech Processing stream is thought to mediate important auditory-motor integration that may utilize visual mapping (Smalt et al., 2013). Whereas increased activity in the cuneus may represent the recruitment of visual cortical areas for improved abstract representation of degraded speech, more intense activity in the cingulate gyrus may represent increased processing of meaning (Giraud et al., 2001; Kang et al., 2004). It is therefore worthwhile evaluating whether NIBS may facilitate these adaptations during structured listening practice.

6.3.3.2.5. Cross modal reorganization. There is growing evidence of the benefit of audiovisual integration for improving communication with a CI, with positive impact on both speech perception (Stevenson et al., 2017) and lip reading (Strelnikov et al., 2013, 2015). The cuneus has been mentioned previously as a potential site for integration of visual modalities with associative processes involved with speech perception. Although the strong correlation between speech processing activity within the occipital cortex and CI performance was measured at baseline rather than during active rehabilitation, it is worthy of study as a potential site for NIBS and/or effect monitoring (Strelnikov et al., 2013). There is also data that contradicts the notion that cross modal reorganization is beneficial, although differences in relative activity measures and performance metrics may account for some of the differences. If indeed cross modal visual reorganization is associated with poorer CI performance, it remains unclear whether a better-developed visual response is a cause or a consequence of poorer speech perception.

Increased baseline activity in the right superior temporal gyrus and left inferior frontal cortex, was also associated with better speech outcomes post-implantation (Strelnikov et al., 2013). These are also sites noted to become activated early during acquired hearing loss and are thought to belong to multi-sensory cortical circuits (H. J. Lee et al., 2007). Likewise grey matter hypertrophy of the right angular gyrus in hearing impaired adults may represent multi-sensory integration (Alfandari et al., 2018). These multi-sensory “crossroads” may be useful sites for monitoring the impact of therapeutic NIBS or guiding subsequent adjustments (Fig. 4).

6.3.4. Auditory training and potential relevance to offline effects of NIBS

Hearing aids and CIs deliver modified auditory signals to impaired and reorganized auditory systems (Tremblay, 2007; Tremblay and Kraus, 2002). Inconsistent device outcome is often linked to the central auditory system’s variable adaptability to these modified signals (Tremblay and Kraus, 2002). Auditory training is one rehabilitative strategy increasingly recognized as a necessary adjunct to hearing augmentation by directly exercising central auditory processes (Stephens, 1987).

Auditory training involves structured repetitive listening exercises designed to enhance the brain’s ability to process auditory information by leveraging neuroplasticity (Dornhoffer et al., 2024; Tremblay, 2007). Training can lead to improved neural synchrony, increased responsiveness of sensory neurons, and enhanced functional specificity, all of which maximize the representation of the unique characteristics of acoustic features (Tremblay, 2007). Programs are often categorized as analytic (bottom up), synthetic (top down), or a combination of both. Analytic training focuses on recognizing contrasting fine acoustic details, while synthetic training emphasizes understanding speech by using contextual information (Tremblay, 2007; Tremblay and Kraus, 2002). Auditory training methods vary widely, ranging from passive home-based exercises, such as listening to audiobooks, to clinician-directed programs and computer-based auditory training programs such as AngelSound™ (TigerSpeech Technology, Los Angeles, California, USA) (Dornhoffer et al., 2024; Sweetow and Sabes, 2010; M. Zhang et al., 2014). Despite a lack of clinical guidelines for adult post-implantation auditory training, nearly all CI providers recommend auditory training soon after CI activation, with sessions lasting several months (Dornhoffer et al., 2024).

Extensive research highlights both clinical and electrophysiological evidence of training benefits (S. Anderson and Jenkins, 2015; Tremblay, 2007). Auditory training also drives cortical reorganization in the auditory cortex, reinforcing its role in improving auditory perception (Neuman, 2005). These measurable changes in neural activity have been observed to occur early and often precede and predict perceptual gains (S. Anderson and Jenkins, 2015; Tremblay, 2007; Tremblay et al., 2009). Additionally, auditory training has been shown to partially restore age-related deficits in temporal processing, facilitating better cognitive and perceptual skills, and communication in noisy environments (S. Anderson et al., 2013; S. Anderson and Jenkins, 2015; Asal et al., 2018). Specifically for CI users, a few studies have shown improvement in speech perception after undergoing auditory training (Green et al., 2019; Reis et al., 2021; Schumann et al., 2015). Despite this, additional research in the efficacy and appropriate use of auditory training for CI users is needed to dictate future treatment guidelines.

Several factors impact the efficacy of auditory training. Despite nearly universal recommendation of auditory training, only about two-thirds of CI recipients utilize it (Dornhoffer et al., 2024). Compliance is a significant challenge, with only about 30% of patients completing home-based auditory training programs (Sweetow and Sabes, 2010). Maintenance of training gains is another concern, underscoring the need for periodic booster sessions (S. Anderson and Jenkins, 2015). Furthermore, individual factors such as age, cognitive reserve, and sleep quality play crucial roles in optimizing outcomes (S. Anderson and Jenkins, 2015). tES offers a promising avenue to enhance auditory training outcomes. tES can modulate cortical excitability, potentially accelerating neural plasticity associated with auditory training. When combined with auditory training and CIs, tES could augment the brain's capacity to adapt to modified auditory signals, improving speech perception and enhancing the outcomes of auditory rehabilitation. Studies by Mansouri et al. for example, provide preliminary evidence of synergistic benefits of tDCS with auditory attention training compared to either alone (Mansouri, Javanbakht, et al., 2025; 2025).

6.3.5. *Monitoring cortical responses to rehabilitation strategies*

To advance the clinical utility of neuroplasticity-driven interventions, a key area for development lies in the objective and dynamic monitoring of auditory and cortical responses to therapy. Monitoring is essential to understanding the neural mechanisms behind individual variability and optimizing rehabilitation strategies. While several neuroimaging techniques have been explored for this purpose, many present significant limitations when applied to CI users.

PET, fMRI, and EEG have all been used to study cortical responses to auditory stimuli. However, these techniques often face compatibility issues with CI hardware, safety constraints due to electromagnetic fields, limitations in spatial resolution or are not practical for longitudinal monitoring (Dewey and Hartley, 2015; Saliba et al., 2016; X. Zhou et al., 2022).

Functional near-infrared spectroscopy (fNIRS) is emerging as a particularly promising technique for this purpose. As a safe, portable, and cost-effective neuroimaging tool, fNIRS is ideally suited for repeated, longitudinal use in both clinical and home environments. Unlike fMRI or PET, fNIRS operates quietly and does not interfere with CI hardware, making it feasible for tracking real-time changes in cortical activation in response to auditory or cross-modal stimuli (Bálint et al., 2025; Farrar et al., 2024; Saliba et al., 2016).

Recent studies have demonstrated that fNIRS can detect beneficial and maladaptive cross-modal reorganization patterns and their relationship to speech perception outcomes (C. A. Anderson et al., 2017; L. C. Chen et al., 2016; Mushtaq et al., 2020; X. Zhou et al., 2022). For example, auditory-evoked activation in the visual cortex has been associated with improved speech perception, while excessive visual-evoked activity in auditory regions may be detrimental (L. C. Chen et al., 2016; Mushtaq et al., 2020). These insights are critical for identifying neuroplastic changes that can guide personalized rehabilitation. As protocols become more standardized and the association between cortical activity and behavioral outcomes is clarified, fNIRS could become an essential tool for optimizing CI outcomes.

Regarding tES, fNIRS may play a pivotal role in providing feedback on whether stimulation is promoting adaptive plasticity. fNIRS could be used to tailor stimulation parameters and cortical targets to individual neural profiles. Combining imaging modalities such as fNIRS with behavioral metrics (hearing thresholds, speech perception tests, hearing and quality of life questionnaires) enables a more comprehensive, data-driven approach to managing hearing outcomes.

6.4. *Practical implementation of tES in rehabilitation*

6.4.1. *Duration and timing*

It is encouraging that favorable results of tES in patients with hearing loss have been reported following relatively short treatment periods (Table 4). Longer protocols may be required however, in patients with more severe and/or prolonged hearing impairment which are typical for patients with cochlear implants. As for the timing of rehabilitation with tES, it would probably work best if started soon after activation of the new implant and acquisition of stable initial maps. Late tES rehabilitation of CI users who have reached a low performance plateau may be more challenging, but further work will be needed to identify which patient characteristics predict optimal responsiveness to NIBS-assisted rehabilitation.

If temporary online effects are found to improve hearing and speech perception in patients with CIs, in the future a minimally invasive device (e.g. epicranial array) that delivers continuous and synchronized tES may offer an alternative adjunct for concomitant use with a CI.

6.4.2. *What are the preferred settings?*

We believe that because multiple tES sessions over a long period of time may be required while acclimating to a new CI, most of the sessions should take place at home under tele-health guidance after initial instruction sessions at the office. tES is amenable to safe administration at home by the patient or under remote supervision, which is relevant to increasing economic and public health barriers to in-person therapy (Charvet et al., 2015; Shaw et al., 2017). These features of tES have been markedly advantageous during isolation and social distancing measures during the COVID-19 pandemic (Bikson et al., 2020). Remote supervision has proven safe for post-stroke motor rehabilitation tDCS (Van De Winckel et al., 2018). The increasing availability of online auditory therapy platforms provides ideal contexts for combined tES-aided training at home.

6.4.3. *Current limitations and future directions for clinical translation*

Although NIBS offers a promising avenue for enhancing auditory rehabilitation, there remains a significant gap between our understanding of therapeutically relevant cortical neuroplasticity and evidence-based clinical applications. To date, most studies investigating the effect of NIBS on hearing have been conducted in healthy populations and no validated or standardized protocols exist for patients with hearing loss or for integration with cochlear implant use. Consequently, all strategies discussed in this review are conceptual and extrapolated from findings in other rehabilitation contexts and from the few articles that included patients with hearing loss.

Establishing safe, effective and reproducible protocols will require systematic clinical trials assessing both efficacy and safety within this specific population. Until such data are available, it is not yet possible to provide concrete stimulation protocols or cost-effectiveness analyses. Nonetheless, these gaps represent important opportunities for translational research.

6.5. *Safety with cochlear implants and hearing aids*

6.5.1. *tES*

Preliminary safety testing conducted as part of the original FDA approval by one of the CI manufacturers (MED-EL Corporation) showed that the implant can tolerate external voltages of at least 20 V (Zimmerling, 2020). While the maximum voltage applied across the electrodes in subthreshold tES paradigms can exceed this value (Hahn et al., 2013), the voltage reaching the implant is substantially reduced. Since the maximum electric field in the head is less than 0.1 V/cm

(Alekseichuk et al., 2019) and the distance between the implanted CI components (from the receiver/simulator under the scalp to the electrode array in the cochlea) is approximately 10 cm, the maximum voltage across the CI does not exceed 1 V. Also, there are reports of patients with CIs who have developed Parkinson's disease and required deep brain stimulation with an implantable device. The two devices can work in the same patient without interruptions (Buell et al., 2015; Eddelman et al., 2017; Jansen et al., 2019). Additionally, there is no evidence to indicate that the use of ECT (Electroconvulsive Therapy) in CI users is contraindicated (Albertsen and Lauridsen, 2022). In ECT, much higher electrical currents are used compared to other forms of tES (Fridgeirsson et al., 2021; Thirthalli et al., 2023). Currently, there is no evidence suggesting that tES techniques are inherently unsafe for individuals using hearing aids.

