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Enhancing low-frequency perception through self-optimized phantom stimulation

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Objectives: Cochlear implant (CI) users often face challenges with speech understanding in noisy environments, the overall naturalness of sound, and music perception due to limited access to low-frequency hearing. To address this, a "Phantom" channel was developed to enhance low-frequency sound perception. This technique is based on the current steering concept and involves stimulating the two most apical electrodes with opposite-phase signals and varying amplitudes, effectively shifting the electric field deeper into the cochlea to create a localized pitch shift. The objectives of this study were to compare various settings aimed at optimizing this virtual Phantom channel for everyday listening situations and to evaluate a potential learning effect over time.

Methods: A total of 15 CI users, both unilateral and bilateral, participated in the study. The participants had a mean age of 60.0 years and an average CI usage duration of 8.1 years. The study involved adapting the CI programs through two methods: an electrical adjustment of the low-frequency channel, comparable to standard clinical adaptation, and a self-adjustment by participants for both speech comprehension and music listening using acoustic sound sample presentation. Word comprehension was assessed with the HSM sentence test under an individually set signal-to-noise ratio (SNR) with an interfering speaker, while speech intelligibility threshold (SRT) was measured using the Oldenburg sentence test (OLSA) in stationary noise. Additionally, hearing thresholds were recorded, and the CI settings were evaluated based on sound perception. The various study programs were compared to standard clinical fittings after extended adaptation phases lasting several weeks.

Results: The hearing threshold measurements indicate that frequencies as low as 125 Hz were transmitted across the study programs. In subjective evaluations, 80% of participants strongly preferred the program with the self-adjusted low-frequency channel. Preferences varied depending on the listening situation, with participants favoring either the speech-optimized or music-optimized program accordingly. There were no significant differences in speech comprehension found between the study programs and the standard clinical program.

Conclusion: Cochlear implant users strongly preferred the programs featuring the self-adjusted Phantom channel. This approach provided a noticeable improvement in sound perception without compromising speech comprehension.

KEYWORDS
cochlear implant, current steering, low-frequency perception, Phantom, self-optimization

Introduction

Cochlear Implants (CIs) as a standard treatment of severe to profound sensorineural hearing impairment allow for restoring speech understanding abilities in quiet (Wilson and Dorman, 2008; Rak et al., 2017) shortly after implantation. However, speech understanding in noise (Nelson et al., 2003), sound quality perception (Caldwell et al., 2017) as well as music appreciation remains limited for a large proportion of study participants (Kong et al., 2004). Reasons for these shortcomings are—among others—a low spectral resolution due to the limited number of electrodes or channels respectively, and a poor representation of low frequencies due to a frequency-place mismatch of the electrode contacts along with suboptimal stimulation paradigms. To overcome the limited number of channels in cochlear implants, Townshend et al. (1987) already suggested generating so-called virtual channels or pitches by simultaneous stimulation of two adjacent physical electrode contacts to increase the spectral resolution. The so-called current steering technique is possible if each electrode contact is driven by a separate current source. Stimulating two adjacent electrodes simultaneously results in an electric field that can be shifted between the contacts by adjusting the current ratio between the two electrodes. This method allows CI users to perceive intermediate pitches between the two physical contacts. Subsequent research demonstrated that many users could discriminate at least one virtual pitch, and some even up to 400 distinct pitch percepts (Brendel et al., 2009; Firszt et al., 2007). This current steering technology has been implemented in sound coding strategies, such as HiRes 120 by Advanced Bionics (Koch et al., 2007) to technically deliver up to 120 spectral channels resulting in an improved speech perception as well as music appreciation (Brendel et al., 2008; Firszt et al., 2009). Another limitation of CI systems has been their relatively narrow frequency range, originally based on the minimally acceptable telephone bandwidth of 300–3,400 Hz (ITU, 1988), which is sufficient for understanding speech in contextual situations. While extending the upper frequency limit to 8,000 Hz has clearly improved consonant perception, widening the bandwidth below 300 Hz has been shown to enhance the perception of naturalness in speech and music (Moore and Tan, 2003). The transmission of low-frequency information, either contralaterally via bimodal provision (CI in one ear and hearing aid in the other) or ipsilaterally via electro-acoustic stimulation (EAS; CI and hearing aid in the same ear), has proven beneficial for CI users, improving speech perception (Turner et al., 2004; Illg et al., 2014; Büchner et al., 2009), sound quality and music appreciation (Roy et al., 2012; Kong et al., 2005). Attempts to provide access to low-frequency information in CI users without residual hearing have included the use of longer electrode arrays inserted deeper into the cochlea. However, results have been mixed: some studies demonstrated improved speech understanding with deeper insertions (Büchner et al., 2017), while others found no significant effect of electrode position on outcomes (van der Marel et al., 2015; van der Jagt et al., 2016).

Most of today's cochlear implant systems provide monopolar electrical stimulation to the auditory neurons using an intracochlear electrode contact and an extracochlear ground electrode. With sound coding strategies like HiRes (16 channel strategy), HiRes 120 (current steering strategy) or HiRes Optima (strategy based on HiRes 120; Advanced Bionics, 2012) frequencies between 250 Hz and 8,000 Hz are processed in the Advanced Bionics CI system.

To extend the frequency range independently of electrode length and position, the current steering technique was adapted to develop a concept for eliciting pitches lower than those evoked by the most apical electrode contact of the array (Wilson et al., 1992). For this so-called "Phantom electrode stimulation" concept (Saoji and Litvak, 2010; Saoji et al., 2013) the electrical field of the stimulation is shaped toward the apical end of the cochlea by additionally applying a compensating current during stimulation of the most apical contact. Previous studies have investigated the effects of Phantom electrode stimulation on various aspects of auditory perception, including pitch discrimination, speech understanding, sound quality, and music appreciation. They showed the successful creation of lower pitch percepts via Phantom stimulation and the ability of CI users to discriminate between these pitches (Saoji and Litvak, 2010; Saoji et al., 2013; Nogueira et al., 2015; Klawitter et al., 2018; Luo and Garrett, 2020; Lamping et al., 2020). However, the lowest perceived pitch did not consistently correspond to the highest individual compensating current or the greatest estimated apical shift. In some CI users, increasing the compensating current even led to a pitch reversal, with percepts becoming higher rather than lower (Saoji et al., 2013; de Jong et al., 2020). Speech perception outcomes using Phantom sound processing did not show any significant improvement compared to the clinically used strategy (Nogueira et al., 2015; Carlyon et al., 2014) for CI users with electric stimulation only. However, as the acclimatization time to the modified hearing impression was limited, a longer adaptation phase for the new sound processing might be required to demonstrate improved outcomes in speech perception tests. For CI users with electric-acoustical stimulation, significantly improved speech perception abilities could be shown (Krüger et al., 2022). Prior investigations focusing on sound quality aspects showed improvements with Phantom stimulation in terms of vocal production (Caldwell et al., 2019) or music appreciation (Nogueira et al., 2015; Stein et al., 2017; Munjal et al., 2015).

One objective of this study was to investigate the role of adaptation time in the effectiveness of Phantom stimulation, using extended take-home phases with individualized programs. In addition, given the individual variability in optimal compensation currents observed in previous research, CI users were actively involved in the fitting process to explore the impact of personalized parameter optimization—specifically the compensation current and the most comfortable Phantom stimulation level (M-level). Speech perception, sound quality, and music appreciation were assessed through standardized listening tests and subjective ratings. A further aim was to explore whether the fitting process could be streamlined by identifying a generally effective default setting for the Phantom channel, potentially eliminating the need for individualized fitting. Therefore, the study examined correlations between optimal compensation settings and factors such as electrode position, compensation coefficient, and hearing thresholds.

