

# Phantom Stimulation for Cochlear Implant Users With Residual Low-Frequency Hearing

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**Objective:** In cochlear implants (CIs), phantom stimulation can be used to extend the pitch range toward apical regions of the cochlea. Phantom stimulation consists of partial bipolar stimulation, in which current is distributed across two intracochlear electrodes and one extracochlear electrode as defined by the compensation coefficient  $\sigma$ . The aim of this study was, (1) to evaluate the benefit of conveying low-frequency information through phantom stimulation for cochlear implant (CI) subjects with low-frequency residual hearing using electric stimulation alone, (2) to compare the speech reception thresholds obtained from electric-acoustic stimulation (EAS) and electric stimulation in combination with phantom stimulation (EPS), and (3) to investigate the effect of spectrally overlapped bandwidth of speech conveyed via simultaneous acoustic and phantom stimulation on speech reception thresholds.

**Design:** Fourteen CI users with ipsilateral residual hearing participated in a repeated-measures design. Phantom stimulation was used to extend the frequency bandwidth of electric stimulation of EAS users towards lower frequencies without changing their accustomed electrode-frequency allocation. Three phantom stimulation configurations with different  $\sigma$ 's were tested causing different degrees of electric field shaping towards apical regions of the cochlea that may affect the place of stimulation. A baseline configuration using a moderate value of  $\sigma$  ( $\sigma = 0.375$ ) for all subjects, a configuration that was equivalent to monopolar stimulation by setting  $\sigma$  to 0 ( $\sigma = 0$ ) and a configuration that used the largest value of  $\sigma$  for each individual subject ( $\sigma_{\text{Max}}$ ). Speech reception thresholds were measured for electric stimulation alone, EAS and EPS. Additionally, acoustic stimulation and phantom stimulation were presented simultaneously (EAS+PS) to investigate their mutual interaction. Besides the spectral overlap, the electrode insertion depth obtained from cone-beam computed-tomography scans was determined to assess the impact of spatial overlap between electric and acoustic stimulation on speech reception.

**Results:** Speech perception significantly improved by providing additional acoustic or phantom stimulation to electric stimulation. There was no significant difference between EAS and EPS. However, two of the tested subjects were able to perform the speech perception test using EAS but not using EPS. In comparison to the subject's familiar EAS listening mode, the speech perception deteriorated when acoustic stimulation and phantom stimulation conveyed spectrally overlapped information simultaneously and this deterioration increased with larger spectral overlap.

**Conclusions:** (1) CI users with low-frequency acoustic residual hearing benefit from low-frequency information conveyed acoustically through combined EAS. (2) Improved speech reception thresholds through low-frequency information conveyed via phantom stimulation were observed for EAS subjects when acoustic stimulation was not used. (3) Speech perception was negatively affected by combining acoustic and phantom stimulation when both stimulation modalities overlapped spectrally in comparison to the familiar EAS.

**Key words:** Cochlear implant, EAS interaction, Electric-acoustic stimulation, Phantom stimulation.

**Abbreviations:** CI = cochlear implant; CBCT = cone beam computed tomography; EAS = electric-acoustic stimulation; EAFD = electric acoustic frequency difference; EPS = electric-phantom stimulation; ES = electric stimulation; OLSA = Oldenburger Satztest; MCL = most comfortable level; SNR = signal to noise ratio; SPL = sound pressure level; SRT = speech reception threshold; STFT = short time fast Fourier transform

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## INTRODUCTION

### Electric-Acoustic Stimulation

Achievements in cochlear implant (CI) technology and surgical techniques during the last 15 years have made it possible to preserve residual hearing after implantation (Fraysse et al. 2006; Hochmair et al. 2015; James et al. 2005; Kiefer et al. 2005; Lenarz et al. 2009; C. von Ilberg et al. 1999; C. A. von Ilberg et al. 2011). Preservation of residual hearing in the low frequencies enables CI candidates to obtain combined electric-acoustic stimulation (EAS), which can significantly improve their speech perception in comparison to electric stimulation alone (Gantz et al. 2005; Turner et al. 2004). Therefore, most CI companies equip their speech processors with a hearing aid, also termed acoustic component, for acoustic stimulation. Inspired by the benefits of EAS, in the recent years, stimulation modes based on phantom stimulation (Wilson et al. 1992; Saoji and Litvak 2010) were proposed to virtually extend the electrode array towards more apical regions of the cochlea and convey low-frequency information (Nogueira et al. 2015; Luo and Garrett 2020). This work investigates the use of phantom stimulation for EAS users in terms of speech understanding.

### Phantom Stimulation

Phantom stimulation delivers charge through a pair of adjacent electrodes simultaneously stimulated with opposite polarities to shape the electrical field in the cochlea (Wilson et al. 1992). Applied to the two most apical electrodes, phantom stimulation can be used to elicit a pitch sensation lower than the one elicited by monopolar stimulation using the most apical physical electrode. This method can be used in the Advanced Bionics electrode array with an electrode spacing of approximately 1 mm to virtually extend its insertion depth by up to two physical electrodes (de Jong et al. 2020; Saoji and Litvak 2010; Klawitter et al. 2018). In CI users without residual hearing, Nogueira et al. (2015), Munjal et al. (2015), and Carlyon et al. (2014) proposed a sound coding strategy that used phantom stimulation (EPS) to create an additional channel that conveyed low-frequency information via the CI. Carlyon et al. (2014) tested speech perception acutely and observed no improvement in speech perception with EPS. Nogueira et al. (2015) showed a trend towards better speech understanding as well as a

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significant improvement in sound quality after one month of use with an EPS strategy that also extended the clinical electrode-frequency allocation down to two octaves. Acoustic stimulation in EAS as well as phantom stimulation in EPS share similar functionality as both extend the bandwidth conveyed by the CI toward low frequencies. For EAS users, in general, the lowest frequency allocated to the most apical electrode is substantially higher than for regular CI users. For this reason, introducing phantom stimulation to extend the bandwidth considered for electrical stimulation may have a larger impact for EAS users.