6.5.2. *TMS*

Currently, TMS is not recommended for individuals with CIs. The primary concerns include the potential for the TMS-induced magnetic field to interact with the implanted magnet and receiver antenna as well as with the external CI device. Risks include magnetic forces affecting positioning of the implant; demagnetization of the implanted magnet; induction of high voltages and currents in the internal receiver, which could lead to unsafe electrical output from the cochlear electrodes; and possible damage to the implant electronics (Rossi et al., 2009, 2021). The lack of systematic safety data and basic physics considerations suggest that TMS could be harmful to CI users. With the introduction of newer MRI compatible CIs, it has been argued that a CI should not be an absolute contraindication for TMS treatment (Mandalà et al., 2021; Reveles Jensen et al., 2020), although a systematic assessment of all relevant interactions between the TMS field and the CI is still lacking. Thus, presently, a CI is generally considered a contraindication for TMS. Regarding patients using hearing aids, TMS has been shown to have beneficial effects on auditory rehabilitation (Neri et al., 2024) . It is currently recommended that the devices should be removed during TMS for hearing protection given the generation of noise during treatment. Additionally, the durability of hearing aids may be dependent on the manufacturer (Tendler et al., 2023; Tringali et al., 2012).

6.5.3. *tFUS*

We are not aware of reports assessing the safety of tFUS in the presence of CIs or hearing aids. Because CIs operate using magnetic and electric fields, whereas ultrasound stimulation is mediated by acoustic (mechanical) energy, interaction between the two technologies are expected to be limited. Nonetheless, it appears reasonable to avoid placing ultrasound transducers on top of the subcutaneous receiving antenna and magnet of the CI, since the implant may distort the acoustic field and may be affected by the ultrasound energy. Further, it seems advisable to keep the ultrasound energy away from the cochlear electrode array to minimize mechanical interactions.

7. Conclusion

This review highlights fundamental evidence of hearing loss as a disorder of distributed neural networks rather than a purely peripheral deficit. It is associated with complex patterns of adaptive and maladaptive neuroplasticity spanning auditory, multisensory, and cognitive systems. NIBS offers a promising adjunctive strategy for hearing interventions by directly modulating these central processes, with emerging evidence suggesting that techniques such as tDCS, tACS, and rTMS can enhance speech perception and auditory cognitive outcomes, particularly when paired with structured auditory rehabilitation rather than delivered in isolation. Although early findings support the plausibility of NIBS in hearing-impaired populations, the existing evidence base remains limited by small samples, heterogeneity of protocols, and short follow-up durations, precluding definitive clinical recommendations. Future progress will depend on well-designed, adequately powered trials that integrate standardized auditory outcomes with neurophysiological and imaging biomarkers to identify optimal stimulation targets, timing, and patient subgroups. Ultimately, leveraging NIBS to bias cortical plasticity toward more efficient and adaptive listening networks may help reduce variability in hearing rehabilitation outcomes and address persistent difficulties with speech perception in noise.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used ChatGPT in order to improve language and readability of some sections of the original manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Joshua M. Wright: Writing – review & editing, Writing – original draft, Conceptualization. **Lawrence Gregory Appelbaum:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Sherri L. Smith:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Tobias Overath:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Samantha Kaplan:** Data curation, Formal analysis, Investigation, Methodology. **Matthew Cooper:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Ofri Ronen:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Tamar Tobi:** Writing – review & editing, Writing – original draft, Conceptualization. **Angel V. Peterchev:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Howard W. Francis:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization.

Declaration of competing interest

None

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.heares.2026.109576.

References

Adank, P., Nuttall, H.E., Kennedy-Higgins, D., 2017. Transcranial magnetic stimulation and motor evoked potentials in speech perception research. Lang. Cogn. Neurosci. 32 (7), 900–909. https://doi.org/10.1080/23273798.2016.1257816.

Adjamian, P., Sereda, M., Hall, D.A., 2009. The mechanisms of tinnitus: perspectives from human functional neuroimaging. Hear. Res. 253. https://doi.org/10.1016/j.heares.2009.04.001. Issues 1–2.

Albertsen, L.N., Lauridsen, J.K., 2022. A review electroconvulsive therapy in Cochlear implant patients. In: Journal of ECT, 38. Lippincott Williams and Wilkins, pp. 10–12. https://doi.org/10.1097/YCT.0000000000000803.

Alekseichuk, I., Mantell, K., Shirinpour, S., Opitz, A., 2019. Comparative modeling of transcranial magnetic and electric stimulation in mouse, monkey, and human. Neuroimage 194. https://doi.org/10.1016/j.neuroimage.2019.03.044.

Alfandari, D., Vriend, C., Heslenfeld, D.J., Versfeld, N.J., Kramer, S.E., Zekveld, A.A., 2018. Brain volume differences associated with hearing impairment in adults. Trends. Hear. 22, 233121651876368. https://doi.org/10.1177/2331216518763689.

Allman, B.L., Keniston, L.P., Meredith, M.A., 2009. Adult deafness induces somatosensory conversion of ferret auditory cortex. Proc. Natl. Acad. Sci. USA 106 (14), 5925–5930. https://doi.org/10.1073/pnas.0809483106.

Anderson, C.A., Wiggins, I.M., Kitterick, P.T., Hartley, D.E.H., 2017. Adaptive benefit of cross-modal plasticity following cochlear implantation in deaf adults. Proc. Natl. Acad. Sci. USA 114 (38), 10256–10261. https://doi.org/10.1073/pnas.1704785114.

Anderson, S., Jenkins, K., 2015. Electrophysiologic assessment of auditory training benefits in older adults. Semin. Hear. 36 (4), 250–262. https://doi.org/10.1055/s-0035-1564455.

Anderson, S., White-Schwoch, T., Parbery-Clark, A., Kraus, N., 2013. Reversal of age-related neural timing delays with training. Proc. Natl. Acad. Sci. USA 110 (11), 4357–4362. https://doi.org/10.1073/pnas.1213555110.

Antal, A., Alekseichuk, I., Bikson, M., Brockmöller, J., Brunoni, A.R., Chen, R., Cohen, L. G., Dowthwaite, G., Ellrich, J., Flöel, A., Fregni, F., George, M.S., Hamilton, R., Haueisen, J., Herrmann, C.S., Hummel, F.C., Lefaucheur, J.P., Liebetanz, D., Loo, C. K., Paulus, W., 2017. Low intensity transcranial electric stimulation: safety, ethical, legal regulatory and application guidelines. In: Clin. Neurophysiol., 128. Elsevier Ireland Ltd, pp. 1774–1809. https://doi.org/10.1016/j.clinph.2017.06.001.

Antal, A., Paulus, W., 2013. Transcranial alternating current stimulation (tACS). Front. Hum. Neurosci. 7 (JUN). https://doi.org/10.3389/fnhum.2013.00317.

Arksey, H., O'Malley, L., 2005. Scoping studies: towards a methodological framework. Int. J. Soc. Res. Methodol. 8 (1). https://doi.org/10.1080/1364557032000119616.

Asal, S.I., Sobhy, O.A., Morsy, H.M., 2018. Effect of auditory temporal processing training on behavioral and electrophysiological functions in central presbycusis. Egypt. J. Otolaryngol. 34 (1), 68–75. https://doi.org/10.4103/ejo.ejo_78_17.

Ashcroft, J., Patel, R., Woods, A.J., Darzi, A., Singh, H., Leff, D.R., 2020. Prefrontal transcranial direct-current stimulation improves early technical skills in surgery. Brain Stimul. 13 (6). https://doi.org/10.1016/j.brs.2020.10.013.

Atkinson-Clement, C., Kaiser, M., 2024. Optimizing transcranial focused ultrasound stimulation: an open-source tool for precise targeting. Neuromodulation. https://doi.org/10.1016/j.neurom.2024.06.496.

Bálint, A., Wimmer, W., Caversaccio, M., Rummel, C., Weder, S., 2025. Brain activation patterns in normal hearing adults: an fNIRS study using an adapted clinical speech comprehension task. Hear. Res. 455. https://doi.org/10.1016/j.heares.2024.109155.

Barker, A.T., Jalinous, R., Freeston, I.L., 1985. Non-invasive magnetic stimulation of HUMAN motor cortex. Lancet 325 (8437). https://doi.org/10.1016/S0140-6736(85)92413-4.

Barwood, C.H.S., Wilson, W.J., Malicka, A.N., McPherson, B., Lloyd, D., Munt, K., Murdoch, B.E., 2013. The effect of rTMS on auditory processing in adults with chronic, bilateral tinnitus: a placebo-controlled pilot study. Brain Stimul. 6 (5). https://doi.org/10.1016/j.brs.2013.01.015.

Bavelier, D., Neville, H.J., 2002. Cross-modal plasticity: where and how? Nature Rev. Neurosci. 3 (6). https://doi.org/10.1038/nrn848.

Bengoetxea, H., Ortuzar, N., Bulnes, S., Rico-Barrio, I., Lafuente, J.V., Argandoña, E.G., 2012. Enriched and deprived sensory experience induces structural changes and rewires connectivity during the postnatal development of the brain. In: Neural Plasticity, 2012. Hindawi Publishing Corporation. https://doi.org/10.1155/2012/305693.

Benster, L.L., Weissman, C.R., Stolz, L.A., Daskalakis, Z.J., Appelbaum, L.G., 2023. Pre-clinical indications of brain stimulation treatments for non-affective psychiatric disorders, a status update. Transl. Psychiatry 13 (1). https://doi.org/10.1038/s41398-023-02673-2.

Bergeson, T.R., Pisoni, D.B., Davis, R.A.O., 2005. Development of audiovisual comprehension skills in prelingually deaf children with cochlear implants. Ear Hear. 26 (2), 149–164. https://doi.org/10.1097/00003446-200504000-00004.

Bertrand, J.A., Lassonde, M., Robert, M., Nguyen, D.K., Bertone, A., Doucet, M.È., Bouthillier, A., Lepore, F., 2012. An intracranial event-related potential study on transformational apparent motion. Does its neural processing differ from real motion? Exp. Brain Res. 216 (1), 145–153. https://doi.org/10.1007/s00221-011-2920-8.

Beynel, L., Davis, S.W., Crowell, C.A., Dannhauer, M., Lim, W., Palmer, H., Hilbig, S.A., Brito, A., Hile, C., Luber, B., Lisanby, S.H., Peterchev, A.V., Cabeza, R., Appelbaum, L.G., 2020. Site-specific effects of online rtms during a working memory task in healthy older adults. Brain Sci. 10 (5). https://doi.org/10.3390/brainsci10050255.