Methods

Ethics

The study was approved by the local Medical Ethical Committee (Medical University of Hannover, 8241 BO S 2019) and conducted in accordance with the Declaration of Helsinki. All study participants provided written informed consent prior to participation and received compensation for traveling expenses.

Phantom electrode stimulation

Phantom electrode stimulation employs current steering techniques (Figure 1A). This involves the delivery of simultaneous biphasic pulses to two neighboring electrode contacts, namely the primary and compensating electrodes. One pulse begins with a cathodic phase and the other with an anodic phase, resulting in a deliberate shift of the electrical field. This shift occurs away from the compensating electrode and toward a more apical region, thereby enabling targeted modulation of neural activity. The resulting pitch shift can correspond to a shift between 0.08 and 2.01 physical contacts (Saoji and Litvak, 2010; Klawitter et al., 2018; de Jong et al., 2020). In practical terms, stimulation at the most apical contact can be shifted by up to two electrode positions, resulting in a lower pitch percept, corresponding to a difference of up to 5.4 semitones, as predicted by Greenwood's frequency-place function (Greenwood, 1996). The ratio of current delivered to the compensating vs. the primary electrode is described by the current compensation coefficient (σ). A value of $\sigma = 0$ corresponds to monopolar stimulation (only the primary electrode is active), while $\sigma = 1$ represents full compensation (equal current on both electrodes; Figure 1B).

Device programming

The participants in this study utilized their clinically established program, referred to as the "clinical program", which was fitted within the clinical routine using Advanced Bionics' fitting software SoundWave. This clinical program served as reference for evaluations. All study participants used the Naída CI sound processor(s) clinically and were equipped with a Naída CI Q90 research processor for the course of the study. The omni-directional microphone T-Mic (Gifford and Revit, 2010) was used as their standard microphone option. As part of the fitting process, the functionality of the T-Mic was systematically examined, and any units found to be faulty were replaced prior to further testing. The clinical sound coding strategy employed was HiRes Optima. Additionally, the signal enhancement algorithm ClearVoice was configured according to each participant's clinical fitting and maintained at their individually preferred setting (off, low, medium, or high) throughout the study. It is noteworthy that no directional microphone settings were applied during this study.

All parameters were transferred from the clinical program to the research software BEPS+ (Bionic Ear Programming Software). Two different variants of the Phantom electrode stimulation were programmed in the study, both using the frequency band of 102 to 238 Hz for the Phantom channel. However, four of the 15 study participants were accidentally fitted with a frequency band of 34 Hz–238 Hz (ID 03, ID 04, ID 06, ID 07) during the first appointment. For the first take-home phase, a standard Phantom program, referred to as "Phantom basic", was used. This version employed a compensation coefficient (σ) of 0.5. The most comfortable level (M-level) of the Phantom channel was adjusted to match the loudness of the surrounding physical electrodes, using the routine clinical loudness balancing procedure. The threshold levels (T-levels) were set at 10% of M-levels as in the CI user's clinical programs. This standardized approach allowed for a quick first impression of low-frequency hearing and was followed by an adaptation phase.

The second fitting was done acoustically via a more intensive self-adjustment procedure in two steps. First, the study participants adjusted the M-level of the Phantom channel via a graphical user interface with a slider that controls the M-Level of the Phantom channel in BEPS+, while listening to sound samples presented in free-field from one loudspeaker in the front. The entire map was active, i.e. in live speech mode. The adjustment was conducted across four different sigma values (0.375, 0.5, 0.625, 0.75) and five listening conditions: own voice (talking live), audiobook with male voice, audiobook with female voice, pop music, classic music, resulting in 20 program variants in total.

Second, participants rated the sound quality of these programs on a scale of 0 (very poor) to 100 (very good), while listening to the same sound samples. For the sound quality ratings, a modified MUSHRA-like procedure (Multi-Stimulus Test with Hidden Reference and Anchor) was used, adapted here without reference or anchor stimulus, where study participants could switch between programs and assign scores using a slider on a touchscreen tablet. Based on the ratings of the study participants, two programs were selected for the take-home phase: "Phantom individual speech" (based on the highest average score for the three voice sound samples) and "Phantom individual music" (based on the highest average score for the two music sound samples). In case of similar ratings for more than one map, a decision for one setting was taken based on the feedback of the study participant in a direct comparison. For two cases (ID 08 left and ID 10 left), participants received the Phantom individual speech program with the second-highest score, as this provided a better match within their bilateral configuration. So, in total, three different Phantom maps were used in the study: (i) Phantom basic, using a conventional fitting procedure, (ii) Phantom individual speech, and (iii) Phantom individual music, both from a self-adjustment approach while listening to samples in live speech mode.

Study design

An uncontrolled open design with within-subject comparisons was implemented to minimize the impact of subject-specific factors, such as age, cognitive capabilities, or a history of hearing impairment, on the investigation outcomes. This design was chosen to allow for a comprehensive evaluation while considering

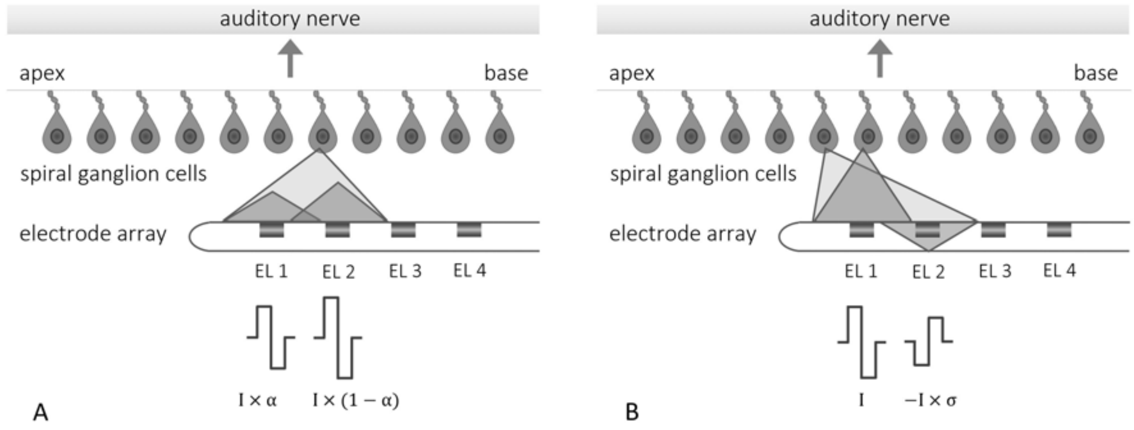

FIGURE 1
Principle of the sound processing current steering **(A)** and phantom stimulation **(B)**; dark gray triangles indicate the electrical fields evoked by simultaneous stimulation of electrodes 1 and 2 (current steering: in-phase, phantom stimulation: out-of-phase), light gray triangles indicate the overlaid electrical field and the resulting position of pitch perception on the auditory nerve. EL, electrode contact; *I*, current; σ, current compensation coefficient.

individual variations among participants. The study involved participants attending four appointments at the center, providing a structured framework for data collection and analysis. This approach enhances the reliability of the findings by enabling within-subject comparisons and effectively addressing potential confounding variables.