### Substitution of Acoustic Stimulation

One aspect that should be investigated in EAS users is the benefit obtained from low-frequency information conveyed through EAS or EPS with respect to electric stimulation using the same CI sound coding strategy as a reference. Thereby, it could be investigated to what extent phantom stimulation can be applied to substitute acoustic stimulation for EAS users. This research could be relevant for EAS users that do not use the acoustic component. Moreover, even if several studies (e.g., Sprinzel et al. 2020; Helbig et al. 2016) reported long-term stability of residual hearing after implantation, some subjects showed hearing loss after a long period of time following implantation (e.g., Gstoettner et al. 2008; Mertens et al. 2014; Helbig et al. 2016; Mamelle et al. 2020). Therefore, the current study could also be relevant for EAS users that have a deterioration in hearing performance caused by the loss of residual hearing or other circumstances that require a replacement of the acoustic component. For the current study, the number of patients at Hannover Medical School for whom the acoustic component was deactivated following initial activation was calculated. Thereby, it has been observed that the probability of no longer being able to use combined EAS increases over time. For example, after 2 years of EAS usage, approximately 15 % of the patients implanted with a HiFocus™ SlimJ electrode array (Advanced Bionics, Valencia, CA, United States) or Flex electrode array (Flex 16, Flex 20, Flex 24 or Flex 28; MED-EL, Innsbruck, Austria) were refitted with electric stimulation only. Within 10 years after cochlear implantation, the acoustic component of 35% of the CI users implanted with a Hybrid-L (Cochlear, Sidney, Australia) electrode array was gradually deactivated. Note that this data only considers the deactivation of the acoustic component but does not include the reason behind it. Besides the loss of residual hearing, there are several other reasons why subjects may not use the acoustic component such as insufficient coupling, comfort issues, or handling problems (Incerti et al. 2013; McCormack & Fortnum 2013; Spitzer et al. 2021). Deactivating the acoustic component of an EAS device usually requires a refitting of the CI including a reallocation of the frequencies assigned to the electrodes to cover the low-frequency range otherwise conveyed by the acoustic component. Although experienced CI users can adapt to new fittings, it has been shown that some subjects require between 18 and 30 months or even longer to adapt and to obtain the best performance in terms of speech understanding (e.g., Dorman and Loizou 1997; Pelizzone et al. 1999). In the context of EAS, Büchner et al. (2009) and Dillon et al. (2015) showed a significant decrease in speech understanding when switching from EAS to electric stimulation without providing an adaptation period to electric stimulation alone. Furthermore, in an acute comparison, Dillon et al. (2015) showed that the speech perception of EAS users listening to electrical stimulation

alone was better with the familiar CI configuration conveying a restricted bandwidth than with a configuration conveying a full bandwidth through a new electrode-frequency allocation. Moreover, Reiss et al. (2012) as well as Imsiecke et al. (2020) reported that some CI users were not able to tolerate a frequency reallocation towards low frequencies. For this reason, one potential application of phantom stimulation for EAS subjects would be to substitute acoustic stimulation without requiring an electrode-frequency reallocation.

### Interaction Between Electric and Acoustic Stimulation

Another aspect that should be investigated using phantom stimulation for EAS subjects is the effect of spectral overlap between electric and acoustic stimulation on speech understanding. The amount of spectral overlap is an important parameter for EAS fitting and this question has been addressed in several previous studies. For instance, Kiefer et al. (2005) and Vermeire et al. (2008) compared speech understanding with EAS using separated or overlapped frequency bandwidths for electric and acoustic stimulation. In case of separated bandwidths, a cutoff frequency determined from the subject's audiogram was used to assign the low-frequency bandwidth conveyed via acoustic stimulation. Higher frequencies above this cutoff frequency, where acoustic amplification was not sufficient for the hearing loss, were conveyed via electric stimulation. In case of overlapped bandwidth, acoustic stimulation was used to convey low frequencies and electric stimulation was used to convey low and high frequencies in the same manner as in a regular CI fitting. The EAS users tested by Kiefer et al. (2005) performed better using the overlap condition whereas Vermeire et al. (2008) observed better speech perception for EAS users with separated frequency bandwidths. Karsten et al. (2013) and Imsiecke et al. (2020) compared speech perception of EAS users when the spectral bandwidth associated with electric and acoustic stimulation were partially overlapped by lowering the CI's cutoff frequency used for electric stimulation to a specific amount of 50% or 2 octaves, respectively. Both studies observed a significant decrement in performance for the overlap bandwidth condition when listening through EAS. However, for the electric stimulation alone, none of these studies observed a significant difference between the separated or the overlapped bandwidth configuration. It is possible that these subjects could not adapt to the new electrode-frequency allocation causing the lack of benefit from the extended electric frequency range. The advantage of using phantom stimulation to investigate the effect of spectral overlap between electric and acoustic stimulation is that phantom stimulation can be used as an extra channel to extend the bandwidth conveyed through electric stimulation without requiring an electrode-frequency reallocation in their accustomed clinical processor.

As electric and acoustic stimulation interact with each other, it is important to consider the potential masking caused by phantom stimulation. Previous studies have described masking between electric and acoustic stimulation through psychoacoustic (Lin et al. 2011, Krüger et al. 2017, Imsiecke et al. 2018) and electrophysiological (Koka and Litvak 2017, Krüger et al. 2020a and 2020b) experiments in humans. Krüger et al. (2017) showed that EAS masking increases with decreasing distance between the stimulation site of electric and acoustic stimulation in the cochlea, the so-called electric-acoustic frequency difference (EAFD). Imsiecke et al. (2020) showed

a correlation between psychoacoustic EAS masking and the deterioration in speech perception for EAS subjects fitted with a spectral overlap. Moreover, Saoji et al. (2018) observed that phantom stimulation increases masking between electric and acoustic stimulation. From these previous studies, it is hypothesized that an increase in the interaction between electric stimulation and acoustic stimulation caused by phantom stimulation may impact speech understanding. However, the extent of this impact and whether it actually leads to a deterioration is not clear.

**Objectives**

This work benchmarks the use of low-frequency information conveyed through electric stimulation in comparison to acoustic stimulation in the same CI subjects. In contrast to previous studies, the spectral bandwidth for electric stimulation was extended by additional phantom stimulation without changing the subject’s accustomed electrode-frequency allocation. Thereby, it could be investigated how beneficial low-frequency information can be used for EAS subjects if conveyed through acoustic or phantom stimulation. In addition, the effect of an extended bandwidth for electric stimulation that overlapped with the bandwidth conveyed through acoustic stimulation could be examined without changing the subject’s accustomed electrode-frequency allocation. For this, speech perception in noise was investigated for CI users with residual low-frequency acoustic hearing using electric stimulation alone, EAS and EPS. Additionally, speech perception for EAS in combination with phantom stimulation was tested to investigate the effect of low-frequency spectral overlap. Besides the spectral overlap between the electric and the acoustic stimulation modality, the electrode insertion depth estimated from cone-beam computed-tomography scans was determined to assess its impact on EAS interaction.