Bhattacharya, A., Mrudula, K., Sreepada, S.S., Sathyaprabha, T.N., Pal, P.K., Chen, R., Udupa, K., 2022. An overview of noninvasive brain stimulation: basic principles and clinical applications. Can. J. Neurol. Sci. 49 (4). https://doi.org/10.1017/cjn.2021.158.

Bikson, M., Esmaeilpour, Z., Adair, D., Kronberg, G., Tyler, W.J., Antal, A., Datta, A., Sabel, B.A., Nitsche, M.A., Loo, C., Edwards, D., Ekhtiari, H., Knotkova, H., Woods, A.J., Hampstead, B.M., Badran, B.W., Peterchev, A.V., 2019. Transcranial electrical stimulation nomenclature. Brain Stimulation 12 (6), 1349–1366. https://doi.org/10.1016/j.brs.2019.07.010.

Bikson, M., Hanlon, C.A., Woods, A.J., Gillick, B.T., Charvet, L., Lamm, C., Madeo, G., Holczer, A., Almeida, J., Antal, A., Ay, M.R., Baeken, C., Blumberger, D.M., Campanella, S., Camprodon, J.A., Christiansen, L., Loo, C., Crinion, J.T., Fitzgerald, P., Ekhtiari, H., 2020. Guidelines for TMS/tES clinical services and research through the COVID-19 pandemic. Brain Stimul. 13 (4), 1124–1149. https://doi.org/10.1016/j.brs.2020.05.010.

Boisvert, I., Reis, M., Au, A., Cowan, R., Dowell, R.C., 2020. Cochlear implantation outcomes in adults: a scoping review. In S. Usami (Ed.). PLoS. One 15 (5), e0232421. https://doi.org/10.1371/journal.pone.0232421.

Boucher, P.O., Ozdemir, R.A., Momi, D., Burke, M.J., Jannati, A., Fried, P.J., Pascual-Leone, A., Shafi, M.M., Santarnecchi, E., 2021. Sham-derived effects and the minimal reliability of theta burst stimulation. Sci. Rep. 11 (1), 21170. https://doi.org/10.1038/s41598-021-98751-w.

Boyen, K., Langers, D.R.M., de Kleine, E., van Dijk, P., 2013. Gray matter in the brain: differences associated with tinnitus and hearing loss. Hear. Res. 295, 67–78. https://doi.org/10.1016/j.heares.2012.02.010.

Buch, E.R., Santarnecchi, E., Antal, A., Born, J., Celnik, P.A., Classen, J., Gerloff, C., Hallett, M., Hummel, F.C., Nitsche, M.A., Pascual-Leone, A., Paulus, W.J., Reis, J., Robertson, E.M., Rothwell, J.C., Sandrini, M., Schambra, H.M., Wassermann, E.M., Ziemann, U., Cohen, L.G., 2017. Effects of tDCS on motor learning and memory formation: a consensus and critical position paper. Clin. Neurophysiol. 128 (4). https://doi.org/10.1016/j.clinph.2017.01.004.

Buell, T.J., Ksendzovsky, A., Shah, B.B., Kesser, B.W., Elias, W.J., 2015. Deep brain stimulation in the setting of Cochlear implants: case report and literature review. In: Stereotactic and Functional Neurosurgery, 93. S. Karger AG, pp. 245–249. https://doi.org/10.1159/000380824.

Calderone, A., Cardile, D., Gangemi, A., De Luca, R., Quartarone, A., Corallo, F., Calabrò, R.S., 2024. Traumatic Brain injury and neuromodulation techniques in rehabilitation: a scoping review. Biomedicines. 12 (2). https://doi.org/10.3390/biomedicines12020438.

Campbell, J., Sharma, A., 2014. Cross-modal re-organization in adults with early stage hearing loss. PLoS. One 9 (2), e90594. https://doi.org/10.1371/journal.pone.0090594.

Campbell, J., Sharma, A., 2016. Visual cross-modal re-organization in children with cochlear implants. PLoS. One 11 (1), e0147793. https://doi.org/10.1371/journal.pone.0147793.

Cardin, V., 2016. Effects of aging and adult-onset hearing loss on cortical auditory regions. Front. Neurosci. 10. https://doi.org/10.3389/fnins.2016.00199. Issue MAY.

Chagas, A.P., Monteiro, M., Mazer, V., Baltar, A., Marques, D., Carneiro, M., Rodrigues de Araújo, M.das G., Piscitelli, D., Monte-Silva, K., 2018. Cortical excitability variability: insights into biological and behavioral characteristics of healthy individuals. J. Neurol. Sci. 390, 172–177. https://doi.org/10.1016/j.jns.2018.04.036.

Chandrasekaran, B., Skoe, E., Kraus, N., 2014. An integrative model of subcortical auditory plasticity. Brain Topogr. 27 (4). https://doi.org/10.1007/s10548-013-0323-9.

Charvet, L.E., Kasschau, M., Datta, A., Knotkova, H., Stevens, M.C., Alonzo, A., Loo, C., Krull, K.R., Bikson, M., 2015. Remotely-supervised transcranial direct current stimulation (tDCS) for clinical trials: guidelines for technology and protocols. Front. Syst. Neurosci. 9 (MAR). https://doi.org/10.3389/fnsys.2015.00026.

Chen, L.C., Sandmann, P., Thorne, J.D., Bleichner, M.G., Debener, S., 2016. Cross-modal functional reorganization of visual and auditory cortex in adult cochlear implant users identified with fNIRS. Neural Plast. 2016. https://doi.org/10.1155/2016/4382656.

Chen, R., Classen, J., Gerloff, C., Celnik, P., Wassermann, E.M., Hallett, M., Cohen, L.G., 1997. Depression of motor cortex excitability by low-frequency transcranial magnetic stimulation. Neurology. 48 (5). https://doi.org/10.1212/WNL.48.5.1398.

Chhatbar, P.Y., Chen, R., Deardorff, R., Dellenbach, B., Kautz, S.A., George, M.S., Feng, W., 2017. Safety and tolerability of transcranial direct current stimulation to stroke patients – A phase I current escalation study. Brain Stimul. 10 (3). https://doi.org/10.1016/j.brs.2017.02.007.

Chu, N.S., 1985. Computed tomographic correlates of auditory brainstem responses in alcoholics. J. Neurol. Neurosurg. Psychiatry 48 (4). https://doi.org/10.1136/jnnp.48.4.348.

Clark, J.H., Yeagle, J., Arbaje, A.I., Lin, F.R., Niparko, J.K., Francis, H.W., 2012. Cochlear implant rehabilitation in older adults: literature review and proposal of a conceptual framework. J. Am. Geriatr. Soc. 60 (10). https://doi.org/10.1111/j.1532-5415.2012.04150.x.

Cox, M.L., Deng, Z.De, Palmer, H., Watts, A., Beynel, L., Young, J.R., Lisanby, S.H., Migaly, J., Appelbaum, L.G, 2020. Utilizing transcranial direct current stimulation to enhance laparoscopic technical skills training: a randomized controlled trial. Brain Stimul. 13 (3), 863–872. https://doi.org/10.1016/j.brs.2020.03.009.

Davis, M.H., Johnsrude, I.S., 2007. Hearing speech sounds: top-down influences on the interface between audition and speech perception. Hear. Res. 229 (1–2), 132–147. https://doi.org/10.1016/j.heares.2007.01.014.

Dayan, E., Censor, N., Buch, E.R., Sandrini, M., Cohen, L.G., 2013. Noninvasive brain stimulation: from physiology to network dynamics and back. Nat. Neurosci. 16 (7). https://doi.org/10.1038/nn.3422.

De Ridder, D., Adhia, D., Langguth, B., 2021. Tinnitus and brain stimulation. Current Topics in Behavioral Neurosciences. Curr Top Behav Neurosci. https://doi.org/10.1007/7854_2021_219.

Deng, Z.De, Lisanby, S.H., Peterchev, A.V, 2013a. Controlling stimulation strength and focality in electroconvulsive therapy via current amplitude and electrode size and spacing: comparison with magnetic seizure therapy. J. ECT 29 (4). https://doi.org/10.1097/YCT.0b013e3182a4b4a7.

Deng, Z.De, Lisanby, S.H., Peterchev, A.V, 2013b. Electric field depth-focality tradeoff in transcranial magnetic stimulation: simulation comparison of 50 coil designs. Brain Stimul. 6 (1). https://doi.org/10.1016/j.brs.2012.02.005.

Department of Heath and Human Services, & Food and Drug Administration. (2019). *Neurological Devices; Reclassification of Cranial Electrotherapy Stimulator Devices Intended To Treat Anxiety and/or Insomnia; Effective Date of Requirement for Premarket Approval for Cranial Electrotherapy Stimulator Devices Intended To Treat Depression* (pp. 70003–70013).

Dewey, R.S., Hartley, D.E.H., 2015. Cortical cross-modal plasticity following deafness measured using functional near-infrared spectroscopy. Hear. Res. 325, 55–63. https://doi.org/10.1016/j.heares.2015.03.007.

Dmochowski, J.P., Datta, A., Bikson, M., Su, Y., Parra, L.C., 2011. Optimized multi-electrode stimulation increases focality and intensity at target. J. Neural Eng. 8 (4). https://doi.org/10.1088/1741-2560/8/4/046011.

Dornhoffer, J.R., Lohse, C.M., Tamati, T.N., Moberly, A.C., Carlson, M.L., 2024. Current practices and opinions on auditory training in adult cochlear implant recipients. Am. J. Otolaryngol. 45 (4). https://doi.org/10.1016/j.amjoto.2024.104339.

Doucet, M.E., Bergeron, F., Lassonde, M., Ferron, P., Lepore, F., 2006. Cross-modal reorganization and speech perception in cochlear implant users. Brain 129 (12). https://doi.org/10.1093/brain/awl264.

Draganski, B., May, A., 2008. Training-induced structural changes in the adult human brain. Behav. Brain Res. 192 (1). https://doi.org/10.1016/j.bbr.2008.02.015.

Dubin, M.J., Ilieva, I.P., Deng, Z.De, Thomas, J., Cochran, A., Kravets, K., Brody, B.D., Christos, P.J., Kocsis, J.H., Liston, C., Gunning, F.M, 2019. A double-blind pilot dosing study of low field magnetic stimulation (LFMS) for treatment-resistant depression (TRD). J. Affect. Disord. 249. https://doi.org/10.1016/j.jad.2019.02.039.

Eckert, M.A., Cute, S.L., Vaden, K.I., Kuchinsky, S.E., Dubno, J.R., 2012. Auditory cortex signs of age-related hearing loss. JARO 13 (5), 703–713. https://doi.org/10.1007/s10162-012-0332-5.

Eckert, M.A., Vaden, K.I., Dubno, J.R., 2019. Age-related hearing loss associations with changes in brain morphology. Trends. Hear. 23. https://doi.org/10.1177/2331216519857267, 233121651985726.