Appointments

During the first appointment, the participants' clinical program was evaluated to establish a reference for comparison. Speech perception, hearing thresholds, and subjective sound quality ratings were assessed. For the subsequent take-home phase of 2–4 weeks, the study processors were programmed with the Phantom basic setting, based on a conventional fitting procedure. No other program was available on the device during this period. The purpose of this phase was to familiarize participants with the general sound impression of Phantom stimulation.

At the second appointment, speech perception and hearing thresholds were re-assessed using the Phantom basic setting. For the following take-home phase (lasting 4–6 weeks), participants received individually fitted Phantom individual speech and Phantom individual music programs based on their prior self-adjustment session. Again, only these programs were active on the study device during this period.

During the third appointment speech perception measures and hearing thresholds were repeated using the Phantom individual speech setting. For the following 4–6 weeks take-home phase study devices were programmed with the four different settings: (i) Phantom individual speech, (ii) Phantom individual music, (iii) Phantom basic, and (iv) clinical program. Study participants were instructed to switch and compare, single-blinded, the programs in their various listening situations.

At the fourth and final appointment, speech perception measures were repeated for the three settings: (i) Phantom individual speech, (ii) Phantom basic, and (iii) clinical program.

Throughout all take-home phases, subjective feedback was collected as absolute quality ratings for each program. Due to the repeated use of each strategy across multiple take-home periods, participants had ample opportunity to acclimatize to the different stimulation settings. This ensured a realistic and ecologically valid comparison between the clinical baseline and the various Phantom stimulation programs.

Figure 2 shows the sequence of appointments and the respective assessments as well as fittings.

During each appointment, the order of measurement types was randomized to prevent potential procedural bias. In the final appointment, the sequence of the three programs under investigation was also randomized for the speech perception testing. This randomization of test procedures and program order helped minimize the influence of external factors and supported a robust, unbiased assessment of the study variables.

Study group

A total of 15 postlingually deafened participants (twelve male, three female) were enrolled in this clinical study. Six participants were unilaterally implanted and nine were bilaterally implanted, resulting in a total of 24 cochlear implants.

One participant (ID 06) withdrew from the study prior to the final appointment. Another participant (ID 13) received a second implant shortly before the first appointment, after study enrollment; thus, implant experience for this ear was less than 6 months at the time of testing.

At enrollment, the average age was 60.0 years (range: 22.9–84.1 years). The average duration of implant use was 8.1 years (range: 0.1–20.6 years), the average duration of hearing impairment was 32.7 years (range: 10.3–69.1 years), and the average duration of deafness was 4.5 years (range: 0.0–37.1 years). Etiologies of deafness included sudden hearing loss ($n = 6$), meningitis ($n = 2$), genetic causes ($n = 1$), and unknown

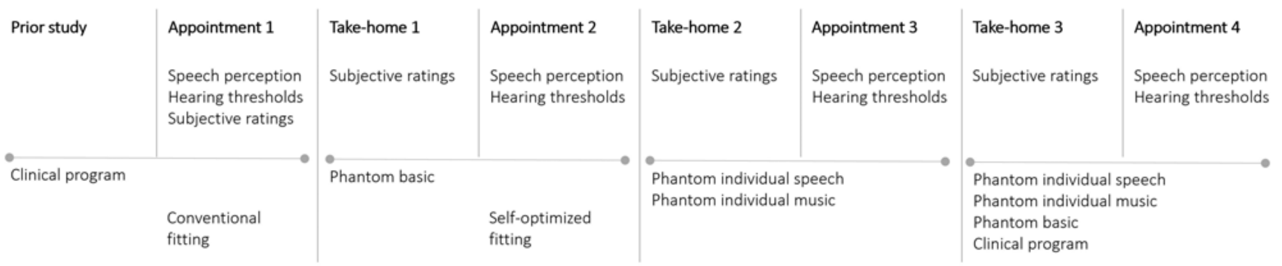

FIGURE 2
Study design showing the assessments and fitting procedures during the appointments and the take-home phases as well as the programs under investigation.

TABLE 1 Demographical data of study participants.

ID	Gender	Age [yrs]	Implant|electrode|# of deactivated electrodes		Duration of implant use [yrs]		Duration of hearing impairment [yrs]		Duration of deafness [yrs]	
			Left	Right	Left	Right	Left	Right	Left	Right
ID 01	Male	70.11		HR 90K|Helix		15.43		69.11	69.11	21.53
ID 02	Male	76.86		HR 90K|Helix		10.64	11.63	66.58	11.55	
ID 03	Male	22.85	HR 90K|Helix		20.61					
ID 04	Male	60.96		HR 90K|Helix		10.18	11.53	10.34		10.34
ID 05	Male	33.23	HR Ultra|HF SlimJ	HR Ultra|HF SlimJ	1.99	1.16	33.23	33.23	1.99	
ID 06	Female	62.89	HR 90K|Helix	HR 90K|Helix|#12	12.92	11.35	55.84	55.84	12.92	12.90
ID 07	Male	54.97	CII|HF 1j		18.69		54.97	54.97	22.47	
ID 08	Male	68.78	HR 90K Adv|HF ms	HR 90K Adv|HF ms	5.29	6.79	38.89	39.89	7.45	7.45
ID 09	Male	62.76	HR 90K|Helix|#14.15	HR 90K|Helix|#15.16	12.88	9.02	25.84	29.85		18.84
ID 10	Male	84.08	HR 90K|Helix	HR 90K|Helix|#3	11.89	11.89	11.99	11.99	11.99	11.99
ID 11	Female	38.15	HR Ultra|HF ms	CII|HF 1j|#16	1.81	19.15	38.15	38.15		19.95
ID 12	Male	68.20	HR Ultra|HF ms		3.03		53.12		40.11	
ID 13	Male	64.36	HR 90K Adv|HF ms	HR 90K Adv|HF ms	0.14	3.79	24.06	24.06		
ID 14	Male	72.60	HR Ultra|HF SlimJ|#15.16	HR Ultra3D|HF SlimJ|#15.16	2.63	0.64	15.32	15.32	3.22	
ID 15	Female	58.88	HR Ultra3D|HF SlimJ|#15.16	HR Ultra3D|HF SlimJ|#15.16	0.64	1.38	13.33	13.33		

yrs, years; HR, HiRes; HF, HiFocus; Adv, advantage; ms, mid-scala.

causes ($n = 6$). Detailed demographic information is provided in Table 1. Unilateral participants had a profound hearing loss of at least 70 dB across the frequencies 125 Hz−8 kHz, with one exception being ID 04 with 50 dB at 250 Hz and 60 dB at 500 Hz, on the contralateral ear. None of the participants used a hearing aid.

Hearing thresholds

Aided thresholds were measured in free field using warble tones at the frequencies: 125, 250, 500, 750, 1k, 1.5k, 2k, 3k, 4k, 6k and 8 kHz for the different test conditions after the respective take-home phases.

Electrode insertion depth

The electrode insertion depth was determined retrospectively based on post-operative CT (computer tomography) images and place pitch frequencies were calculated following Greenwood and the Stakhovskaya correction (Stakhovskaya et al., 2007). Table 2 shows individual data.

Speech perception

All tests were conducted in a sound-treated room. Participants were seated facing a single loudspeaker positioned at 0° azimuth (S_0N_0) at a distance of 1.1 m from the head. Both the target speech signal and the interfering noise were presented from

TABLE 2 Electrode insertion depth and corresponding characteristic frequency for $N = 14$ cochlear implants of eight study participants and their favored sigma setting for the sound coding strategies Phantom individual speech/music.