**METHODS**

**Subjects**

Fourteen CI users with residual hearing in the implanted ear participated in this study. Figure 1 shows the ipsilateral and contralateral unaided air conduction pure tone thresholds measured via headphones (Sennheiser electronic GmbH & Co. KG, Wedemark) connected to a clinical audiometer (Audio 4000, Homoth Medizinelektronik GmbH & Co. KG, Kalttenkirchen, Germany). Ipsilateral audiograms were measured at the study appointment. Contralateral audiograms were obtained from the last clinical visit before the study appointment. Detailed demographic data of each subject is shown in Table 1. Table 1 includes the cutoff frequency obtained from the clinical map of each EAS user. The cutoff frequency for the acoustic and electric stimulation was determined individually as part of the clinical fitting procedure by an audiologist. Based on the subject’s audiogram the clinical fitting software, SoundWave 3.2 (Advanced Bionics, Valencia, CA) proposed one out of 8 possible cutoff frequencies (250, 350, 520, 690, 850, 1010, 1190, and 1540 Hz) for electric stimulation and for acoustic stimulation. After fitting the CI’s M- and T-levels, the volume of the acoustic component as well as the cutoff frequencies for electric and acoustic stimulation were individually adjusted based on the subjective feedback of the patient’s sound perception. After this adjustment, the fitting parameters were unchanged if the speech understanding scores as measured through the monosyllabic Freiburg test and the HSM sentence test in noise were within the expectations of the audiologist. The cutoff frequency was used across conditions in the present study. All subjects were implanted with a HiFocus™ SlimJ electrode array (Advanced Bionics, Valencia, CA, United States). All subjects provided written informed consent to the study conditions that were approved by the Institutional Review Board of the Hannover Medical School.

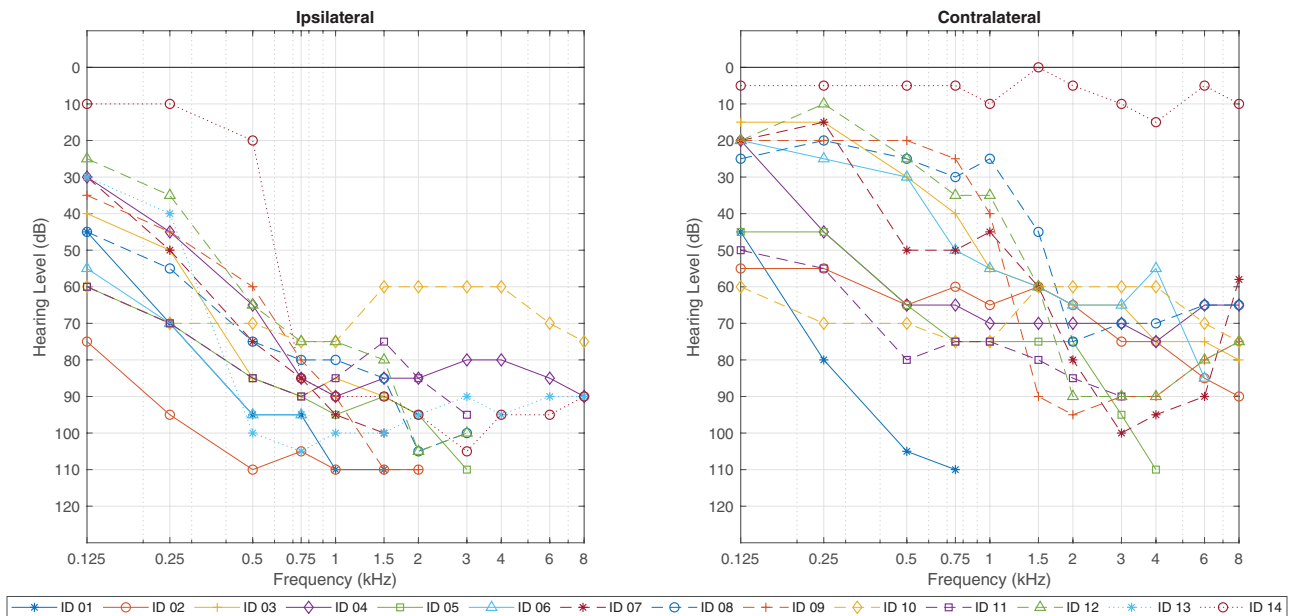


Fig. 1. Audiometric data of all subjects, ipsilateral and contralateral with respect to the tested side in this study. The unaided air conduction pure tone thresholds were measured via headphones (Sennheiser electronic GmbH & Co. KG, Wedemark) and a clinical audiometer (Audio 4000, Homoth Medizinelektronik GmbH & Co. KG, Kalttenkirchen, Germany). Hearing level is given in dB HL in compliance with DIN ISO 389-8:2004. Ipsilateral audiograms were measured at the study appointment. Contralateral audiograms were obtained from the last clinical visit before the study appointment.

**TABLE 1. Subject data with ID, gender, age at testing for present study, duration of CI experience, etiology of deafness in the implanted ear, side of implantation, tested frequency as well as the disabled electrodes**

ID	Gender	Age (yrs)	CI Experience (mo)	Etiology of Deafness	Side	Cutoff Frequency (Hz)	Disabled Electrodes	Channel Rate (pps)
1	Female	35	17	Unknown	Left	250	16	1736
2	Male	75	14	Sudden hearing loss	right	250	16	1736
3	Male	56	16	Unknown	Left	350	—	1634
4	Female	49	18	Usher-Syndrome	right	520	—	1634
5	Male	77	14	Unknown	right	250	16	1736
6	Male	74	8	Unknown	Left	350	—	1634
7	Female	58	6	Unknown	Left	350	—	1634
8	Male	54	18	Sudden hearing loss	Left	350	15, 16	1852
9	Female	47	18	Cogan-I-syndrome	Left	520	15, 16	1852
10	Male	71	23	Sepsis	right	520	—	1634
11	Female	55	14	Unknown	Left	250	15, 16	1852
12	Male	69	22	Noise-related hearing loss	Left	520	—	1634
13	Female	77	11	Unknown	right	350	—	1634
14	Female	41	22	Unknown	right	520	16	1736

Disabled electrodes are electrode contacts that were deactivated in the clinical routine. The numbers indicate the specific deactivated electrode contacts starting from 1 most apical to 16 most basal electrode located in the cochlea. All subjects were implanted with an Advanced Bionics SlimJ electrode array. All subjects were implanted with an Advanced Bionics SlimJ electrode array.