Eddelman, D., Wewel, J., Wiet, R.M., Metman, L.V., Sani, S., 2017. Deep brain stimulation with a pre-existing cochlear implant: surgical technique and outcome. Surg. Neurol. Int. 8 (1), 47. https://doi.org/10.4103/sni.sni_412_16.

Erkens, J., Schulte, M., Vormann, M., Herrmann, C.S., 2020. Lacking effects of envelope transcranial alternating current stimulation indicate the need to revise envelope transcranial alternating current stimulation methods. Neurosci. Insights. 15. https://doi.org/10.1177/2633105520936623.

Erkens, J., Schulte, M., Vormann, M., Wilsch, A., Herrmann, C.S., 2021. Hearing impaired participants improve more under envelope-transcranial alternating current stimulation when signal to noise ratio is high. Neurosci. Insights. 16. https://doi.org/10.1177/2633105520988854.

Fan, W., Zhang, W., Li, J., Zhao, X., Mella, G., Lei, P., Liu, Y., Wang, H., Cheng, H., Shi, H., Xu, H., 2015. Altered contralateral auditory cortical morphology in unilateral sudden sensorineural hearing loss. Otol. Neurotol. 36 (10), 1622–1627. https://doi.org/10.1097/MAO.0000000000000892.

Farrar, R., Ashjaei, S., Arjmandi, M.K., 2024. Speech-evoked cortical activities and speech recognition in adult cochlear implant listeners: a review of functional near-infrared spectroscopy studies. Experimental Brain Research. Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/s00221-024-06921-9.

Francis, H.W., Yeagle, J.A., Thompson, C.B., 2015. Clinical and psychosocial risk factors of hearing outcome in older adults with cochlear implants. Laryngoscope 125 (3). https://doi.org/10.1002/lary.24921.

Fridgeirsson, E.A., Deng, Z.De, Denys, D., van Waarde, J.A., van Wingen, G.A, 2021. Electric field strength induced by electroconvulsive therapy is associated with clinical outcome. NeuroImage 30. https://doi.org/10.1016/j.nicl.2021.102581.

Fröhlich, F., Sellers, K.K., Cordle, A.L., 2014. Targeting the neurophysiology of cognitive systems with transcranial alternating current stimulation. Expert. Rev. NeurOther 15 (2). https://doi.org/10.1586/14737175.2015.992782.

Galea, J.M., Jayaram, G., Ajagbe, L., Celnik, P., 2009. Modulation of cerebellar excitability by polarity-specific noninvasive direct current stimulation. J. Neurosci. 29 (28). https://doi.org/10.1523/JNEUROSCI.2184-09.2009.

Geddes, L.A., 1991. History of magnetic stimulation of the nervous system. J. Clin. Neurophysiol. 8 (1). https://doi.org/10.1097/00004691-199101000-00003.

Gilley, P.M., Sharma, A., Dorman, M.F., 2008. Cortical reorganization in children with cochlear implants. Brain Res. 1239, 56–65. https://doi.org/10.1016/j.brainres.2008.08.026.

Giraud, A.L., Poeppel, D., 2012. Cortical oscillations and speech processing: emerging computational principles and operations. In: Nature Neuroscience, 15. Nat Neurosci, pp. 511–517. https://doi.org/10.1038/nn.3063.

Giraud, A.L., Price, C.J., Graham, J.M., Truy, E., Frackowiak, R.S.J, 2001. Cross-modal plasticity underpins language recovery after cochlear implantation. Neuron (3), 30. https://doi.org/10.1016/S0896-6273(01)00318-X.

Giustolisi, B., Vergallito, A., Cecchetto, C., Varoli, E., Romero Lauro, L.J., 2018. Anodal transcranial direct current stimulation over left inferior frontal gyrus enhances sentence comprehension. Brain Lang. 176, 36–41. https://doi.org/10.1016/j.bandl.2017.11.001.

Glennon, E., Svirsky, M.A., Froemke, R.C., 2020. Auditory cortical plasticity in cochlear implant users. Curr. Opin. Neurobiol. 60, 108–114. https://doi.org/10.1016/j.conb.2019.11.003.

Glick, H., Sharma, A., 2017. Cross-modal plasticity in developmental and age-related hearing loss: clinical implications. Hear. Res. 343, 191–201. https://doi.org/10.1016/j.heares.2016.08.012.

Goudey, B., Plant, K., Kiral, I., Jimeno-Yepes, A., Swan, A., Gambhir, M., Büchner, A., Kludt, E., Eikelboom, R.H., Sucher, C., Gifford, R.H., Rottier, R., Anjomshoa, H., 2021. A MultiCenter analysis of factors associated with hearing outcome for 2,735 adults with cochlear implants. Trends. Hear. 25. https://doi.org/10.1177/23312165211037525.

Green, T., Faulkner, A., Rosen, S., 2019. Computer-based connected-text training of speech-in-noise perception for Cochlear implant users. Trends. Hear. 23. https://doi.org/10.1177/2331216519843878.

Gröschel, M., Götze, R., Ernst, A., Basta, D., 2010. Differential impact of temporary and permanent noise-induced hearing loss on neuronal cell density in the mouse central auditory pathway. J. Neurotrauma 27 (8), 1499–1507. https://doi.org/10.1089/neu.2009.1246.

Hahn, C., Rice, J., Macuff, S., Minhas, P., Rahman, A., Bikson, M., 2013. Methods for extra-low voltage transcranial direct current stimulation: current and time dependent impedance decreases. Clin. Neurophysiol. 124 (3). https://doi.org/10.1016/j.clinph.2012.07.028.

Han, J.H., Lee, H.J., Kang, H., Oh, S.H., Lee, D.S., 2019. Brain plasticity can predict the cochlear implant outcome in adult-onset deafness. Front. Hum. Neurosci. 13. https://doi.org/10.3389/fnhum.2019.00038.

HARMS, E., 1955. The origin and early history of electrotherapy and electroshock. Am. J. Psychiatry 111 (12).

Hartwigsen, G., 2015. The neurophysiology of language: insights from non-invasive brain stimulation in the healthy human brain. Brain Lang. 148. https://doi.org/10.1016/j.bandl.2014.10.007.

Hastings, S., Zhong, H., Feinstein, R., Zelczer, G., Mitrovich, C., Gad, P., Edgerton, V.R., 2022. A pilot study combining noninvasive spinal neuromodulation and activity-based neurorehabilitation therapy in children with cerebral palsy. Nat. Commun. 13 (1). https://doi.org/10.1038/s41467-022-33208-w.

Heimrath, K., Fiene, M., Rufener, K.S., Zaehle, T., 2016. Modulating human auditory processing by transcranial electrical stimulation. In: Frontiers in Cellular Neuroscience, 10. Frontiers Research Foundation. https://doi.org/10.3389/fncel.2016.00053.

Henry, M.J., Herrmann, B., Kunke, D., Obleser, J., 2017. Aging affects the balance of neural entrainment and top-down neural modulation in the listening brain. Nat. Commun. 8. https://doi.org/10.1038/ncomms15801.

Hensch, T.K., 2004. Critical period regulation. In: Annual Review of Neuroscience, 27. Annu Rev Neurosci, pp. 549–579. https://doi.org/10.1146/annurev.neuro.27.070203.144327.

Hickok, G., Poeppel, D., 2004. Dorsal and ventral streams: a framework for understanding aspects of the functional anatomy of language. Cognition 92 (1–2). https://doi.org/10.1016/j.cognition.2003.10.011.

Hickok, G., Poeppel, D., 2007. The cortical organization of speech processing. Nature Rev. Neurosci. 8 (5). https://doi.org/10.1038/nrn2113.

Hinder, M.R., Goss, E.L., Fujiyama, H., Canty, A.J., Garry, M.I., Rodger, J., Summers, J.J., 2014. Inter- and intra-individual variability following intermittent theta burst stimulation: implications for rehabilitation and recovery. Brain Stimul. 7 (3), 365–371. https://doi.org/10.1016/j.brs.2014.01.004.

Huang, C., Li, J., Tan, G., Liu, L., 2025. Clinical characteristics and correlation of hearing outcomes following varying courses of repetitive transcranial magnetic stimulation for idiopathic sudden sensorineural hearing loss: a prospective Clinical study. J. Clin. Med. 14 (20). https://doi.org/10.3390/jcm14207369.

Huang, W.A., Stitt, I.M., Negahbani, E., Passey, D.J., Ahn, S., Davey, M., Dannhauer, M., Doan, T.T., Hoover, A.C., Peterchev, A.V., Radtke-Schuller, S., Fröhlich, F., 2021. Transcranial alternating current stimulation entrains alpha oscillations by preferential phase synchronization of fast-spiking cortical neurons to stimulation waveform. Nat. Commun. 12 (1). https://doi.org/10.1038/s41467-021-23021-2.

Hyo, J.L., Kang, E., Oh, S.H., Kang, H., Dong, S.L., Myung, C.L., Kim, C.S., 2005. Preoperative differences of cerebral metabolism relate to the outcome of cochlear implants in congenitally deaf children. Hear. Res. 203 (1–2), 2–9. https://doi.org/10.1016/j.heares.2004.11.005.

Irvine, D.R.F., 2018. Plasticity in the auditory system. In: Hearing Research, 362. Elsevier B.V, pp. 61–73. https://doi.org/10.1016/j.heares.2017.10.011.

Ito, J., Iwasaki, Y., Sakakibara, J., Yonekura, Y., 1993. Positron emission tomography of auditory sensation in deaf patients and patients with cochlear implants. Ann. Otol. Rhinol. Laryngol. 102 (10). https://doi.org/10.1177/000348949310201011.

Jae, S.L., Dong, S.L., Seung, H.O., Chong, S.K., Kim, J.W., Chan, H.H., Koo, J., Kang, E., Chung, J.K., Myung, C.L., 2003. PET evidence of neuroplasticity in adult auditory cortex of postlingual deafness. J. Nucl. Med. 44 (9), 1435–1439. https://pubmed.ncbi.nlm.nih.gov/12960189/.

Jansen, N., Glaas, M., Volpert, S., Slotty, P., Vesper, J., Klenzner, T., 2019. Cochlear implantation with deep brain or occipital nerve stimulation: case studies for parallel application. HNO 67 (10), 786–790. https://doi.org/10.1007/s00106-019-00731-0.

Jerger, J., Hall, J., 1980. Effects of age and sex on auditory brainstem response. Arch. Otolaryngol. 106 (7). https://doi.org/10.1001/archotol.1980.00790310011003.

Kadir, S., Kaza, C., Weissbart, H., Reichenbach, T., 2020. Modulation of speech-in-noise comprehension through transcranial current stimulation with the phase-shifted speech envelope. IEEE Trans. Neural Syst. Rehabil. Eng. 28 (1), 23–31. https://doi.org/10.1109/TNSRE.2019.2939671.

Kan, R.L.D., Zhang, B.B.B., Zhang, J.J.Q., Kranz, G.S., 2020. Non-invasive brain stimulation for posttraumatic stress disorder: a systematic review and meta-analysis. Transl. Psychiatry 10 (1). https://doi.org/10.1038/s41398-020-0851-5.