ID	Insertion depth [°]	Characteristic frequency [Hz]	σ of phantom individual speech	σ of phantom individual music
ID 02|right	370	734.9	0.625	0.625
ID 05|right	412	637.8	0.375	0.5
ID 05|left	377	718.7	0.375	0.625
ID 08|right	369	737.2	0.5	0.5
ID 08|left	350	844.8	0.5	0.5
ID 09|right	396	674.8	0.625	0.5
ID 09|left	373	728.0	0.625	0.375
ID 11|right	372	730.3	0.75	0.5
ID 11|left	350	844.8	0.375	0.625
ID 12|left	377	718.7	0.625	0.625
ID 14|right	355	801.4	0.375	0.75
ID 14|left	339	940.2	0.5	0.375
ID 15|right	360	758.0	0.375	0.375
ID 15|left	405	654.0	0.625	0.5

this loudspeaker. Speech perception in noise was measured using the Hochmair-Desoyer, Schulz, Moser (HSM) sentence test (Hochmair-Desoyer et al., 1997) in German language. The target speech was presented at 65 dB SPL (conversational level), and the interfering talker noise (Illg et al., 2014) was presented at one of three fixed signal-to-noise ratios (SNRs): 0, 5, or 10 dB. This fixed SNR was selected based on the participant's performance with their clinical program, targeting 40–60% correct word recognition, and was kept constant across all test conditions. Two sentence lists were administered per condition. The percentage of correctly identified words was calculated for each list, and the average of both lists was used as the final score for that condition. To obtain a further measure of speech perception in noise, the adaptive Oldenburg Sentence Test (OLSA) in German was also administered (Wagener et al., 1999). In this test, the speech level was adaptively adjusted to determine the speech reception threshold (SRT)—defined as the SNR required for 50% correct word recognition—while the stationary noise level was kept constant at 65 dB SPL. Each condition included two OLSA lists (20 sentences each), and the SRTs from both lists were averaged to yield the final SRT per condition.

Both speech perception tests (HSM and OLSA) were performed during the first three appointments following the take-home phase of the respective setting, the HSM was repeated for the clinical as well as both Phantom settings at the fourth appointment as direct comparison.

Subjective ratings

To investigate subjective perception with the four different programs in everyday life, a short version of the Speech, Spatial and Qualities of Hearing scale (SSQ-12, Gatehouse and Noble, 2004; Noble et al., 2013) was completed; questions are listed in Supplementary Table 5. Study participants were asked to rate their hearing abilities on an 11-point Likert scale from 0 (very poor/strong/mixed) to 10 (very good/weak/not mixed). In addition, participants completed a custom questionnaire that addressed specific aspects of sound quality based on findings from previous studies. This questionnaire used the same 11-point scale, and the individual items are listed in Supplementary Table 6. Both questionnaires were completed during the first appointment for the clinical program as well as during the upcoming take-home phases for Phantom basic and Phantom individual speech/music. During the last take-home phase, study participants were asked to compare all four programs and indicate their most favorite program for the respective items of the questionnaire. If no single program was preferred across all categories, preferences were allowed to vary between subcategories (e.g., speech, music, or environmental sounds), resulting in a distribution of votes across different programs.

Statistical analysis

As data are not normally distributed and compared within one study participant over the course of the study, the Wilcoxon signed-rank test for dependent samples was used and a Bonferroni *post-hoc* correction was applied. With a p-value below 0.05, differences were considered statistically significant. Data was analyzed using Statsoft Statistica.

Results

Hearing thresholds

Hearing thresholds show a difference in perception for a frequency of 125 Hz (Figure 3). While there is

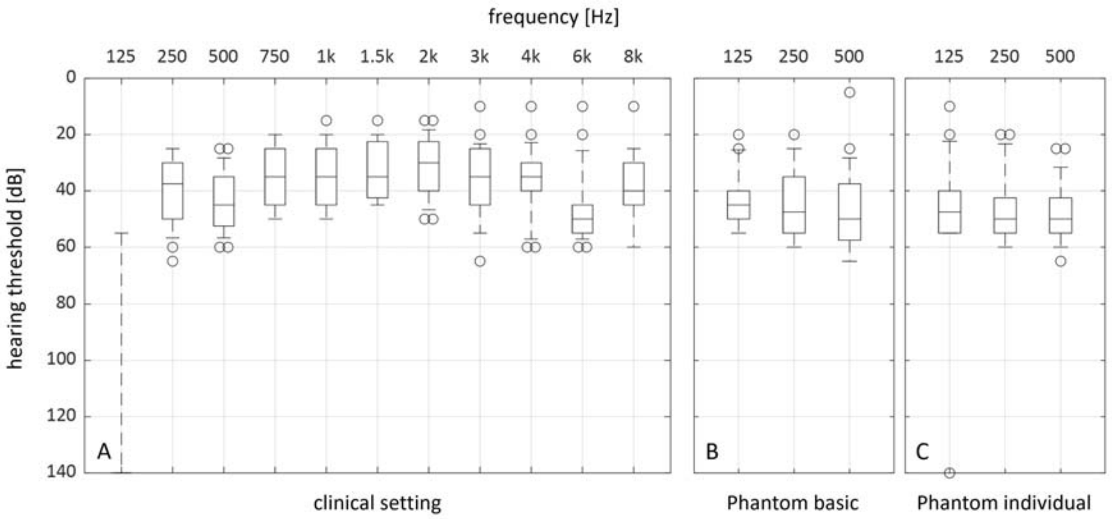

FIGURE 3
Aided hearing thresholds measured with the clinical setting **(A)**, phantom basic **(B)**, phantom individual **(C)**. Line = median, box = quartiles 25% and 75%, circle = outlier, whisker = 1.5 × IQR (interquartile range).

no perception of this frequency possible with the use of the clinical program, with both Phantom programs the frequency was perceived equally as the higher neighboring frequencies.

Individualized fitting

Self-adjusted M-levels (Figure 4) showed consistent effects of the compensation coefficient (σ) across different sound samples.

The following statistically significant differences were observed, with "$>$" indicating significantly higher M-levels between the conditions listed (p-values in parentheses):

- Own voice:
    - $\sigma = 0.75 > \sigma = 0.375$ ($p < 0.001$),
    - $\sigma = 0.75 > \sigma = 0.5$ ($p < 0.001$),
    - $\sigma = 0.75 > \sigma = 0.625$ ($p < 0.05$),
    - $\sigma = 0.625 > \sigma = 0.375$ ($p < 0.05$),
    - $\sigma = 0.5 > \sigma = 0.375$ ($p < 0.05$).
- Female voice:
    - $\sigma = 0.75 > \sigma = 0.375$ ($p < 0.05$),
    - $\sigma = 0.625 > \sigma = 0.375$ ($p < 0.05$),
    - $\sigma = 0.5 > \sigma = 0.375$ ($p < 0.001$).
- Male voice:
    - $\sigma = 0.75 > \sigma = 0.375$ ($p < 0.05$),
    - $\sigma = 0.75 > \sigma = 0.5$ ($p < 0.05$),
    - $\sigma = 0.75 > \sigma = 0.625$ ($p < 0.05$).
- Pop music:
    - $\sigma = 0.75 > \sigma = 0.375$, $\sigma = 0.5$, and $\sigma = 0.625$ (all $p < 0.05$),
    - $\sigma = 0.625 > \sigma = 0.375$ ($p < 0.05$),
    - $\sigma = 0.5 > \sigma = 0.375$ ($p < 0.05$).
- Classical music:
    - $\sigma = 0.75 > \sigma = 0.375$ and $\sigma = 0.5$ (both $p < 0.05$),
    - $\sigma = 0.625 > \sigma = 0.375$ ($p < 0.05$),
    - $\sigma = 0.5 > \sigma = 0.375$ ($p < 0.05$).