At the testing appointment, it turned out that the hearing thresholds of subject ID 2 had worsened about 20 dB across all frequencies since the last clinical appointment. Furthermore, speech understanding in noise as tested in this study was not possible for this subject even in the EAS condition. Therefore, subject ID 2 could not be tested with the Oldenburger Satztest (OLSA) and was not included for any grouped analysis. Subjects ID 3 and ID 10 were excluded from part of the analysis because the testing could not be completed during the study appointment. Therefore, only a subset of conditions was tested and included in the analysis for subjects ID 3 and ID 10 (electric stimulation [ES] and EAS). Unfortunately, for subject ID 3, it was not possible to measure the speech reception thresholds (SRTs) for the EPS listening mode. In contrast to the other study participants, at the study appointment, it was discovered that subject ID 3 did not use the acoustic component and thus, he used a map that transmitted the whole frequency bandwidth to the CI. For this reason, the hearing condition of subject ID 3 was different than the hearing condition of the other subjects. A refitting of the device was conducted for this subject; however, time was only available to measure the EAS and ES conditions. The test appointment for the subject ID 10 took place within a clinical examination at the Hannover Medical School; therefore, the time for the study appointment was strictly limited and only a subset of conditions could be measured. Because the SlimJ electrode has been recently commercialized, only a limited population of EAS subjects has been implanted with this implant. Therefore, we think it is of interest for the research community to show EAS data of these subjects. Due to time constraints, we have decided to at least collect the data for the two conditions ES and EAS for the subjects ID 3 and ID 10.

For each subject the EAFD is presented in Table 2. The EAFD is defined as the difference between the tonotopic frequency of the most apical electrode and the used cutoff frequency in octaves (Krüger et al. 2017). The tonotopic frequency of the most apical electrode is estimated from its insertion angle. The insertion angle is obtained using the three reference points registered in the cone-beam computed-tomography scans: the posterior margin of the round window, the modiolus and the center of the most apical electrode. The insertion angle was

transformed into a corresponding tonotopic frequency using the spiral ganglion pitch map by Stakhovskaya et al. (2007). Finally, the EAFD was obtained as the difference in octaves between the cutoff frequency specified in the subject's map and the determined tonotopic frequency from the most apical electrode.

### Test Conditions

Table 3 gives a description of the test conditions and their abbreviations used in this study. Note EPS as well as EAS+PS are used in three variations that differ in the used compensation coefficient  $\sigma$  indicated by the subscripted identifiers  $\sigma = 0$ ,  $\sigma = 0.375$ , and  $\sigma_{\text{Max}}$ .

The results from the conditions in Table 3 were used to determine the benefit obtained from low-frequency information through acoustic stimulation (EAS-ES) or through phantom stimulation (EPS-ES). The benefit of low-frequency

**TABLE 2. Insertion angle of the most apical electrode for each subject, determined from CBCT scans, corresponding tonotopic frequency transformed using the spiral ganglion frequency map by Stakhovskaya et al. (2007) and the EAFD computed as the difference in octaves between the subject's cutoff frequency (Table 1) and the tonotopic frequency**

ID	Insertion Angle	Tonotopic Frequency	EAFD
1	462	526	1.07
2	372	738	—
3	409	632	0.85
4	389	683	0.39
5	381	707	1.50
6	428	593	0.76
7	485	478	0.45
8	365	764	1.13
9	360	785	0.59
10	379	714	0.46
11	312	1078	2.11
12	318	1030	0.99
13	386	692	0.98
14	359	789	0.60

CBCT, cone-beam computed-tomography; EAFD, electric-acoustic frequency difference.



**TABLE 3. Definition of the test conditions (top) and overview of tests and conditions performed by each subject (bottom)**

Abbreviations	Full Form	Description
EAS	Electric-acoustic stimulation	The combination of electric and acoustic stimulation in the same ear with complementary bandwidths. Low frequencies up to the individual cutoff frequency are amplified by a hearing aid. High frequencies starting from the individual cutoff frequency and above are considered for electric stimulation.
ES	Electric stimulation	Electric stimulation with a limited bandwidth restricted to high frequencies as used in the clinical EAS configuration. High frequencies starting from the individual cutoff frequency and above are considered for electric stimulation.
EPS	Electric-phantom stimulation	The combination of ES and phantom stimulation. The electrical stimulation as used in the clinical configuration for EAS (limited bandwidth) is supplemented by phantom stimulation to expand the conveyed bandwidth towards the low frequencies. Low frequencies up to the cutoff frequency are conveyed through phantom stimulation.
EAS+PS	Electric-acoustic stimulation combined with phantom stimulation	In addition to the EAS, PS is presented simultaneously. Thereby low frequency information is conveyed through acoustic stimulation and through phantom stimulation.

ID	Audiogram	Phantom Fitting	Sentence Test (OLSA)				
			Training	EAS	ES	EPS	EAS+PS
1,4,5,6,7,8,9,11,13	X	X	X	X	X	x	X
2	X	X	*	-	-	-	-
3,10	X	X	X	X	X	-	-
12,14	X	X	X	X	*	*	X

(x) The test was successfully performed and in the case of the conditions ES, EAS, EPS, and EAS+PS an SRT could be determined. (-) Condition was not tested. (\*) The test was performed but an SRT could not be determined because the system limit of the OLSA test of 25 dB SNR was exceeded. Only subject's corresponding conditions in which the valid SRT could be determined were considered for further analysis

EAS, electric-acoustic stimulation; ES, electric stimulation; OLSA, Oldenburger Satztest; PS, phantom stimulation; SNR, signal to noise ratio; SRT, speech reception thresholds.

information was defined as the SRT difference between ES and EAS or between ES and EPS. Where ES considered only a limited bandwidth restricted to high frequencies, starting from the subject's individual cutoff frequency (Table 1) and above. In EAS or EPS, this bandwidth was extended towards low frequencies with the aid of acoustic or phantom stimulation, respectively. For this, low-frequency information, starting from the subject's individual cutoff frequency and below, was conveyed through acoustic stimulation in EAS or through phantom stimulation in EPS. Furthermore, the effect of low-frequency information presented simultaneously through acoustic and phantom stimulation on speech perception was analyzed through the SRT difference between EAS+PS and EAS listening modes.

### Hardware and Software Instrumentation

Ipsilateral SRT were measured in EAS subjects by presenting speech and noise signals through the CI and the acoustic component. For this, two channels of an audio interface (RME Babyface, Audio AG, Haimhausen, Germany) connected to a computer were used. For electric stimulation, one output channel of the audio interface was connected to the auxiliary input of the CI sound processor (Harmony sound processor, Advanced Bionics, Valencia, CA, United States). For acoustic stimulation, the second output channel of the audio interface was connected via a headphone amplifier (Phone-Amp G103, Lake People electronic GmbH, Konstanz, Germany) to headphones (HDA-200, Sennheiser electronic GmbH & Co. KG, Wedemark, Germany). The use of a single acoustic channel in combination with circumaural headphones ensured that the sound was only perceived on the ipsilateral ear while minimizing the sound perception on the contralateral ear to the CI. The electric pathway was calibrated using the LIST Player (Advanced Bionics, Valencia, CA, United States), a calibration tool provided by

Advanced Bionics that outputs the level of the auxiliary input of the CI sound processor as dB sound pressure level (SPL) equivalent. The acoustic pathway was calibrated with a sound pressure meter (Type 2250, Brüel & Kjær Vibro A/S, Nærum, Denmark) and an artificial ear (Type 4153, Brüel & Kjær Vibro A/S, Nærum, Denmark). The two channels were separately processed using Matlab (The Mathworks, Inc, Natick, MA, United States) running on the computer.