Kang, E., Lee, D.S., Kang, H., Lee, J.S., Oh, S.H., Lee, M.C., Kim, C.S., 2004. Neural changes associated with speech learning in deaf children following cochlear implantation. Neuroimage 22 (3). https://doi.org/10.1016/j.neuroimage.2004.02.036.

Keshavarzi, M., Kegler, M., Kadir, S., Reichenbach, T., 2020. Transcranial alternating current stimulation in the theta band but not in the delta band modulates the comprehension of naturalistic speech in noise. Neuroimage 210. https://doi.org/10.1016/j.neuroimage.2020.116557.

Koponen, L.M., Peterchev, A.V., 2020. Transcranial Magnetic stimulation: principles and applications. Neural Engineering. Springer International Publishing, pp. 245–270. https://doi.org/10.1007/978-3-030-43395-6_7.

Kral, A., Eggermont, J.J., 2007. What's to lose and what's to learn: development under auditory deprivation, cochlear implants and limits of cortical plasticity. Brain Res. Rev. 56 (1), 259–269. https://doi.org/10.1016/j.brainresrev.2007.07.021.

Kral, A., Kronenberger, W.G., Pisoni, D.B., O'Donoghue, G.M, 2016. Neurocognitive factors in sensory restoration of early deafness: a connectome model. Lancet Neurol. 15 (6), 610–621. https://doi.org/10.1016/S1474-4422(16)00034-X.

Kral, A., Sharma, A., 2012. Developmental neuroplasticity after cochlear implantation. Trends. Neurosci. 35 (2), 111–122. https://doi.org/10.1016/j.tins.2011.09.004.

Kral, A., Sharma, A., 2023. Crossmodal plasticity in hearing loss. In: Trends in Neurosciences, 46. Elsevier Ltd, pp. 377–393. https://doi.org/10.1016/j.tins.2023.02.004.

Kraus, N., McGee, T., Carrell, T., Sharma, A., Micco, A., Nicol, T., 1993. Speech-evoked cortical potentials in children. J. Am. Acad. Audiol. 4 (4).

Kuchinsky, S.E., Vaden, K.I., Keren, N.I., Harris, K.C., Ahlstrom, J.B., Dubno, J.R., Eckert, M.A., 2012. Word intelligibility and age predict visual cortex activity during word listening. Cereb. Cortex 22 (6), 1360–1371. https://doi.org/10.1093/cercor/bhr211.

Kujawa, S.G., Liberman, M.C., 2015. Synaptopathy in the noise-exposed and aging cochlea: primary neural degeneration in acquired sensorineural hearing loss. Hear. Res. 330, 191–199. https://doi.org/10.1016/j.heares.2015.02.009.

Labruna, L., Merrick, C., Peterchev, A.V., Inglis, B., Ivry, R.B., Sheltraw, D., 2024. Kilohertz transcranial magnetic perturbation (kTMP): a new non-invasive method to modulate cortical excitability. bioRxiv.

Lalor, E.C., Foxe, J.J., 2010. Neural responses to uninterrupted natural speech can be extracted with precise temporal resolution. Eur. J. Neurosci. 31 (1), 189–193. https://doi.org/10.1111/j.1460-9568.2009.07055.x.

Land, R., Baumhoff, P., Tillein, J., Lomber, S.G., Hubka, P., Kral, A., 2016. Cross-modal plasticity in higher-order auditory cortex of congenitally deaf cats does not limit auditory responsiveness to cochlear implants. J. Neurosci. 36 (23), 6175–6185. https://doi.org/10.1523/JNEUROSCI.0046-16.2016.

Langers, D.R.M., Melcher, J.R., 2011. Hearing without listening: functional connectivity reveals the engagement of multiple nonauditory networks during basic sound processing. Brain Connect. 1 (3), 233–244. https://doi.org/10.1089/brain.2011.0023.

Langguth, B., 2020. Non-invasive neuromodulation for tinnitus. In: Journal of Audiology and Otology, 24. Korean Audiological Society and Korean Otological Society, pp. 113–118. https://doi.org/10.7874/JAO.2020.00052.

Lee, H.J., Truy, E., Mamou, G., Sappey-Marinier, D., Giraud, A.L., 2007. Visual speech circuits in profound acquired deafness: a possible role for latent multimodal connectivity. Brain 130 (11), 2929–2941. https://doi.org/10.1093/brain/awm230.

Lee, K., Park, T.Y., Lee, W., Kim, H., 2024. A review of functional neuromodulation in humans using low-intensity transcranial focused ultrasound. Biomed. Eng. Lett. 14 (3). https://doi.org/10.1007/s13534-024-00369-0.

Lee, Y.J., Heo, H., Joo, H.A., Choi, Y., Shim, W.H., Park, H.J., 2024. Cortical volumetric changes after cochlear implantation in postlingually deaf adults: correlation with speech perception abilities. Sci. Rep. 14 (1). https://doi.org/10.1038/s41598-024-68002-9.

Lefebvre-Demers, M., Doyon, N., Fecteau, S., 2021. Non-invasive neuromodulation for tinnitus: a meta-analysis and modeling studies. In: Brain Stimulation, 14. Elsevier Inc, pp. 113–128. https://doi.org/10.1016/j.brs.2020.11.014.

Legon, W., Bansal, P., Tyshynsky, R., Ai, L., Mueller, J.K., 2018. Transcranial focused ultrasound neuromodulation of the human primary motor cortex. Sci. Rep. 8 (1), 10007. https://doi.org/10.1038/s41598-018-28320-1.

Lesicko, A.M.H., Llano, D.A., 2017. Impact of peripheral hearing loss on top-down auditory processing. In: Hearing Research, 343. https://doi.org/10.1016/j.heares.2016.05.018.

Lin, F.R., Ferrucci, L., An, Y., Goh, J.O., Doshi, J., Metter, E.J., Davatzikos, C., Kraut, M. A., Resnick, S.M., 2014. Association of hearing impairment with brain volume changes in older adults. Neuroimage 90, 84–92. https://doi.org/10.1016/j.neuroimage.2013.12.059.

Lomber, S.G., Meredith, M.A., Kral, A., 2010. Cross-modal plasticity in specific auditory cortices underlies visual compensations in the deaf. Nat. Neurosci. 13 (11), 1421–1427. https://doi.org/10.1038/nn.2653.

Macherey, O., Carlyon, R.P., 2014. Cochlear implants. Current Biol. 24 (18). https://doi.org/10.1016/j.cub.2014.06.053.

Mandalà, M., Baldi, T.L., Neri, F., Mencarelli, L., Romanella, S., Ulivelli, M., Prattichizzo, D., Santarnecchi, E., Rossi, S., 2021. Feasibility of TMS in patients with new generation cochlear implants. Clin. Neurophysiol. 132 (3), 723–729. https://doi.org/10.1016/j.clinph.2020.12.013.

Mansouri, N., Javanbakht, M., Jahan, A., Bakhshi, E., Shaabani, M., 2025. Improve the behavioral auditory attention training effects on the Speech-In-noise perception with simultaneous electrical stimulation in children with hearing loss: a randomized clinical trial. Int. J. Pediatr. Otorhinolaryngol. 188. https://doi.org/10.1016/j.ijporl.2024.112197.

Mansouri, N., Shaabani, M., Jahan, A., Bakhshi, E., Javanbakht, M., 2025. A new method of auditory training through the addition of attentional neuromodulation techniques: a pilot study. Auditory Vestibular Res. 34 (3), 257–268. https://doi.org/10.18502/avr.v34i3.18466.

Marquardt, L., Kusztrits, I., Craven, A.R., Hugdahl, K., Specht, K., Hirnstein, M., 2021. A multimodal study of the effects of tDCS on dorsolateral prefrontal and temporo-parietal areas during dichotic listening. Eur. J. Neurosci. 53 (2), 449–459. https://doi.org/10.1111/ejn.14932.

Matt, E., Radjenovic, S., Mitterwallner, M., Beisteiner, R., 2024. Current state of clinical ultrasound neuromodulation. Front. Neurosci. 18. https://doi.org/10.3389/fnins.2024.1420255.

Merton, P.A., Morton, H.B., 1980. Stimulation of the cerebral cortex in the intact human subject. Nature 285 (5762). https://doi.org/10.1038/285227a0.

Mishra, S., Lunner, T., Stenfelt, S., Rönnberg, J., Rudner, M., 2013. Visual information can hinder working memory processing of speech. J. Speech Lang. Hear.Res. 56 (4), 1120–1132. https://doi.org/10.1044/1092-4388(2012/12-0033).

Mishra, S., Stenfelt, S., Lunner, T., Rönnberg, J., Rudner, M., 2014. Cognitive spare capacity in older adults with hearing loss. Front. Aging Neurosci. 6 (MAY). https://doi.org/10.3389/fnagi.2014.00096.

Moberly, A.C., Lewis, J.H., Vasil, K.J., Ray, C., Tamati, T.N., 2021. Bottom-up signal quality impacts the role of top-down cognitive-linguistic processing during speech recognition by adults with Cochlear implants. Otol. Neurotol. 42 (10). https://doi.org/10.1097/MAO.0000000000003377.

Mori, T., Takeuchi, N., Suzuki, S., Miki, M., Kawase, T., Izumi, S.I., 2016. Anodal transcranial direct current stimulation over the auditory cortex improved hearing impairment in a patient with brainstem encephalitis. J. Int. Med. Res. 44 (3), 760–764. https://doi.org/10.1177/0300060516630843.

Mushtaq, F., Wiggins, I.M., Kitterick, P.T., Anderson, C.A., Hartley, D.E.H., 2020. The benefit of cross-modal reorganization on speech perception in pediatric cochlear implant recipients revealed using functional near-infrared spectroscopy. Front. Hum. Neurosci. 14. https://doi.org/10.3389/fnhum.2020.00308.

Nagappan-Chettiar, S., Burbridge, T.J., Umemori, H., 2023. Activity-dependent synapse refinement: from mechanisms to molecules. Neuroscientist. https://doi.org/10.1177/10738584231170167.

Neacsiu, A.D., Beynel, L., Graner, J.L., Szabo, S.T., Appelbaum, L.G., Smoski, M.J., LaBar, K.S., 2022. Enhancing cognitive restructuring with concurrent fMRI-guided neurostimulation for emotional dysregulation–A randomized controlled trial. J. Affect. Disord. 301. https://doi.org/10.1016/j.jad.2022.01.053.

Neacsiu, A.D., Beynel, L., Powers, J.P., Szabo, S.T., Appelbaum, L.G., Lisanby, S.H., LaBar, K.S., 2022. Enhancing cognitive restructuring with concurrent repetitive transcranial magnetic stimulation: a transdiagnostic randomized controlled trial. PsychOther Psychosom. 91 (2). https://doi.org/10.1159/000518957.

