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HOW FREQUENCY-BASED PROCESSING MAY HELP CLINICIANS IMPROVE SOUND QUALITY PERCEPTION IN COCHLEAR IMPLANT USERS?

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ABSTRACT

Sound quality in cochlear implants (CIs) remains a critical challenge despite advancements in speech understanding. While CI technology's impact on sound quality degradation is well-documented, less is known about specific "frequency-to-place factors" such as frequency-to-place mismatch (FTPM) and issues with the electrode-neuron interface (ENI). This study explores innovative methods to assess the relationship between sound quality and these factors. The first experiment examines vowel perception through combinations of the first and second formant frequencies varied across a spectral continuum. Participants selected vowels from a close-set list (/a/, /i/, /ɔ/, /u/, /ɜ/) and then rated their confidence of their selection. Individual vowel maps were calculated to assess shifts in internal vowel representation potentially linked to FTPM (although not accounting for other ENI aspects). The second experiment evaluates sound quality transmission across electrodes using paired chord comparisons. Participants rated sound quality between chords and their inversions, isolating electrode-specific degradation. Ten post-lingually deafened adult CI users with over 12 months of experience participated. Preliminary findings reveal good test-retest reliability. Vowel experiments showed some preference for shifted configurations, while chord tests highlighted significant variability across electrodes. These methods may serve as clinical tools to optimize CI setup, improving sound quality for users.

1. INTRODUCTION

A cochlear implant (CI) is a neuroprosthetic device designed for people with severe hearing loss. Once implanted, users must adapt to new stimulation patterns imposed by both the CI technology and individual factors. Some of these individual factors are referred to as "frequency-to-place factors" because they alter the distribution of frequency information delivered to the auditory system.

The primary individual factor of interest here is frequency-to-place mismatch (FTPM). FTPM refers to the discrepancy between the frequency information delivered by an electrode and the frequency typically processed at the location stimulated by this electrode. This phenomenon occurs mainly because electrode arrays rarely allow stimulation along the entire length of the cochlea. Specifically, electrode arrays seldom reach the apex of the cochlea, where low frequencies are usually processed. To maintain effective transmission of the frequency spectrum, fitting strategies often involve a trade-off: a wide range of frequency information is transmitted, although not always to the ideal location. For example, frequencies ranging roughly from 100 Hz to 8000 Hz are transmitted, even though the most apical electrode typically corresponds to a location associated with a characteristic frequency (CF) of approximately 290 Hz [1]

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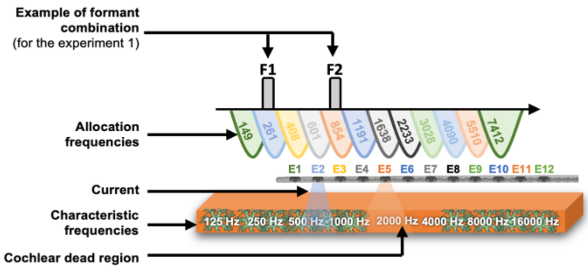

Figure 1. Simplified representation of cochlear implant processing illustrating the concepts of FTPM, poor ENI quality, and the functionality examined in Experiment 1. For FTPM, the illustration depicts a discrepancy between the allocated frequencies—the frequency information that is filtered and transmitted—and the characteristic frequencies—the cochlear regions typically responsible for processing those frequencies. Poor ENI quality is represented by missing neurons (i.e., a cochlear dead region). Its potential impact on transmission is illustrated by the wide current spread around electrode 5 (E5).

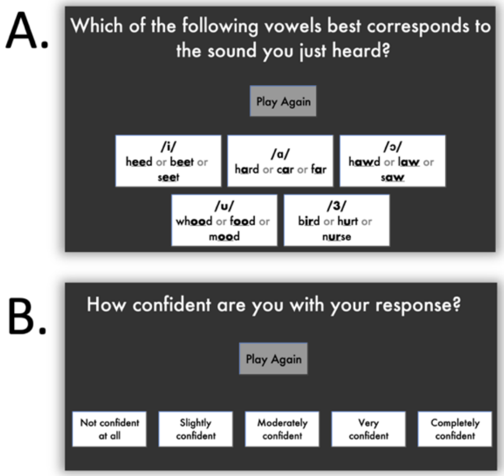

Figure 2. Illustration of the two consecutive questions presented during each trial in Experiment 1. Part A represents the identification task, while Part B assesses participants' confidence in their identification judgments.

(Figure 1). The term CF refers to the estimated frequency typically processed at a specific location within the cochlea. CF is determined through imaging methods such as computed tomography. Once estimated, the CF at the place stimulated by each electrode is compared to the allocated frequencies (AL) of each electrode—i.e., the frequencies around which information is extracted during CI processing—resulting in the FTPM value (Equation 1).

While most CI users experience some degree of FTPM, much remains unclear regarding its effects on perception and the adaptation process. This knowledge gap likely arises because the perceptual impact of FTPM varies significantly depending on the type of auditory signal. In speech understanding tasks, whether conducted in quiet or in noise, the long-term impact appears minimal [2]. However, FTPM has a more noticeable negative effect on sound quality, as indicated by one study [3]. The detrimental effects of FTPM are even more pronounced in music-related tasks such as pitch scaling, pitch discrimination, or melody recognition [4].