The subjects' low-frequency hearing loss was compensated using a hearing aid model implemented in Matlab. After calibrating the hearing aid input to 65 dB SPL, the audio stream sampled at 44100 Hz was transformed from the time domain into the frequency domain through an analysis filter bank based on a short-time fast Fourier transform with a hamming window of 256 samples and 75% overlapping. Individual hearing loss, up to the clinically used cutoff frequency, was compensated by reshaping the spectrum using a half-gain rule (Lybarger 1944, 1963) with a maximal gain of 35 dB. After reshaping the spectrum, the audio stream was transformed back into the time domain through a synthesis filter bank using an inverse short-time fast Fourier transform. High-frequency hearing was restored through electrical stimulation using the HiRes Optima Sound Processing® strategy in sequential stimulation mode (Advanced Bionics, Valencia, CA, United States) running on a Harmony sound processor. The HiRes Optima Sound Processing® strategy uses channel stimulation. Thereby, a channel is implemented as two adjacent electrodes that are simultaneously stimulated with in-phase pulses (Fig. 2A). The current steering coefficient  $\alpha$  corresponds with a weight that is applied to the current amplitudes of the presented pulses to steer the elicited pitch between the two adjacent electrodes. In the current study, additional phantom stimulation was provided through a phantom stimulation channel in the HiRes Optima strategy. The phantom stimulation channel is used to extend the

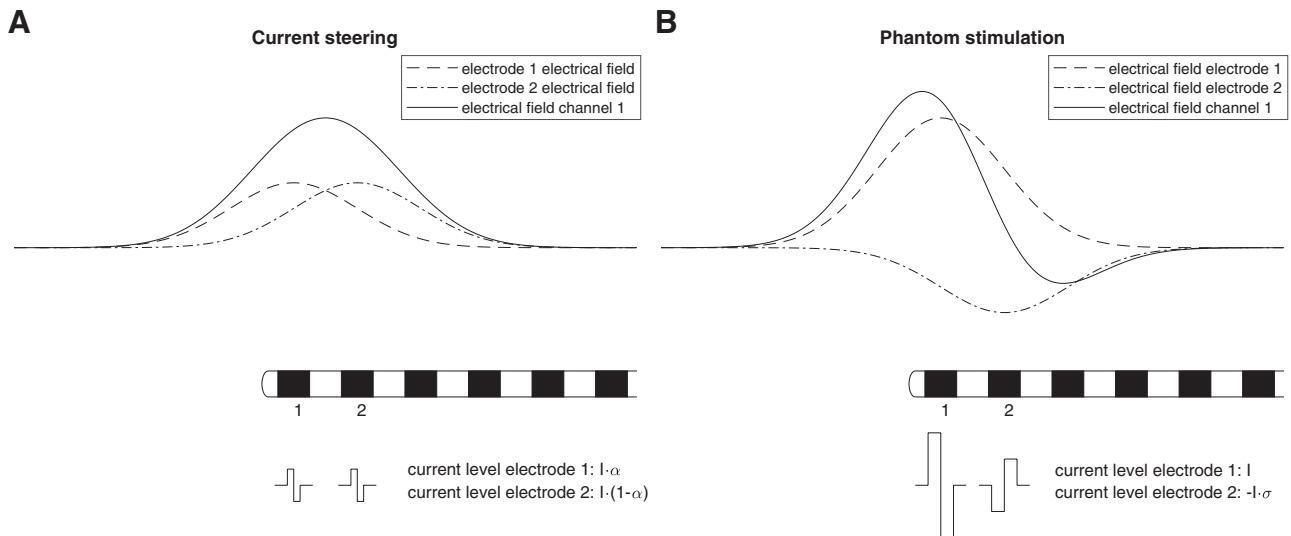


Fig. 2. A, Schematic illustration of current steering stimulation used by the HiRes Optima Sound Processing® strategy at the most apical channel. Electrode 1 and 2 are stimulated with current  $I \cdot \alpha$  and  $I \cdot (1 - \alpha)$  with the current steering coefficient  $\alpha = 0.5$ . In the HiRes Optima Sound Processing® strategy  $\alpha$  can range between  $0.25 \leq \alpha \leq 0.75$ . B, Schematic illustration of phantom stimulation in the most apical channel 1. Electrode 1 is used for stimulation with current  $I$  and electrode 2 with current  $-I \cdot \sigma$  using the compensation coefficient  $\sigma = 0.5$ . In the current study,  $\sigma$  can range between  $0 \leq \sigma \leq 0.75$ .

frequency bandwidth provided by the HiRes Optima strategy towards low frequencies without the need of remapping the electrode-frequency allocation of each subject. The phantom stimulation channel was configured to convey the frequency range normally amplified by the hearing aid of the EAS system down to 102 Hz, corresponding to the third bin of the short-time fast Fourier transform used by the sound coding strategy. The first two short-time fast Fourier transform bins were omitted assuming that these predominantly contained noise.

Phantom stimulation uses the two most apical CI electrodes to shape the electrical field in the cochlea to elicit a lower pitch (Klawitter et al. 2018; Saoji & Litvak, 2010) in comparison to the pitch elicited by the HiRes Optima channels. For this, the most apical electrode is stimulated with current  $I$  whereas the second most apical electrode, also termed compensating electrode, is stimulated with current  $-I \cdot \sigma$ . Where  $\sigma$  is the compensation coefficient defining the ratio of the current between the two electrodes (Fig. 2B). For the particular case of  $\sigma = 0$ , the current amplitude of the compensating electrode is zero resulting in stimulation of the primary electrode in monopolar mode. Phantom stimulation typically requires more charge per phase to elicit the same loudness as monopolar stimulation (e.g., Nogueira et al. 2015). For this reason, the phantom stimulation channel was configured with a phase duration two times longer than the HiRes Optima channels to achieve a comfortable loudness level without exceeding the maximum compliance voltage of the device.

## Procedure

**Fitting** • The hearing aid was fitted using the unaided air conduction pure tone thresholds measured at the test appointment (Fig. 1). The overall volume of the acoustic stimulation was individually adjusted for each subject using the headphone amplifier by presenting sentences from the OLSA test while listening through EAS.