Neri, F., Cappello, C., Viberti, F., Donniacuo, A., Burzi, L., Cinti, A., Benelli, A., Luca Smeralda, C., Romanella, S., Santarnecchi, E., Mandalà, M., Rossi, S., 2024. rTMS of the auditory association cortex improves speech intelligibility in patients with sensorineural hearing loss. Clin. Neurophysiol. 160, 38–46. https://doi.org/10.1016/j.clinph.2024.02.007.

Neuman, A.C., 2005. Central auditory system plasticity and aural rehabilitation of adults. J. Rehabil. Res. Dev. 42 (4 SUPPL. 2), 169–185. https://doi.org/10.1682/JRRD.2005.01.0020.

Nguyen, A., Khaleel, H.M., Razak, K.A., 2017. Effects of noise-induced hearing loss on parvalbumin and perineuronal net expression in the mouse primary auditory cortex. Hear. Res. 350, 82–90. https://doi.org/10.1016/j.heares.2017.04.015.

Nitsche, M.A., Paulus, W., 2000. Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation. J. Physiol. 527 (3). https://doi.org/10.1111/j.1469-7793.2000.t01-1-00633.x.

Obleser, J., Eisner, F., Kotz, S.A., 2008. Bilateral speech comprehension reflects differential sensitivity to spectral and temporal features. J. Neurosci. 28 (32), 8116–8123. https://doi.org/10.1523/JNEUROSCI.1290-08.2008.

Obleser, J., Wise, R.J.S., Dresner, M.A., Scott, S.K., 2007. Functional integration across brain regions improves speech perception under adverse listening conditions. J. Neurosci. 27 (9), 2283–2289. https://doi.org/10.1523/JNEUROSCI.4663-06.2007.

Otto, W.C., McCandless, G.A., 1982. Aging and the auditory brain stem response. Int. J. Audiol. 21 (6). https://doi.org/10.3109/00206098209072759.

Pang, E.W., Taylor, M.J., 2000. Tracking the development of the N1 from age 3 to adulthood: an examination of speech and non-speech stimuli. Clin. Neurophysiol. 111 (3). https://doi.org/10.1016/S1388-2457(99)00259-X.

Pantev, C., Dinnesen, A., Ross, B., Wollbrink, A., Knief, A., 2006. Dynamics of auditory plasticity after cochlear implantation: a longitudinal study. Cereb. Cortex 16 (1), 31–36. https://doi.org/10.1093/cercor/bhi081.

Park, D.C., Reuter-Lorenz, P., 2009. The adaptive brain: aging and neurocognitive scaffolding. Annu. Rev. Psychol. 60. https://doi.org/10.1146/annurev.psych.59.103006.093656.

Paulus, W., Peterchev, A.V., Ridding, M., 2013. Transcranial electric and magnetic stimulation: technique and paradigms. In: Handbook of Clinical Neurology, 116. Elsevier B.V, pp. 329–342. https://doi.org/10.1016/B978-0-444-53497-2.00027-9.

Pauly, K.B., Qiu, Z., Legon, W., 2021. Transcranial ultrasound modulation. The Oxford Handbook of Transcranial Stimulation. Oxford University Press, pp. 251–275. https://doi.org/10.1093/oxfordhb/9780198832256.013.9.

Peelle, J.E., 2010. Hierarchical processing for speech in human auditory cortex and beyond. Front. Hum. Neurosci. https://doi.org/10.3389/fnhum.2010.00051.

Peelle, J.E., 2018. Listening effort: how the cognitive consequences of acoustic challenge are reflected in brain and behavior. Ear Hear. 39 (2), 204–214. https://doi.org/10.1097/AUD.0000000000000494.

Peelle, J.E., Troiani, V., Grossman, M., Wingfield, A., 2011. Hearing loss in older adults affects neural systems supporting speech comprehension. J. Neurosci. 31 (35), 12638–12643. https://doi.org/10.1523/JNEUROSCI.2559-11.2011.

Peelle, J.E., Wingfield, A., 2016. The neural consequences of age-related hearing loss. Trends. Neurosci. 39 (7), 486–497. https://doi.org/10.1016/j.tins.2016.05.001.

Peter, N., Kleinjung, T., 2019. Neuromodulation for tinnitus treatment: an overview of invasive and non-invasive techniques. J. Zhejiang Univ. 20 (2). https://doi.org/10.1631/jzus.B1700117.

Peterchev, A.V., Wagner, T.A., Miranda, P.C., Nitsche, M.A., Paulus, W., Lisanby, S.H., Pascual-Leone, A., Bikson, M., 2012. Fundamentals of transcranial electric and magnetic stimulation dose: definition, selection, and reporting practices. Brain Stimul. 5 (4), 435–453. https://doi.org/10.1016/j.brs.2011.10.001.

Petersen, B., Gjedde, A., Wallentin, M., Vuust, P., 2013. Cortical plasticity after cochlear implantation. Neural Plast. 2013, 1–11. https://doi.org/10.1155/2013/318521.

Pichora-Fuller, M.K., Kramer, S.E., Eckert, M.A., Edwards, B., Hornsby, B.W.Y., Humes, L.E., Lemke, U., Lunner, T., Matthen, M., Mackersie, C.L., Naylor, G., Phillips, N.A., Richter, M., Rudner, M., Sommers, M.S., Tremblay, K.L., Wingfield, A., 2016. Hearing impairment and cognitive energy: the framework for understanding effortful listening (FUEL). Ear Hear. 37. https://doi.org/10.1097/AUD.0000000000000312.

Pilloni, G., Vogel-Eyny, A., Lustberg, M., Best, P., Malik, M., Walton-Masters, L., George, A., Mirza, I., Zhovtis, L., Datta, A., Bikson, M., Krupp, L., Charvet, L., 2022. Tolerability and feasibility of at-home remotely supervised transcranial direct current stimulation (RS-tDCS): single-center evidence from 6,779 sessions. Brain Stimul. 15 (3). https://doi.org/10.1016/j.brs.2022.04.014.

Polanía, R., Nitsche, M.A., Ruff, C.C., 2018. Studying and modifying brain function with non-invasive brain stimulation. Nat. Neurosci. 21 (2). https://doi.org/10.1038/s41593-017-0054-4.

Ponton, C.W., Eggermont, J.J., Kwong, B., Don, M., 2000. Maturation of human central auditory system activity: evidence from multi-channel evoked potentials. Clin. Neurophysiol. 111 (2). https://doi.org/10.1016/S1388-2457(99)00236-9.

Price, C.J., 2012. A review and synthesis of the first 20years of PET and fMRI studies of heard speech, spoken language and reading. Neuroimage 62 (2), 816–847. https://doi.org/10.1016/j.neuroimage.2012.04.062.

Qian, Z.J., Chang, P.D., Moonis, G., Lalwani, A.K., 2017. A novel method of quantifying brain atrophy associated with age-related hearing loss. NeuroImage 16, 205–209. https://doi.org/10.1016/j.nicl.2017.07.021.

Quaranta, N., Wagstaff, S., Baguley, D.M., 2004. Tinnitus and cochlear implantation. In: International Journal of Audiology, 43. Int J Audiol, pp. 245–251. https://doi.org/10.1080/14992020400050033.

Reed, T., Cohen Kadosh, R., 2018. Transcranial electrical stimulation (tES) mechanisms and its effects on cortical excitability and connectivity. J. Inherit. Metab. Dis. 41 (6). https://doi.org/10.1007/s10545-018-0181-4.

Regenold, W.T., Deng, Z.De, Lisanby, S.H, 2022. Noninvasive neuromodulation of the prefrontal cortex in mental health disorders. Neuropsychopharmacology 47 (1). https://doi.org/10.1038/s41386-021-01094-3.

Reis, M., McMahon, C.M., Távora-Vieira, D., Humburg, P., Boisvert, I., 2021. Effectiveness of computer-based auditory training for adult Cochlear implant users: a randomized crossover study. Trends. Hear. 25. https://doi.org/10.1177/23312165211025938.

Ren, F., Ma, W., Li, M., Sun, H., Xin, Q., Zong, W., Chen, W., Wang, G., Gao, F., Zhao, B., 2018. Gray matter atrophy is associated with cognitive impairment in patients with presbycusis: a comprehensive morphometric study. Front. Neurosci. 12. https://doi.org/10.3389/fnins.2018.00744.

Resnik, J., Polley, D.B., 2021. Cochlear neural degeneration disrupts hearing in background noise by increasing auditory cortex internal noise. Neuron 109 (6). https://doi.org/10.1016/j.neuron.2021.01.015.

Reveles Jensen, K.H., Navntoft, C.A., Sindahl, C.H., Cayé-Thomasen, P., Jørgensen, M.B., 2020. Cochlear implant should not be absolute contraindication for electroconvulsive therapy and transcranial magnetic stimulation. In: Brain Stimul., 13. https://doi.org/10.1016/j.brs.2020.08.007.

Riecke, L., 2016. Studying effects of transcranial alternating current stimulation on hearing and auditory scene analysis. Adv. Exp. Med. Biol. 894, 371–379. https://doi.org/10.1007/978-3-319-25474-6_39.

Riecke, L., Formisano, E., Sorger, B., Başkent, D., Gaudrain, E., 2018. Neural entrainment to speech modulates speech intelligibility. Current Biol. 28 (2), 161–169. https://doi.org/10.1016/j.cub.2017.11.033. .e5.

Rohan, M.L., Yamamoto, R.T., Ravichandran, C.T., Cayetano, K.R., Morales, O.G., Olson, D.P., Vitaliano, G., Paul, S.M., Cohen, B.M., 2014. Rapid mood-elevating effects of low field magnetic stimulation in depression. Biol. Psychiatry 76 (3). https://doi.org/10.1016/j.biopsych.2013.10.024.

Rönnberg, J., Lunner, T., Zekveld, A., Sörqvist, P., Danielsson, H., Lyxell, B., Dahlström, Ö., Signoret, C., Stenfelt, S., Pichora-Fuller, M.K., Rudner, M., 2013. The Ease of Language understanding (ELU) model: theoretical, empirical, and clinical advances. Front. Syst. Neurosci. 7 (JUNE). https://doi.org/10.3389/fnsys.2013.00031.

Rosenhall, U., Björkman, G., Pedersen, K., Kall, A., 1985. Brain-stem auditory evoked potentials in different age groups. Electroencephalography and Clin. Neurophysiol./Evoked Potentials 62 (6). https://doi.org/10.1016/0168-5597(85)90052-8.

Rossi, S., Antal, A., Bestmann, S., Bikson, M., Brewer, C., Brockmöller, J., Carpenter, L.L., Cincotta, M., Chen, R., Daskalakis, J.D., Di Lazzaro, V., Fox, M.D., George, M.S., Gilbert, D., Kimiskidis, V.K., Koch, G., Ilmoniemi, R.J., Pascal Lefaucheur, J., Leocani, L., Hallett, M., 2021. Safety and recommendations for TMS use in healthy subjects and patient populations, with updates on training, ethical and regulatory issues: expert Guidelines. Clin. Neurophysiol. 132 (1). https://doi.org/10.1016/j.clinph.2020.10.003.