1.1 Experiment 1

The first experiment aims to explain how post-lingually deafened CI users with extensive implant experience process vowels in relation to the frequency distribution pattern imposed by FTPM. The experiment consisted of presenting combinations of first and second formants associated with a constant fundamental frequency (at 100 Hz). "The first formant ranged from approximately 230 Hz to 1720 Hz, and the second formant ranged from 415 Hz to 4000 Hz. Sounds were synthesized using the Parselmouth library, which enables the use of Praat directly within a Python environment.

For each combination, participants selected the perceived vowel from a closed-set list (/a/, /i/, /ɔ/, /u/, /ɜ/) and rated their confidence in their choice using a Likert scale. Using these two responses, individual perception heatmaps for each vowel were computed separately for each CI user. The same paradigm was performed with 10 normal-hearing (NH) listeners to create vowel reference heatmaps, which were then compared to CI users' individual heatmaps. The calculated shifts were then related to FTPM values to estimate the degree of adaptation to FTPM (see Equation 2).

1.2 Experiment 2

Experiment 2 builds on the findings from previous FTPM re-mapping studies that there are individual differences in the efficacy of the approach. One hypothesis is that adaptation depends not only on FTPM but also on the quality of the electrode-neuron interface (ENI).

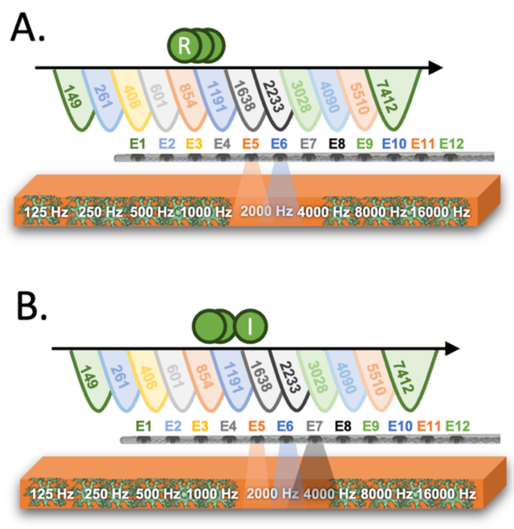

Figure 3. Illustration of an example chord pair used in Approach 2. Part A depicts the root chord, where the root note primarily stimulates electrode 5 (E5). Part B shows the inverted version of the chord, specifically stimulating electrode 7 (E7).

ENI quality describes how effectively the signal is transmitted between a specific electrode and targeted neurons. It encompasses factors such as the distance between the electrode and neurons, fibrosis around the electrode, current spread, and the number and health of stimulated neurons. Negative consequences of poor neural health have been documented for speech understanding [5].

To estimate the ENI quality of each electrode, we employed a method involving paired comparisons of chords. For each paired comparison, the root and inverted versions of a chord were presented to participants. Chords are musical units defined as combinations of notes that, when played together, are perceived as pleasant. In Western music, the most basic chord is a triad (consisting of three notes): a root note, a third interval, and a fifth interval. An inverted chord maintains the third and fifth interval notes, while the root is moved one octave higher. Theoretically, the root and its inversion differ slightly but should sound similarly pleasant. However, within paired comparisons and CI testing, differences in ENI quality at stimulation sites might influence participants' preferences between the root and inverted chords (see Figure 2). This hypothesis underlies the second approach described here: each pair of root/inverted chords was tailored to each

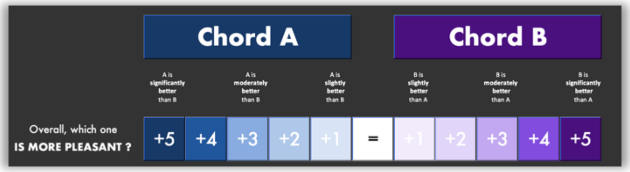

Figure 4. Illustration of the testing interface used in Experiment 2. After listening to each pair of chords—one root and one inverted—participants were asked to indicate which chord sounded more pleasant using this 10-option rating scale. Collected data were then analyzed using a Bayesian statistical model to estimate the pleasantness associated with each electrode.

CI user's mapping strategy, stimulating two different electrodes differently.

To validate this approach for estimating ENI quality, results from Experiment 2 were compared with the Panoramic ECAP (PECAP) method. The PECAP method uses forward-masked electrically evoked compound action potentials (ECAPs) to estimate neural activation patterns during CI stimulation. Specifically, PECAP provides estimations of current spread and neural health for each electrode along the cochlea.

$$FTPM = abs\left[\frac{log_{10}\left(\frac{CF}{AL}\right)}{log_{10}(2)}\right] \quad (1)$$

$$Shift = (Adaptation\ Completed) - FTPM \quad (2)$$

These experiments provide new tools for investigating how sound quality perception differs between NH and CI users. Initial results suggest that vowel perception in CI users may be shifted relative to NH listeners, potentially reflecting the influence of FTPM. The chord comparison task revealed variability across electrodes that could relate to differences in ENI quality and current spread. Further results, including detailed comparisons and relationships with neural health measures, will be presented at the conference.

2. REFERENCES

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