The fitting of the CI for ES, EAS, and EPS was based on the clinical HiRes Optima sound coding strategy used by the subject. The most comfortable levels (MCLs) and threshold levels (T-Level) for each individual electrode were imported and

converted from the clinical fitting software SoundWave (Advanced Bionics, Valencia, CA, United States) into the research software BEPS+ (Advanced Bionics, Valencia, CA, United States) for all monopolar channels to program the research speech processor. In BEPS+, an additional phantom stimulation channel was added to the HiRes Optima sound coding strategy. The phantom stimulation channel was disabled by setting its level to zero for ES and EAS to ensure the same stimulation rate for all stimulation configurations (ES, EAS, EPS, and EAS+PS). To verify the loudness of the imported MCLs, all channels were stimulated one after the other allowing the subject to detect level differences. Additionally, the processor was activated using the microphone to verify that no subjective differences in comparison to the subject's clinical fitting were detectable.

The phantom stimulation channel was individually fitted for each subject with various configurations of  $\sigma$ , ranging from 0.0 to 0.75. Unmodulated pulse trains with  $\sigma$  values of 0.0, 0.125, 0.375, 0.5, 0.625, and 0.75 were compared in pitch to unmodulated pulse trains presented in monopolar stimulation at the most apical HiRes Optima CI channel. Note that the most apical HiRes Optima channel consists of stimulation with electrode 1 and 2 using  $\alpha = 0.5$  (Fig. 2). First, the loudness of each phantom configuration was fitted using a ten-scale loudness table, ranging from extremely soft to extremely loud. The level of the phantom stimulation channel was successively increased until the MCL, indicated as number six on the loudness table, was reached. In an A/B comparison, the MCLs on the phantom channel were further adjusted to ensure that the phantom and the most apical HiRes Optima channel were presented with the same loudness and to minimize the effect of level differences on pitch perception (Carlyon et al. 2010). In the following,  $f_{comp}$  represents the ratio between the currents required to elicit MCL with HiRes Optima in the most apical channel and phantom stimulation [Eq. (1)]. Next, four runs of an A/B pitch comparison between the most apical HiRes Optima channel and the phantom stimulation channel were performed for each  $\sigma$  configuration. The task of the subjects was to indicate which of the presentations elicited a lower pitch.

$$f_{comp} = \frac{MCL_{Phantom}}{MCL_{HiRes}}; \quad (1)$$

For each subject, the three phantom configurations,  $EPS_{\sigma=0}$ ,  $EPS_{\sigma=0.375}$ , and  $EPS_{\sigma_{Max}}$  were used to evaluate speech perception in noise.  $EPS_{\sigma=0.375}$  was the baseline configuration for phantom stimulation using a moderate value of  $\sigma$  of 0.375 for all subjects.  $EPS_{\sigma=0}$  represents phantom stimulation using a  $\sigma$  of 0.0 for all subjects.  $EPS_{\sigma_{Max}}$  was configured individually for each subject using the largest  $\sigma$  that elicited a lower pitch in comparison to the most apical HiRes Optima channel.

**Speech Perception and Statistical Analysis** • The OLSA (Wagener et al. 1999a, 1999b, 1999c) is a German matrix sentence test that was used to determine the SRT in noise. For this, the Oldenburger noise (OLnoise) as part of the OLSA test was presented at a fixed level of 65 dB SPL. The OLnoise is a speech shaped stationary noise generated from the speech material of the OLSA test. The noise was presented simultaneously to the speech and the speech level was iteratively adapted in level to determine the SRT that converged to a speech intelligibility in noise of 50% (Brand & Kollmeier 2002). The output level of the OLSA was limited to 90 dB SPL or an signal to noise ratio (SNR) of 25 dB. After an initial practice, two runs of 20 sentences were performed for each test condition. The reported SRTs were estimated as the mean values obtained from the two runs. The practice was performed to familiarize the subject with the OLSA test. The practice consisted of two lists of 20 sentences listening with EAS as this is the condition they used with their clinical devices. No practice was performed in other conditions. Therefore, only the effect of an acute switch from EAS to ES or EPS was investigated. To minimize the effect of adaptation or habituation, the order of presentation of the conditions were randomized for each subject. The test was conducted in one session with the possibility of taking breaks between conditions. Short breaks were made when needed. The study was single-blind, that is, the tests were conducted and scored by the experimenter who was aware of which conditions were tested. The grouped SRTs were analyzed using non-parametric statistical analysis because of the heavy-tailed distributions towards positive SRTs (Hey et al. 2014), the SRT limit of 25 dB SNR and the relatively small sample sizes. For the comparison of the SRTs between two test conditions considering the same subjects, the related-samples Wilcoxon signed-rank was used. Multiple comparisons for various test conditions were analyzed using the Friedman test. Dunn-Bonferroni tests were performed for supplemented post hoc testing. To counteract the type I error (false negative) for multiple comparisons, the Bonferroni-Holm method was used to adjust the  $p$  values allowing the comparisons to a constant significance level of 0.05. According to Cohen (1988), the effect size  $r$  is defined as small for  $0.1 \leq r \leq 0.3$ , medium for  $0.3 \leq r \leq 0.5$  and large for  $r > 0.5$ .

## RESULTS

### Phantom Fitting

Figure 3 shows the compensation factor  $f_{comp}$  across  $\sigma$  for each subject (data) as well as the mean across subjects (mean) with its standard deviation. The dashed line represents the estimated factor  $M_{factor}$  based on the equation proposed by Nogueira et al. (2015) [see Eq. (2)]. In Eq. (2),  $N$  is the pulse duration multiplier, defined as the ratio between the used pulse

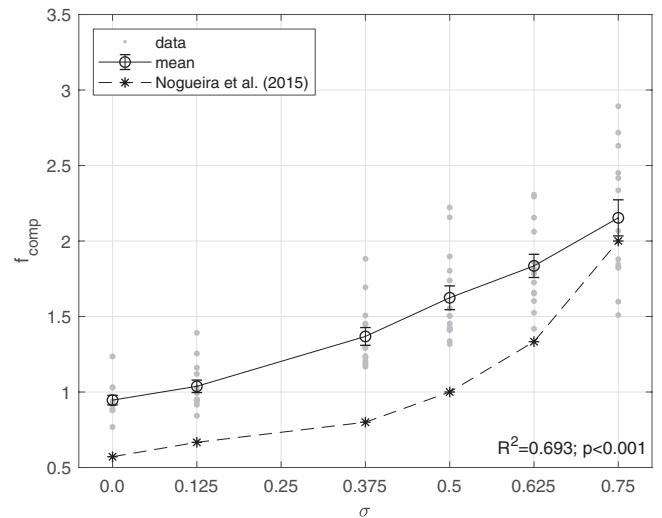


Fig. 3. MCL compensation for phantom stimulation as function of  $\sigma$ . The compensation factor  $f_{comp}$  needed to elicit the same loudness perception with phantom stimulation in comparison to the most apical HiRes Optima channel for a given  $\sigma$ . MCL indicates most comfortable level.

duration for phantom stimulation and monopolar stimulation. The results indicate a more linear relation (Pearson correlation,  $R^2=0.693$ ,  $p<0.001$ ) between  $f_{comp}$  and  $\sigma$  in comparison to the equation proposed by Nogueira et al. (2015) [see Eq. (2)].

$$M_{factor} = \frac{1}{(1-\sigma)N}. \quad (2)$$

Table 4 shows the number of trials in which phantom stimulation was indicated to elicit a lower pitch in comparison to the most apical HiRes Optima channel as well as the resulting  $\sigma_{Max}$  configuration, i.e., the largest value of  $\sigma$  that elicited a lower pitch than the HiRes Optima channel.