Rossi, S., Hallett, M., Rossini, P.M., Pascual-Leone, A., Avanzini, G., Bestmann, S., Berardelli, A., Brewer, C., Canli, T., Cantello, R., Chen, R., Classen, J., Demitrack, M., Di Lazzaro, V., Epstein, C.M., George, M.S., Fregni, F., Ilmoniemi, R., Jalinous, R., Ziemann, U., 2009. Safety, ethical considerations, and application guidelines for the use of transcranial magnetic stimulation in clinical practice and research. Clin. Neurophysiol. 120 (12), 2008–2039. https://doi.org/10.1016/j.clinph.2009.08.016.

Roth, T.N., 2015. Aging of the auditory system. In: Handbook of Clinical Neurology, 129. Elsevier B.V, pp. 357–373. https://doi.org/10.1016/B978-0-444-62630-1.00020-2.

Rudner, M., Lunner, T., 2014. Cognitive spare capacity and speech communication: a narrative overview. Biomed. Res. Int. 2014, 1–10. https://doi.org/10.1155/2014/869726.

Rufener, K.S., Krauel, K., Meyer, M., Heinze, H.J., Zaehle, T., 2019. Transcranial electrical stimulation improves phoneme processing in developmental dyslexia. Brain Stimul. 12 (4), 930–937. https://doi.org/10.1016/j.brs.2019.02.007.

Rufener, K.S., Oechslin, M.S., Zaehle, T., Meyer, M., 2016. Transcranial alternating Current stimulation (tACS) differentially modulates speech perception in young and older adults. Brain Stimul. 9 (4). https://doi.org/10.1016/j.brs.2016.04.002.

Rufener, K.S., Ruhnau, P., Heinze, H.J., Zaehle, T., 2017. Transcranial random noise stimulation (tRNS) shapes the processing of rapidly changing auditory information. Front. Cell Neurosci. 11. https://doi.org/10.3389/fncel.2017.00162.

Ruhnau, P., Rufener, K.S., Heinze, H.J., Zaehle, T., 2020. Pulsed transcranial electric brain stimulation enhances speech comprehension. Brain Stimul. 13 (5), 1402–1411. https://doi.org/10.1016/j.brs.2020.07.011.

Saliba, J., Bortfeld, H., Levitin, D.J., Oghalai, J.S., 2016. Functional near-infrared spectroscopy for neuroimaging in cochlear implant recipients. In: Hearing Research, 338. Elsevier B.V, pp. 64–75. https://doi.org/10.1016/j.heares.2016.02.005.

Sandmann, P., Plotz, K., Hauthal, N., de Vos, M., Schönfeld, R., Debener, S., 2015. Rapid bilateral improvement in auditory cortex activity in postlingually deafened adults following cochlear implantation. Clin. Neurophysiol. 126 (3), 594–607. https://doi.org/10.1016/j.clinph.2014.06.029.

Sandrini, M., Umiltà, C., Rusconi, E., 2011. The use of transcranial magnetic stimulation in cognitive neuroscience: a new synthesis of methodological issues. Neurosci. Biobehav. Rev. 35 (3). https://doi.org/10.1016/j.neubiorev.2010.06.005.

Savelon, E.C.J., Jordan, H.T., Stinear, C.M., Byblow, W.D., 2024. Noninvasive brain stimulation to improve motor outcomes after stroke. Curr. Opin. Neurol. 37 (6), 621–628. https://doi.org/10.1097/WCO.0000000000001313.

Schneider, P., Andermann, M., Wengenroth, M., Goebel, R., Flor, H., Rupp, A., Diesch, E., 2009. Reduced volume of Heschl's gyrus in tinnitus. Neuroimage 45 (3), 927–939. https://doi.org/10.1016/j.neuroimage.2008.12.045.

Schumann, A., Serman, M., Gefeller, O., Hoppe, U., 2015. Computer-based auditory phoneme discrimination training improves speech recognition in noise in experienced adult cochlear implant listeners. Int. J. Audiol. 54 (3). https://doi.org/10.3109/14992027.2014.969409.

Shaw, M.T., Kasschau, M., Dobbs, B., Pawlak, N., Pau, W., Sherman, K., Bikson, M., Datta, A., Charvet, L.E., 2017. Remotely supervised transcranial direct current stimulation: an update on safety and tolerability. J. Visualized Experim. 2017 (128). https://doi.org/10.3791/56211.

Shekelle, P.G., Shekelle, P., Cook, I., Miake-Lye, I.M., Mak, S., Booth, M.S., Shanman, R., Beroes, J.M., 2018. The effectiveness and risks of cranial electrical stimulation for the treatment of pain, depression, Anxiety, PTSD, and insomnia: a systematic review. VA Evidence-Based Synthesis Program Reports.

Siebner, H.R., Hartwigsen, G., Kassuba, T., Rothwell, J.C., 2009. How does transcranial magnetic stimulation modify neuronal activity in the brain? Implications for studies of cognition. Cortex 45 (9). https://doi.org/10.1016/j.cortex.2009.02.007.

Silvanto, J., Muggleton, N., Walsh, V., 2008. State-dependency in brain stimulation studies of perception and cognition. Trends. Cogn. Sci. 12 (12). https://doi.org/10.1016/j.tics.2008.09.004.

Silvanto, J., Pascual-Leone, A., 2008. State-dependency of transcranial magnetic stimulation. Brain Topogr. 21 (1). https://doi.org/10.1007/s10548-008-0067-0.

Skoe, E., Krizman, J., Anderson, S., Kraus, N., 2015. Stability and plasticity of auditory brainstem function across the lifespan. Cerebral Cortex 25 (6), 1415–1426. https://doi.org/10.1093/cercor/bht311.

Smalt, C.J., Gonzalez-Castillo, J., Talavage, T.M., Pisoni, D.B., Svirsky, M.A., 2013. Neural correlates of adaptation in freely-moving normal hearing subjects under cochlear implant acoustic simulations. Neuroimage 82. https://doi.org/10.1016/j.neuroimage.2013.06.001.

Smith, G.S., 2013. Aging and neuroplasticity. Dialogues. Clin. Neurosci. 15 (1). https://doi.org/10.31887/dcns.2013.15.1/gsmith.

Song, J.J., Lee, H.J., Kang, H., Lee, D.S., Chang, S.O., Oh, S.H., 2015. Effects of congruent and incongruent visual cues on speech perception and brain activity in cochlear implant users. Brain Struct. Funct. 220 (2), 1109–1125. https://doi.org/10.1007/s00429-013-0704-6.

Stephens, S.D.G., 1987. Auditory rehabilitation. BnuiM Medical Bulltim 43 (4). https://academic.oup.com/bmb/article/43/4/999/464465.

Stevenson, R.A., Sheffield, S.W., Butera, I.M., Gifford, R.H., Wallace, M.T., 2017. Multisensory integration in Cochlear implant recipients. Ear Hear. 38 (5), 521–538. https://doi.org/10.1097/AUD.0000000000000435.

Stockard, J.E., Stockard, J.J., Westmoreland, B.F., Corfits, J.L., 1979. Brainstem auditory-evoked responses: normal variation as a function of stimulus and subject characteristics. Arch. Neurol. 36 (13). https://doi.org/10.1001/archneur.1979.00500490037006.

Strelnikov, K., Marx, M., Lagleyre, S., Fraysse, B., Deguine, O., Barone, P., 2015. PET-imaging of brain plasticity after cochlear implantation. Hear. Res. 322. https://doi.org/10.1016/j.heares.2014.10.001.

Strelnikov, K., Rouger, J., Demonet, J.F., Lagleyre, S., Fraysse, B., Deguine, O., Barone, P., 2013. Visual activity predicts auditory recovery from deafness after adult cochlear implantation. Brain 136 (12), 3682–3695. https://doi.org/10.1093/brain/awt274.

Stropahl, M., Chen, L.C., Debener, S., 2017. Cortical reorganization in postlingually deaf cochlear implant users: intra-modal and cross-modal considerations. Hear. Res. 343. https://doi.org/10.1016/j.heares.2016.07.005.

Su, Y.T., Meng, X.X., Zhang, X., Guo, Y.Bin, Zhang, H.J., Cheng, Y.P., Xie, X.P., Chang, Y. M., Bao, J.X, 2017. Doxepin mitigates noise-induced neuronal damage in primary auditory cortex of mice via suppression of acid sphingomyelinase/ceramide pathway. Anatomical Record 300 (12), 2220–2232. https://doi.org/10.1002/ar.23677.

Sukhera, J., 2022. Narrative reviews: flexible, rigorous, and practical. J. Grad. Med. Educ. 14 (4). https://doi.org/10.4300/JGME-D-22-00480.1.

Sweetow, R.W., Sabes, J.H., 2010. Auditory training and challenges associated with participation and compliance. J. Am. Acad. Audiol. 21 (9). https://doi.org/10.3766/jaaa.21.9.4.

Távora-Vieira, D., Acharya, A., Rajan, G.P., 2020. What can we learn from adult cochlear implant recipients with single-sided deafness who became elective non-users? Cochlear. Implants Int. 21 (4), 220–227. https://doi.org/10.1080/14670100.2020.1733746.

Tendler, A., Roth, Y., Hanlon, C.A., 2023. “Can we deliver TMS to patients with implanted devices?" A practical summary of the recent safety recommendations. In: Journal of Clinical Psychiatry, 84. Physicians Postgraduate Press Inc. https://doi.org/10.4088/JCP.23l14857.

Thirthalli, J., Sinha, P., Sreeraj, V.S., 2023. Clinical practice guidelines for the use of electroconvulsive therapy. Indian J. Psychiatry 65 (2). https://doi.org/10.4103/indianjpsychiatry.indianjpsychiatry_491_22.

Thivierge, J., Côté, R., 1990. Brain-stem auditory evoked response: normative values in children. Electroencephalography Clin. Neurophysiol./Evoked Potentials 77 (4). https://doi.org/10.1016/0168-5597(90)90069-P.

Tobey, E.A., Devous, M.D., Buckley, K., Overson, G., Harris, T., Ringe, W., Martinez-Verhoff, J., 2005. Pharmacological enhancement of aural habilitation in adult cochlear implant users. Ear Hear. 26 (4 SUPPL), 45S–56S. https://doi.org/10.1097/00003446-200508001-00007.

Tremblay, K.L., 2007. Training-related changes in the brain: evidence from human auditory-evoked potentials. Semin. Hear. 28 (2), 120–132. https://doi.org/10.1055/s-2007-973438.

Tremblay, K.L., Kraus, N., 2002. Beyond the ear: central auditory plasticity. Otorinolaringologia 52 (3).

Tremblay, K.L., Shahin, A.J., Picton, T., Ross, B., 2009. Auditory training alters the physiological detection of stimulus-specific cues in humans. Clin. Neurophysiol. 120 (1), 128–135. https://doi.org/10.1016/j.clinph.2008.10.005.

Tringali, S., Perrot, X., Collet, L., Moulin, A., 2012. Repetitive transcranial magnetic stimulation: hearing safety considerations. Brain Stimul. 5 (3). https://doi.org/10.1016/j.brs.2011.06.005.