No significant differences were found between $\sigma = 0.5$ and $\sigma = 0.625$ for any of the sound samples. Absolute mean and median values, standard deviations and significance levels are shown in Supplementary Table 3.

Individual results of the average sound quality ratings for speech and for music are shown in Supplementary Table 4. The scores vary for the individual study participants; however, the group results showed no significant differences, except one. The male voice was rated significantly higher ($p < 0.05$) for $\sigma = 0.625$ compared to $\sigma = 0.375$.

Based on individual sound quality ratings, a specific σ value (Supplementary Table 4) and corresponding M-level were selected for each of the 24 ears. The distribution of selected σ values was as follows:

- $\sigma = 0.375$: 11 times (7 for speech, 4 for music),
- $\sigma = 0.5$: 12 times (6 for speech, 6 for music),
- $\sigma = 0.625$: 21 times (9 for speech, 12 for music),
- $\sigma = 0.75$: 4 times (2 for speech, 2 for music).

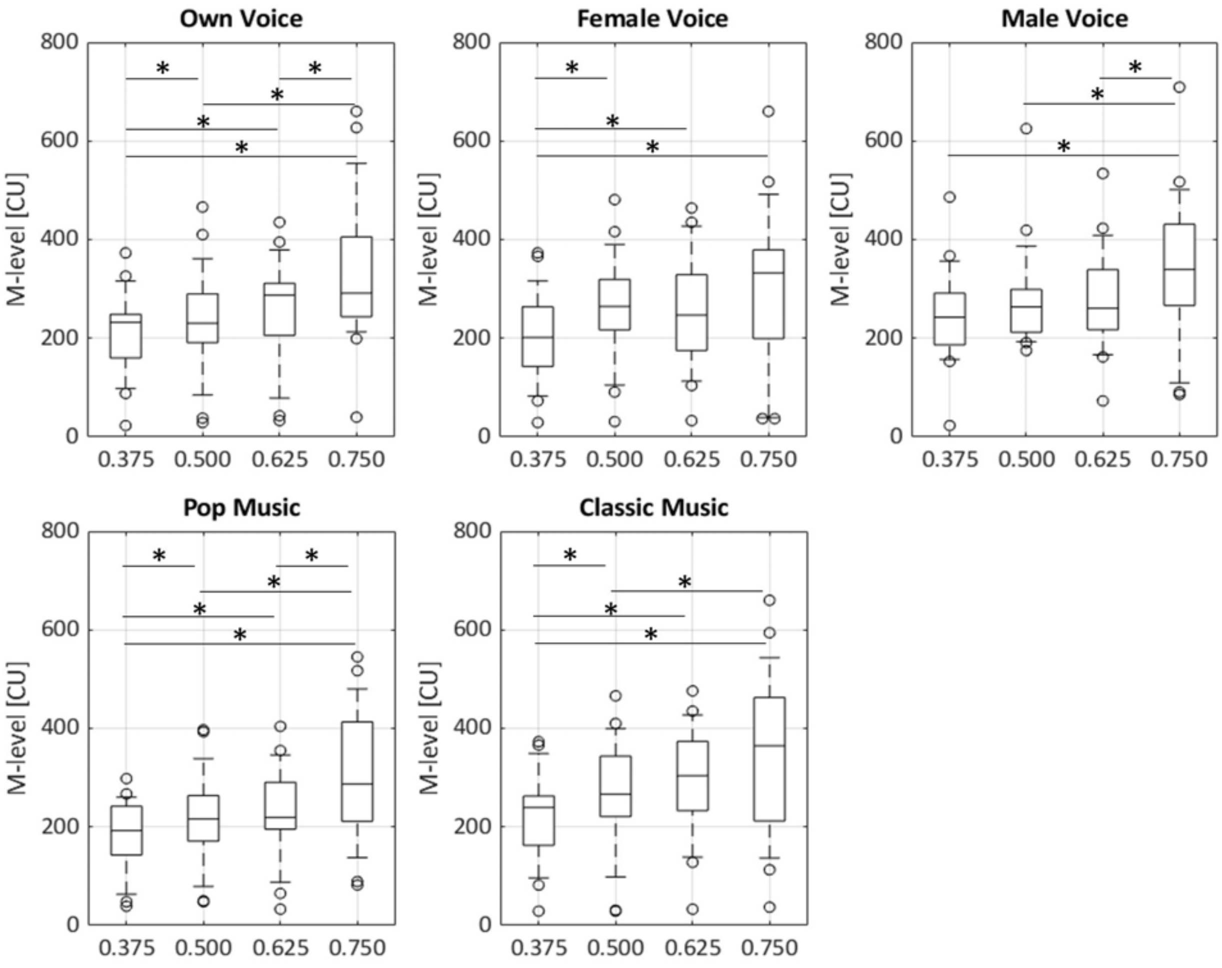

FIGURE 4
Individual M-levels self-adjusted for the four sigma values (0.375, 0.5, 0.625, 0.75) of the phantom channel, each for the five sound samples (own voice, female voice, male voice, pop music, classic music) presented in free-field. Line = median, box = quartiles 25% and 75%, circle = outlier, whisker = 1.5 × IQR (interquartile range), stars indicate significant differences with $p < 0.05$.

In nine cases, the same σ value was selected for both speech and music. In five cases, a higher σ was preferred for speech than for music, and in ten cases, the reverse was true. For bilaterally implanted participants, σ settings could differ between ears. Figure 5 displays the M-levels [CL] of the Phantom channel across different fitting strategies. The first violin plot (black) represents the Phantom basic fitting ($\sigma = 0.5$). The next eight plots (shaded gray) show self-adjusted Phantom programs, with four σ-values each for speech (left group) and music (right group). These represent the M-levels selected by participants during the self-adjustment procedure. The remaining 15 plots (light gray) show the M-levels for virtual stimulation sites located between physical electrode contacts, for comparison. Electrically fitted Phantom channels (Phantom basic) are shown for all 24 ears. Acoustically fitted channels (Phantom individual speech/music) are shown only for those ears in which the corresponding programs were selected for the take-home phase. The number of ears included in each condition (N) is indicated above the plots and reflects the distribution of individually preferred programs.

Electrode insertion depth

Based on CT images for 14 cochleae of eight study participants the electrode insertion depth and the respective characteristic frequency was determined following Greenwood and the Stakhovskaya correction (Stakhovskaya et al., 2007) and correlated with the sigma setting in the programs Phantom individual speech/music. No significant correlation could be found between the insertion depth and the optimized sigma value.