### Benefit From Low-Frequency Information Conveyed Through Acoustic Stimulation

Figure 4 shows the SRTs obtained from combined EAS and from ES alone. Figure 4A shows the SRTs obtained from the OLSA test for ES and EAS for each subject. Subjects ID 12 and ID 14 could not perform the OLSA using ES alone without reaching the SRT limit of 25 dB. Therefore, these two subjects were excluded from the analysis of the group results. Figure 4B shows the grouped ( $N=11$ ) results for ES and EAS. All subjects showed improved SRTs for combined EAS in comparison to ES. The benefit from low-frequency information conveyed through acoustic stimulation ranged from 1.05 dB to 8.7 dB for those subjects who could perform the OLSA with ES. A significant difference between ES and EAS was observed from the grouped data (mean difference 4.31 dB, median difference 4.8 dB,  $p=0.005$ ,  $N=11$ ) using a related-samples Wilcoxon signed-rank test.

The subjects used individual fittings with adjusted cutoff frequencies for electric and acoustic stimulation. Increasing the cutoff frequencies reduced the information conveyed via the CI, potentially compromising the ES performance. Figure 5 shows the SRT difference between ES and EAS (Fig. 5A) as well as the SRTs obtained from ES (Fig. 5B) and EAS (Fig. 5C) as a

**TABLE 4. Pitch comparison results between phantom stimulation and the most apical HiRes optima channel**

ID	Number of Trials (Out of Four) in Which Phantom Stimulation Elicited Lower Pitch Than a HiRes Optima Channel						$\sigma_{Max}$
	Compensation Coefficient $\sigma$						
	0	0.1	0.375	0.5	0.625	0.75	
1	4	4	4	4	4	4	0.75
2	-	1	2	2	0	0	-
3	4	4	4	4	4	4*	0.625
4	4	4	4	4	4	4	0.75
5	4	4	4	4	4	-	0.625
6	4	4	4	4	4	4	0.75
7	4	4	4	4	4	4	0.75
8	1	0	3	0	4	1	0.625
9	4	4	4	4	2*	-	0.5
10	-	-	-	4	-	-	0.5
11	2	4	4	4	4	4*	0.625
12	0	0	0	0	2	2*	0.625
13	4	4	4	4	4	4	0.75
14	3	2	4	4	4	4	0.75

For each subject and  $\sigma$  value, four trials of an A/B comparison between phantom stimulation and HiRes Optima stimulation using the two most apical electrodes were performed. The values in the table show the number of trials in which Phantom stimulation elicited a lower pitch than stimulation with the most apical HiRes Optima channel.  $\sigma_{Max}$  represents the largest value of  $\sigma$  that elicited a lower pitch than the HiRes Optima channel without producing an unpleasant sound sensation. This value of  $\sigma_{Max}$  was selected for  $EPS_{\sigma_{Max}}$ . -Testing was not completed because of unpleasant sound sensation or time restriction. \*Stimulation elicited unpleasant sound sensation.

function of the cutoff frequency. As shown in Fig. 5A, a significant correlation between the SRT difference and the logarithm of the cutoff frequency was observed (Pearson correlation,  $R^2=0.638, p=0.003, N=11$ ).

**Benefit From Low-Frequency Information Conveyed Through Phantom Stimulation**

Figure 6 shows individual and grouped results for ES and EPS configured with  $\sigma = 0, \sigma = 0.375$  or  $\sigma_{Max}$ . Only subjects who could carry out the OLSA without reaching the system’s SNR limit of 25 dB for all EPS conditions were considered in the grouped analysis ( $N=9$ ). For subjects ID 12 and ID 14, at least one condition could not be measured without reaching the SNR limit of 25 dB. For this reason, these subjects were not considered for the group analysis shown in Fig 5B.

A comparison of the repeated measures including ES,  $EPS_{\sigma=0}$ ,  $EPS_{\sigma=0.375}$ , and  $EPS_{\sigma_{Max}}$  showed a significant effect of condition ( $p=0.001, df=3, Z=16.07, N=9$ ) using the Friedman test. Additional post hoc analysis showed significant differences between ES and  $EPS_{\sigma=0.375}$  ( $p<0.001, Z=2.33, N=9$ ) as well as between ES and  $EPS_{\sigma_{Max}}$  ( $p=0.017, Z=1.78, N=9$ ). No significant differences were observed between  $EPS_{\sigma=0.375}$  and  $EPS_{\sigma_{Max}}$  ( $p=0.723, Z=-0.556, N=9$ ),  $EPS_{\sigma=0.375}$  and  $EPS_{\sigma=0}$  ( $p=0.432, Z=0.889, N=9$ ),  $EPS_{\sigma_{Max}}$  and  $EPS_{\sigma=0}$  ( $p=0.584, Z=0.333, N=9$ ) as well as ES and  $EPS_{\sigma=0}$  ( $p=0.071, Z=1.444, N=9$ ). The effect size for ES and  $EPS_{\sigma=0.375}$  as well as for ES and  $EPS_{\sigma_{Max}}$  was large ( $r=0.78$  and  $r=0.59$ ). At an individual level, 8 out of 9 subjects showed lower SRTs with EPS than with ES. However, the EPS condition showing the lowest SRT varied across subjects. Three subjects obtained the lowest SRTs with  $EPS_{\sigma=0}$ , six with  $EPS_{\sigma=0.375}$  and two with  $EPS_{\sigma_{Max}}$ .