Truong, D.Q., Khadka, N., Peterchev, A.V., Bikson, M., 2021. Transcranial electrical stimulation devices. The Oxford Handbook of Transcranial Stimulation. Oxford University Press, pp. 23–74. https://doi.org/10.1093/oxfordhb/9780198832256.013.2.

Turkeltaub, P.E., Branch Coslett, H., 2010. Localization of sublexical speech perception components. Brain Lang. 114 (1), 1–15. https://doi.org/10.1016/j.bandl.2010.03.008.

Vaden, K.I., Eckert, M.A., Dubno, J.R., Harris, K.C., 2020. Cingulo-opercular adaptive control for younger and older adults during a challenging gap detection task. J. Neurosci. Res. 98 (4), 680–691. https://doi.org/10.1002/jnr.24506.

Vaden, K.I., Kuchinsky, S.E., Ahlstrom, J.B., Dubno, J.R., Eckert, M.A., 2015. Cortical activity predicts which older adults recognize speech in noise and when. J. Neurosci. 35 (9), 3929–3937. https://doi.org/10.1523/JNEUROSCI.2908-14.2015.

Vaden, K.I., Kuchinsky, S.E., Ahlstrom, J.B., Teubner-Rhodes, S.E., Dubno, J.R., Eckert, M.A., 2016. Cingulo-opercular function during word recognition in noise for older adults with hearing loss. Exp. Aging Res. 42 (1), 86–106. https://doi.org/10.1080/0361073X.2016.1108784.

Vaden, K.I., Matthews, L.J., Eckert, M.A., Dubno, J.R., 2017. Longitudinal changes in audiometric phenotypes of age-related hearing loss. JARO 18 (2), 371–385. https://doi.org/10.1007/s10162-016-0596-2.

Vaden, K.I., Teubner-Rhodes, S., Ahlstrom, J.B., Dubno, J.R., Eckert, M.A., 2017. Cingulo-opercular activity affects incidental memory encoding for speech in noise. Neuroimage 157, 381–387. https://doi.org/10.1016/j.neuroimage.2017.06.028.

Vaden, K.I., Teubner-Rhodes, S., Ahlstrom, J.B., Dubno, J.R., Eckert, M.A., 2022. Evidence for cortical adjustments to perceptual decision criteria during word recognition in noise. Neuroimage 253. https://doi.org/10.1016/j.neuroimage.2022.119042.

Van De Winckel, A., Carey, J.R., Bisson, T.A., Hauschildt, E.C., Streib, C.D., Durfee, W.K., 2018. Home-based transcranial direct current stimulation plus tracking training therapy in people with stroke: an open-label feasibility study 11 Medical and Health Sciences 1117 Public Health and Health Services. J. Neuroeng. Rehabil. 15 (1). https://doi.org/10.1186/s12984-018-0427-2.

Van Doren, J., Langguth, B., Schecklmann, M., 2014. Electroencephalographic effects of transcranial random noise stimulation in the auditory cortex. Brain Stimul. 7 (6), 807–812. https://doi.org/10.1016/j.brs.2014.08.007.

Veniero, D., Vossen, A., Gross, J., Thut, G., 2015. Lasting EEG/MEG aftereffects of rhythmic transcranial brain stimulation: level of control over oscillatory network activity. In: Frontiers in Cellular Neuroscience, 9. Frontiers Media S.A., pp. 1–17. https://doi.org/10.3389/fncel.2015.00477. Issue DEC.

Vergallito, A., Varoli, E., Giustolisi, B., Cecchetto, C., Del Mauro, L., Romero Lauro, L.J., 2020. Mind the stimulation site: enhancing and diminishing sentence comprehension with anodal tDCS. Brain Lang. 204. https://doi.org/10.1016/j.bandl.2020.104757.

Viale, L., Catoira, N.P., Di Girolamo, G., González, C.D., 2018. Pharmacotherapy and motor recovery after stroke. Expert. Rev. NeurOther 18 (1). https://doi.org/10.1080/14737175.2018.1400910.

Walker-Batson, D., 2000. Use of pharmacotherapy in the treatment of aphasia. Brain Lang. 71 (1). https://doi.org/10.1006/brln.1999.2262.

Walsh, V., Cowey, A., 2000. Transcranial magnetic stimulation and cognitive neuroscience. Nature Rev. Neurosci. 1 (1). https://doi.org/10.1038/35036239.

Wang, B., Aberra, A.S., Grill, W.M., Peterchev, A.V., 2021. Physics and biophysics fundamentals of transcranial stimulation. Oxford Handbook Transcranial Stimul. https://doi.org/10.1093/oxfordhb/9780198832256.013.1.

Wang, X., Xu, P., Li, P., Wang, Z., Zhao, F., Gao, Z., Xu, L., Luo, Y.J., Fan, J., Liu, P., 2016. Alterations in gray matter volume due to unilateral hearing loss. Sci. Rep. 6 (1), 25811. https://doi.org/10.1038/srep25811.

Wang, Y., Shi, L., Dong, G., Zhang, Z., Chen, R., 2020. Effects of transcranial electrical stimulation on human auditory processing and behavior—A review. In: Brain Sciences, 10. MDPI AG, pp. 1–32. https://doi.org/10.3390/brainsci10080531.

Wassermann, E.M., Peterchev, A.V., Ziemann, U., Lisanby, S.H., Siebner, H.R., Walsh, V. (Eds.), 2024. The Oxford Handbook of Transcranial Stimulation, 2nd ed. Oxford University Press. https://doi.org/10.1093/oxfordhb/9780198832256.001.0001.

Wilsch, A., Neuling, T., Obleser, J., Herrmann, C.S., 2018. Transcranial alternating current stimulation with speech envelopes modulates speech comprehension. Neuroimage 172, 766–774. https://doi.org/10.1016/j.neuroimage.2018.01.038.

Wilson, B.S., Dorman, M.F., Woldorff, M.G., Tucci, D.L., 2011. Cochlear implants. Matching the prosthesis to the brain and facilitating desired plastic changes in brain function. Prog. Brain Res. 194. https://doi.org/10.1016/B978-0-444-53815-4.00012-1.

Woods, A.J., Antal, A., Bikson, M., Boggio, P.S., Brunoni, A.R., Celnik, P., Cohen, L.G., Fregni, F., Herrmann, C.S., Kappenman, E.S., Knotkova, H., Liebetanz, D., Miniussi, C., Miranda, P.C., Paulus, W., Priori, A., Reato, D., Stagg, C., Wenderoth, N., Nitsche, M.A., 2016. A technical guide to tDCS, and related non-invasive brain stimulation tools. Clin. Neurophysiol. 127 (2). https://doi.org/10.1016/j.clinph.2015.11.012.

XVII. On the electricity excited by the mere contact of conducting substances of different kinds. In a letter from Mr. Alexander Volta, F. R. S. Professor of Natural Philosophy in the University of Pavia, to the Rt. Hon. Sir Joseph Banks, Bart. K.B. P. R. S. (1800). *Philosophical Transactions of the Royal Society of London*, 90, 403–431. https://doi.org/10.1098/rstl.1800.0018.

Yaakub, S.N., White, T.A., Roberts, J., Martin, E., Verhagen, L., Stagg, C.J., Hall, S., Fouragnan, E.F., 2023. Transcranial focused ultrasound-mediated neurochemical and functional connectivity changes in deep cortical regions in humans. Nat. Commun. 14 (1). https://doi.org/10.1038/s41467-023-40998-0.

Yoo, S., Mittelstein, D.R., Hurt, R.C., Lacroix, J., Shapiro, M.G., 2022. Focused ultrasound excites cortical neurons via mechanosensitive calcium accumulation and ion channel amplification. Nat. Commun. 13 (1). https://doi.org/10.1038/s41467-022-28040-1.

Zangen, A., Moshe, H., Martinez, D., Barnea-Ygael, N., Vapnik, T., Bystritsky, A., Duffy, W., Toder, D., Casuto, L., Grosz, M.L., Nunes, E.V., Ward, H., Tendler, A., Feifel, D., Morales, O., Roth, Y., Iosifescu, D.V., Winston, J., Wirecki, T., George, M. S., 2021. Repetitive transcranial magnetic stimulation for smoking cessation: a pivotal multicenter double-blind randomized controlled trial. World Psychiatry 20 (3). https://doi.org/10.1002/wps.20905.

Zeng, F.G., 2004. Trends in Cochlear implants. Trends. Amplif. 8 (1), 1–34. https://doi.org/10.1177/108471380400800102.

Zhang, D., Ma, Y., 2015. Repetitive transcranial magnetic stimulation improves both hearing function and tinnitus perception in sudden sensorineural hearing loss patients. Sci. Rep. 5. https://doi.org/10.1038/srep14796.

Zhang, F., Anderson, J., Samy, R., Houston, L., 2010. The adaptive pattern of the late auditory evoked potential elicited by repeated stimuli in cochlear implant users. Int. J. Audiol. 49 (4). https://doi.org/10.3109/14992020903321759.

Zhang, M., Miller, A., Campbell, M.M.N, 2014. Overview of nine computerized, home-based auditory-training programs for adult cochlear implant recipients. J. Am. Acad. Audiol. 25 (4). https://doi.org/10.3766/jaaa.25.4.11.

Zhao, E.E., Dornhoffer, J.R., Loftus, C., Nguyen, S.A., Meyer, T.A., Dubno, J.R., McRackan, T.R., 2020. Association of patient-related factors with adult Cochlear Implant speech recognition outcomes: a meta-analysis. JAMA Otolaryngol. 146 (7), 613–620. https://doi.org/10.1001/jamaoto.2020.0662.

Zhou, X., Feng, M., Hu, Y., Zhang, C., Zhang, Q., Luo, X., Yuan, W., 2022. The effects of cortical reorganization and applications of functional near-infrared spectroscopy in deaf people and Cochlear implant users. In: Brain Sciences, 12. MDPI. https://doi.org/10.3390/brainsci12091150.

Zhou, Y., Han, H., Zhang, X., Zhang, Y., Duan, W., Su, L., Li, B., Sun, Z., Wang, L., Wang, G., 2025. Dual improvement of cognitive function and auditory ability in elderly patients with hearing impairment by transcranial direct current stimulation-assisted auditory rehabilitation training. Front. Aging Neurosci. 17. https://doi.org/10.3389/fnagi.2025.1591496.

Zimmerling, M. (2020). *MED-EL Medical Electronics, Personal communication. February 6, 2020.*

Zoefel, B., Allard, I., Anil, M., Davis, M.H., 2019. Perception of rhythmic speech is modulated by focal bilateral transcranial alternating current stimulation. J. Cogn. Neurosci. 32 (2), 226–240. https://doi.org/10.1162/jocn_a_01490.

Zoefel, B., Davis, M.H., 2017. Transcranial electric stimulation for the investigation of speech perception and comprehension. Lang. Cogn. Neurosci. 32 (7), 910–923. https://doi.org/10.1080/23273798.2016.1247970.