Speech perception

Speech perception scores measured during appointments 1–3 via the HSM sentence test showed comparable performance across the three programs in the HSM test (Figure 6A):

- Clinical program: median = 50.0%, mean ± SD = 47.2 ± 16.7%,

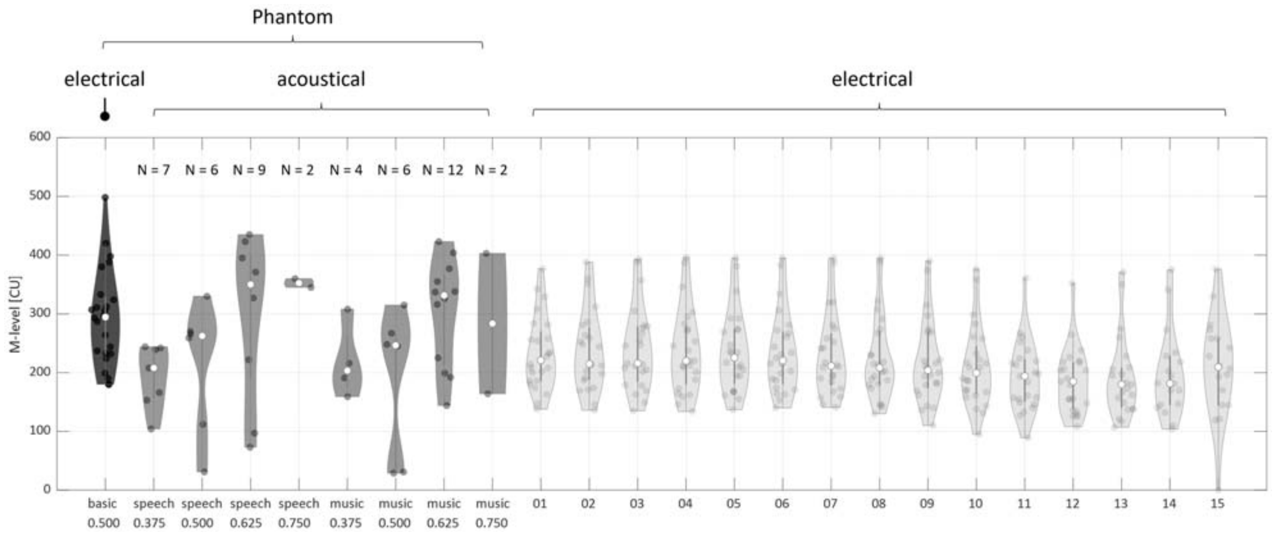

FIGURE 5
Group values of M-levels for the 15 stimulation sites ($N = 24$) as well as the electrically fit phantom basic channel and the self-adjusted (acoustically fitted) phantom individual speech/music channels. M-levels represent the maps used during the take-home phases.

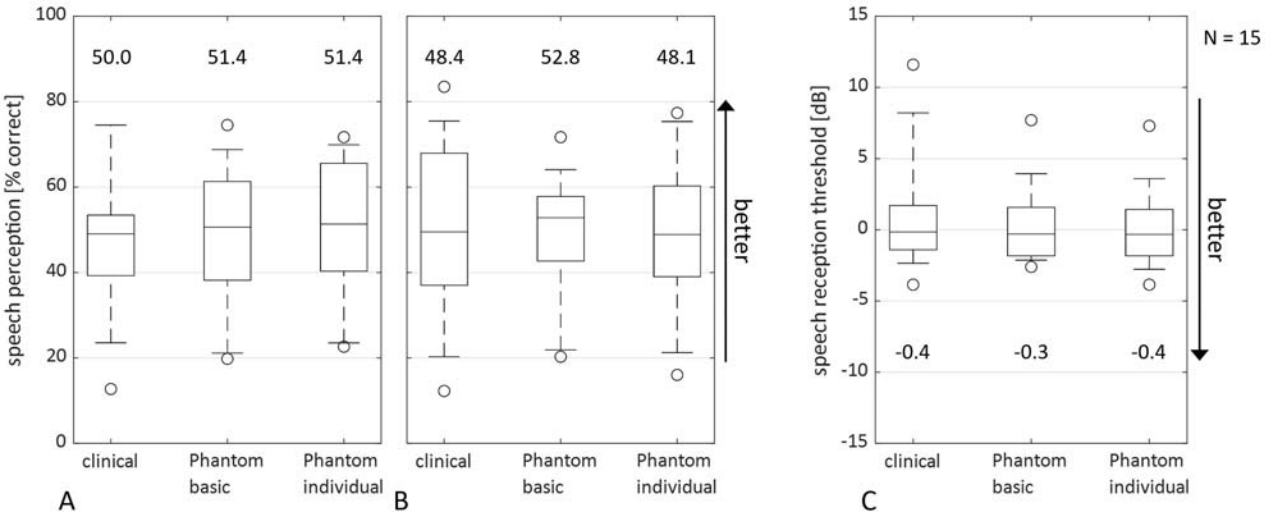

FIGURE 6
Speech perception scores measured via the HSM sentence test in % correct during appointments 1–3 **(A)**, during appointment 4 **(B)** and speech reception thresholds measured via the OLSA matrix test in dB during appointments 1–3 **(C)** for the three conditions (i) clinical program, (ii) Phantom basic, (iii) Phantom individual speech. Line = median, box = quartiles 25% and 75%, circle = outlier, whisker = 1.5 × IQR (interquartile range).

- Phantom basic: median = 51.4%, mean ± SD = 49.8 ± 16.5%,
- Phantom individual speech: median = 51.4%, mean ± SD = 51.3 ± 16.2%.

At appointment 4, when all three programs were tested within a single session (Figure 6B), results remained similar:

- Clinical program: median = 48.4%, mean ± SD = 50.0 ± 20.6%,
- Phantom basic: median = 52.8%, mean ± SD = 48.1 ± 16.1%,
- Phantom individual speech: median = 48.1%, mean ± SD = 48.9 ± 19.0%.

Speech reception thresholds (SRTs) obtained during appointments 1–3 using the OLSA matrix test (Figure 6C) also showed no meaningful differences:

- Clinical program: median = −0.4 dB, mean ± SD = 0.9 ± 4.1 dB,
- Phantom basic: median = −0.3 dB, mean ± SD = 0.3 ± 2.8 dB,
- Phantom individual speech: median = −0.4 dB, mean ± SD = 0.0 ± 2.8 dB.

Across all conditions, no statistically significant differences were observed in HSM or OLSA test results between appointments 1–3 and appointment 4.

Participants who had been fitted with a broader Phantom frequency band of 34–238 Hz instead of 102–238 Hz (IDs 03, 04, 06, and 07) showed no difference in speech perception outcomes compared to the rest of the cohort. This suggests that extending the Phantom channel toward lower frequencies in these cases did not influence speech understanding performance.

Subjective ratings

The results of the SSQ-12 questionnaire, administered during both the initial appointment and the first take-home phase, revealed consistent scores across all 12 questions, as illustrated in Supplementary Table 5. However, when comparing the results of the SSQ-12 questionnaire completed during the first appointment with those from the second take-home phase, notable differences emerged in the scores for individual questions, as depicted in Figure 7.

The Phantom individual speech program was rated significantly better compared to the clinical program for following a one-on-one conversation while following news on TV ($p < 0.05$, QST 2), while other people are talking in the same room ($p < 0.05$, QST 3), while following a group conversation ($p < 0.05$, QST 4). Study participants also rated the ability to tell the distance ($p < 0.05$, QST 7) and the moving direction ($p < 0.05$, QST 8) of a vehicle significantly higher as well as the hearing impression in case of several sounds at a time ($p < 0.05$, QST 9). The ability to make out which instruments are playing when listening to music was rated significantly better with the Phantom individual speech program compared to the clinical program ($p < 0.05$, QST 10). Looking into the comparison between the clinical program and the Phantom program optimized to music perception, there was also a significantly better rating for Phantom ($p < 0.05$). Detailed results are shown in Supplementary Table 5.

The findings from the custom questionnaire, administered during the first appointment and the first take-home phase (comparing clinical baseline vs. Phantom basic), demonstrated uniform scores for all questions, except for the rating on average music perception. Notably, Phantom basic received significantly higher ratings compared to the clinical program ($p = 0.041$, QST 4). A detailed breakdown of the results is presented in Supplementary Table 6.

Conversely, when comparing the custom questionnaire results from the first appointment with those from the second take-home phase (Phantom individual speech vs. clinical baseline), significant differences emerged in the scores for individual questions, as illustrated in Figure 8.

The Phantom individual speech program was rated significantly better compared to the clinical program for discrimination between voices ($p = 0.010$, QST 3) and music perception ($p = 0.014$, QST 5). Study participants rated all three parts of discriminating voices significantly better with Phantom individual speech compared to the clinical program: female/male voice ($p = 0.023$), multiple female ($p = 0.021$) and multiple male ($p = 0.007$). For listening to music two of the sub-questions were rated better: lyrics recognition ($p = 0.013$) and overall impression ($p = 0.008$). The sub-question related to influence of noise of multiple speakers on speech understanding was rated better with Phantom individual speech compared to the clinical program ($p = 0.034$). Detailed results are shown in Supplementary Table 6.

The results of the comparative SSQ-12 questionnaire, illustrated in Figure 9, showed an average percentage of study participants of 69.0% selecting the Phantom individual speech program as their clear favorite program when following an one-to-one conversation while the TV is on, 61.1% while the TV is presenting news, 48.8% while several people are talking in the same room, 53.0 when following a conversation of five people in a restaurant, 59.5% in a group with switching speaker, 56.4%

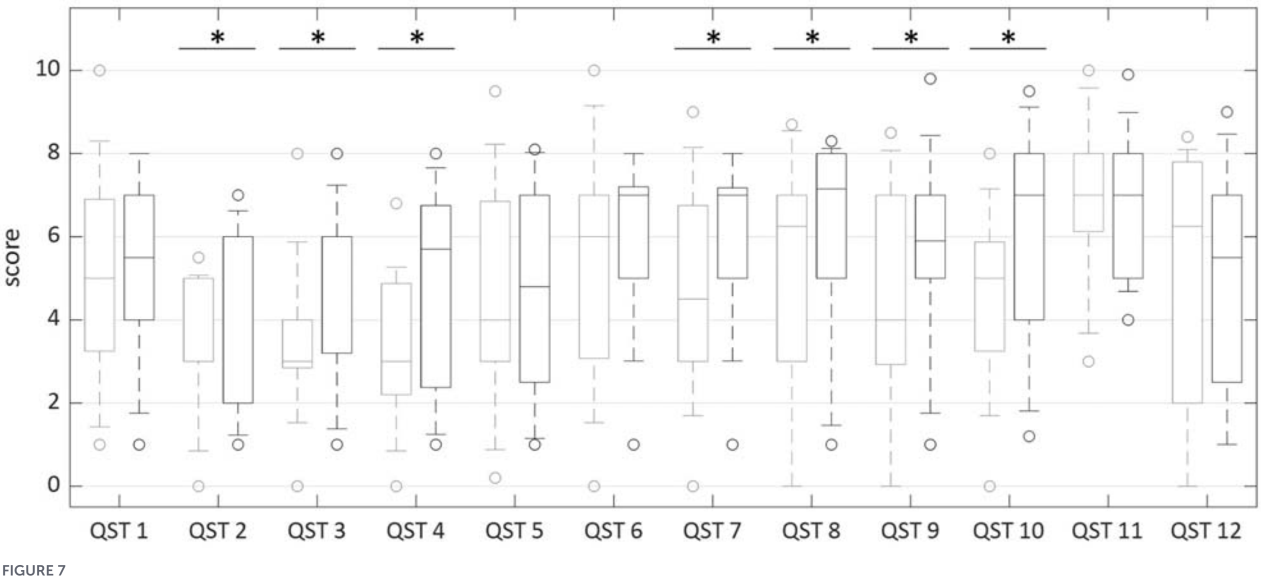

FIGURE 7
Subjective feedback collected via the SSQ-12 questionnaire for the clinically used program (gray) and for the Phantom individual speech program (black) used during the second take-home phase. Line = median, box = quartiles 25% and 75%, circle = outlier, whisker = 1.5 × IQR (interquartile range), stars indicate significant differences with $p < 0.05$.

for localization abilities when a dog is barking outside, 56.9% for distance or direction recognition of a bus or lorry, 58.3% for clarity of everyday noises and 65.5% for the ability to concentrate. For instrument recognition while listening to music 73.8% selected the Phantom individual music program as their clear favorite. Details are shown in Supplementary Table 7.

The results of the comparative custom questionnaire, illustrated in Figure 10, showed an average percentage of study participants of 66.3% selecting the Phantom individual speech program as their clear favorite program in terms of naturalness of voices, 71.0% for the ability of differentiation between multiple voices and 61.5% for the capability to deal with the influence of noises. There is no favorite program on average for the echo of different voices. For music appreciation 55.0% rated the Phantom individual music program as their favorite. As an overall favorite program Phantom individual speech was selected by 56.0% of the study participants. Details are shown in Supplementary Table 8.

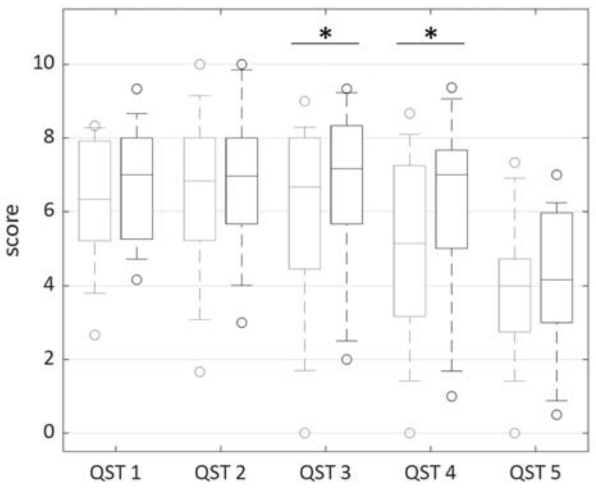

FIGURE 8
Subjective feedback collected via the custom questionnaire for the clinically used program (gray) and for the Phantom individual speech program (black) used during the second take-home phase. Line = median, box = quartiles 25% and 75%, circle = outlier, whisker = 1.5 × IQR (interquartile range), stars indicate significant differences with $p < 0.05$.

Discussion

This study evaluated two different Phantom stimulation strategies—one conventionally fitted (Phantom basic) and one self-adjusted by the user (Phantom individual)—in comparison to each participant's clinical program. Both Phantom programs extended stimulation below 250 Hz, providing low-frequency information at hearing thresholds comparable to those of adjacent frequency bands in conventional speech coding strategies. Objective speech perception outcomes did not differ significantly between the three programs, regardless of whether participants had used only a single setting or were able to compare multiple programs directly after extended take-home phases. These results are consistent with prior studies reporting similar speech understanding with and without Phantom stimulation (Nogueira et al., 2015; Carlyon et al., 2014). For example, Nogueira et al. (2015) observed improved speech perception after 4 weeks of Phantom use, which they attributed to acclimatization, but did not include an acute comparison. In the present study, no such learning effect was observed across repeated test sessions, and participants reported adaptation times similar to those experienced with routine changes to clinical settings. While speech recognition outcomes remained stable, subjective ratings revealed distinct advantages of the Phantom programs, particularly Phantom individual, in domains such as sound quality, voice separation, and music appreciation. Participants noted a clearer perception of low-frequency machine sounds (e.g., engine noise), improved discrimination between female and child voices, and more natural listening experiences. These impressions were reflected in questionnaire scores showing significantly better ratings for voice separation, music clarity, and listening in complex environments. For example, SSQ-12 and custom questionnaire items assessing speech understanding in background noise or crowded situations showed improvements with the individualized Phantom settings. Participants often described music as "very different," and in many cases "better" than with their standard clinical program. Enhanced recognition of melodies and lyrics was also supported by significant improvements in related questionnaire items. Although one participant described a low-frequency "roaring" quality as unpleasant with specific Phantom settings, others emphasized that even marginal losses in speech clarity were offset by superior sound quality. In two cases, family members or friends reportedly noticed improved

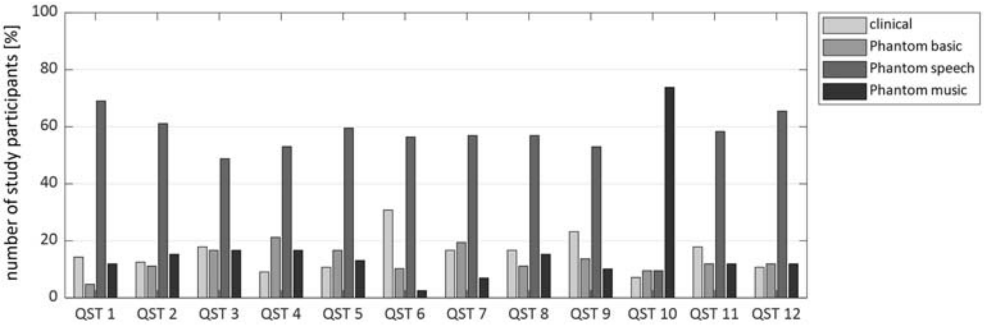

FIGURE 9
Subjective feedback collected via the comparative SSQ-12 questionnaire: number of study participants in percentage choosing the favorite program for different situations.

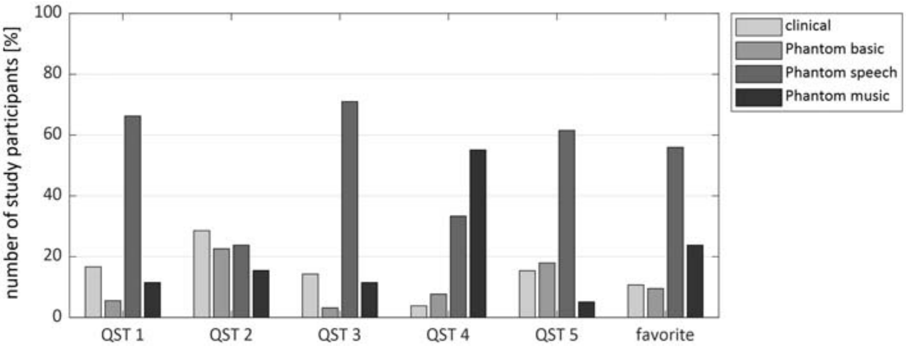

FIGURE 10
Subjective feedback collected via the comparative custom questionnaire: number of study participants in percentage choosing the favorite program for different aspects as well as the favorite program overall.

communication, further underscoring the real-world impact of sound quality on perceived benefit. Previous studies commonly employed a lower cutoff frequency of 34 Hz and σ values of 0.5 or 0.625, but occasionally reported issues such as echo-like effects, especially in response to one's own voice. Informed by these observations, the present study used a cutoff frequency of 102 Hz for most participants to reduce the likelihood of such artifacts while preserving low-frequency benefit. Notably, participants who received the broader 34–238 Hz Phantom band in this study did not report higher rates of echo or discomfort, and their subjective ratings were comparable to those of the 102 Hz group. Still, given that many low-frequency environmental sounds—such as engine rumble, HVAC systems, and building vibrations—fall below 100 Hz and carry no speech-relevant information, limiting the stimulation range to frequencies above 100 Hz appears sensible. This approach is also supported by Arakawa (1976), who reported that excessive low-frequency amplification in hearing aids, particularly in classroom-like environments, could interfere with speech perception by masking important acoustic cues. Thus, the choice of a 102 Hz lower cutoff in the present study strikes a balance between preserving the benefits of low-frequency stimulation and minimizing the risk of perceptual masking or acoustic artifacts. A central innovation of this study was the implementation of an acoustic self-adjustment procedure, allowing participants to optimize both σ and M-level using sound samples from everyday listening situations. This enabled evaluation of four σ values (0.375, 0.5, 0.625, 0.75), extending beyond the typical range used in prior research. The majority of participants selected $\sigma = 0.625$ for both speech and music, although individual preferences varied. Importantly, Phantom individual programs were rated significantly higher than both Phantom basic and the clinical program across nearly all subjective domains, underscoring the value of individualized fitting.

While such an individualization might be too time-consuming in traditional clinical settings, modern technological developments make broader application feasible. Recent work by Kliesch et al. (2024) demonstrated that cochlear implant users can successfully adjust hearing parameters, such as loudness and frequency mapping, via an app on a smartphone or tablet with high acceptance and reproducibility of results. Platforms like these could reduce clinician workload by enabling CI users to perform parameter adjustments, especially M-Level and σ settings, independently in real-world listening environments. Thus, mobile self-fitting technology offers a pathway for bringing the benefits of user-guided Phantom configuration to clinical practice. In our study, we could show that CI users are able to carry out this adjustment process on their own reliably. An important factor for the optimization of the perceived sound quality was the individual fitting of the loudness level based on realistic sound samples. Although this procedure might not be appropriate for a clinical fitting due to the high efforts and time required, it could get implemented using the current progress in new technologies in the cochlear implant field, such as classifiers (Eichenauer et al., 2021), automatically adapting parameter sets to the listening situation, or remote self-fitting applications (Convery et al., 2020), where CI users are actively involved in the modification of parameter sets. These developments could allow for an individualized situation dependent on optimization of settings by the CI user. In the present study all participants had a profound hearing loss and the CI was the only device used for better comparability. Another interesting aspect for future investigations would be the use of the individualized Phantom setting in the CI of bimodal users, aligning the low-frequency information of the CI and the hearing aid.

There was no correlation found between the insertion depth and the preferred sigma-setting; therefore, the fitting of the Phantom strategy could be independent of the availability of CT imaging as well as the electrode type. Also, CI users of previous implant generations could benefit from the low-frequency hearing accessible by the Phantom strategy.

Conclusion

The research sound coding strategy "Phantom", which transmits more low-frequency information, significantly improved music perception, voice discrimination, and subjective speech understanding in environments with background speakers for cochlear implant (CI) users. However, speech performance measures showed no significant difference compared to the commercial speech coding strategy. Individually adjusting the loudness levels of specific frequency bands further increased user satisfaction. The CI users strongly preferred the programs featuring the self-adjusted Phantom channel. Looking ahead, new technologies in CI sound processors, such as automatic scene classification and mobile apps for user-controlled adjustments, could enable more personalized situation-dependent hearing experiences.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author/s.

Ethics statement

The studies involving humans were approved by Ethics Committee of the "Medizinische Hochschule Hannover". The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

MB: Project administration, Formal analysis, Visualization, Methodology, Conceptualization, Supervision, Writing – original draft. TL: Writing – review & editing, Supervision. SK: Project administration, Writing – review & editing, Data curation, Investigation. AB: Supervision, Project administration, Investigation, Conceptualization, Funding acquisition, Writing – review & editing, Methodology.

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Conflict of interest

MB was employed by Advanced Bionics GmbH.

The remaining author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fauot.2026.1721340/full#supplementary-material

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