**Comparison Between Electric-Acoustic Stimulation and Electric-Phantom Stimulation**

The grouped SRTs for ES,  $EPS_{\sigma=0.375}$ , and EAS were compared (Fig. 7). The  $EPS_{\sigma=0.375}$  condition was used as reference or baseline for two reasons: First, all subjects obtained

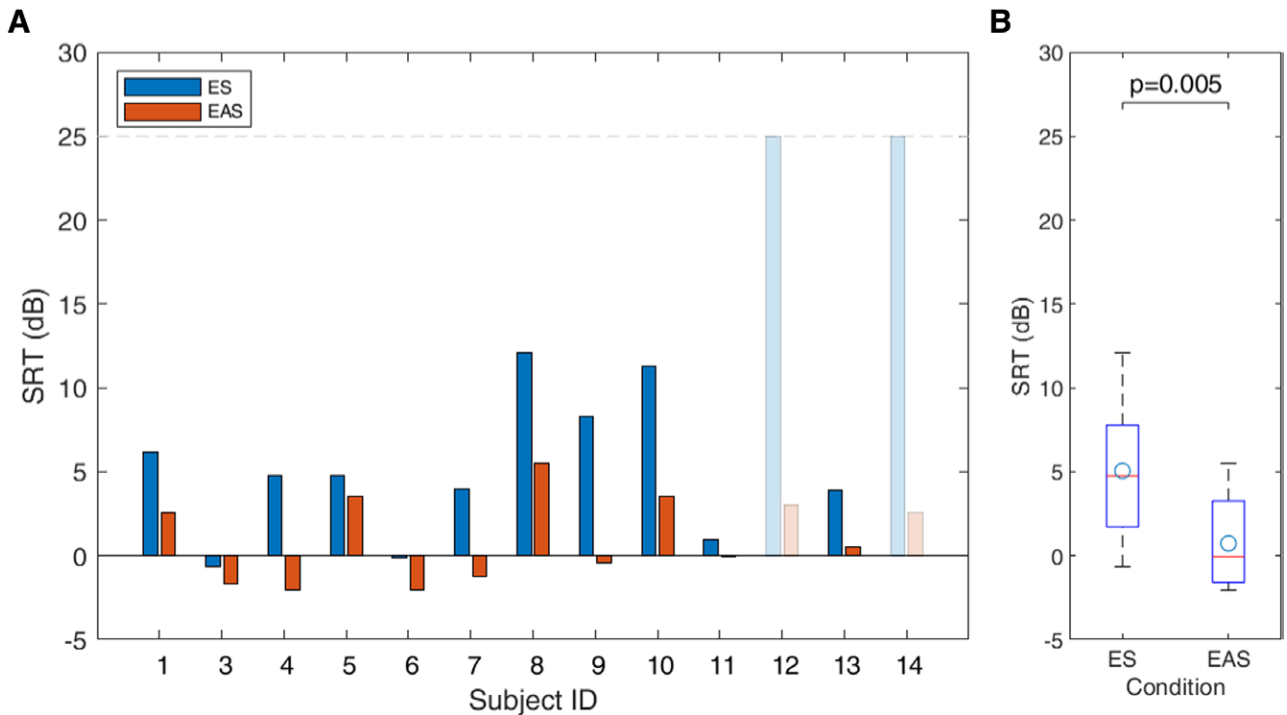


Fig. 4. A, Individual speech reception thresholds (SRTs) for electric stimulation (ES) alone and combined electric acoustic stimulation (EAS). B, Grouped results for the ES and the EAS condition. The measurements indicated by the light shaded bars in panel A were not included in the group analysis because SRTs for the ES condition could not be determined.



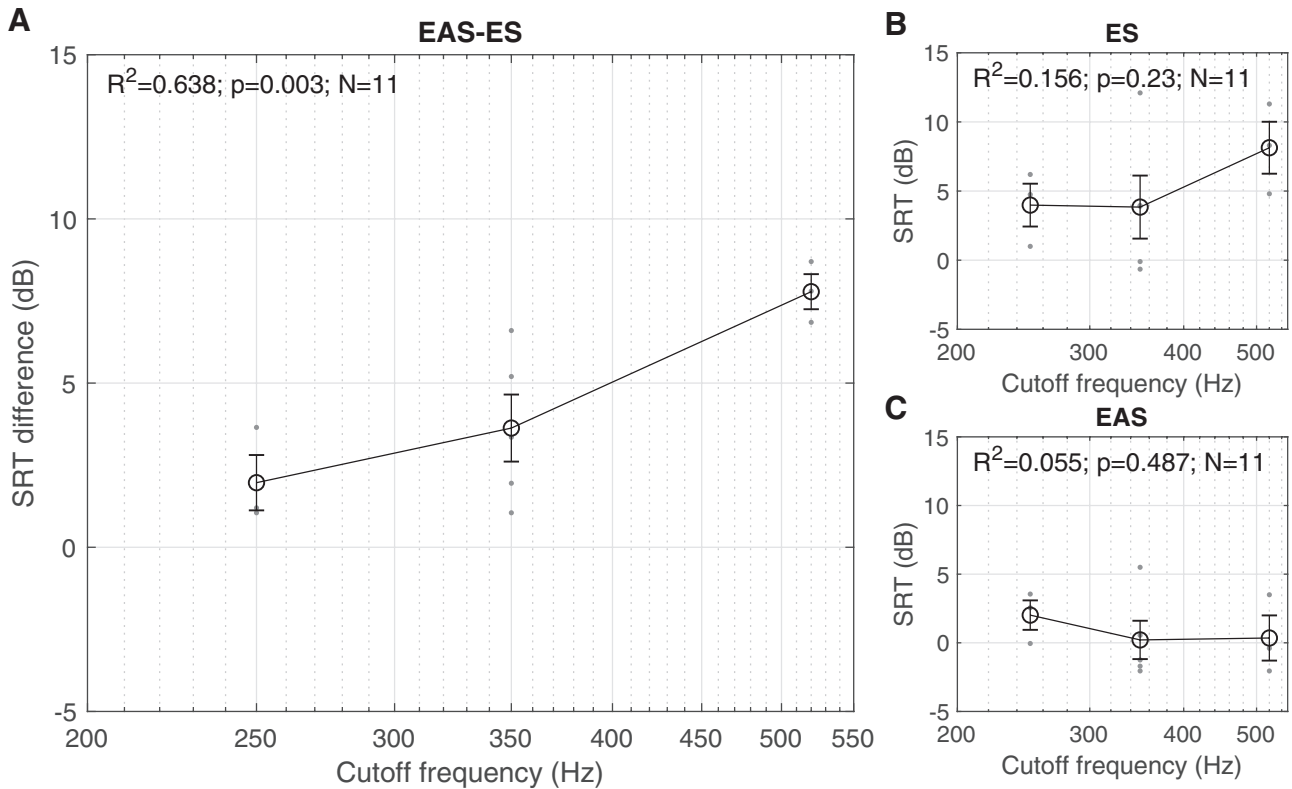


Fig. 5. Speech reception thresholds (SRTs) as function of the cutoff frequency. A, SRT difference between electric stimulation (ES) and combined electric-acoustic stimulation (EAS) as function of the electric cutoff frequency. B, SRT as function of the cutoff frequency for ES. C, SRT as function of the cutoff frequency for EAS.

measurable SRTs and second, all subjects were able to discriminate the pitch between  $EPS_{\sigma=0.375}$  and the HiRes Optima channel using the two most apical electrodes. Figure 7 presents the grouped SRTs excluding subjects ID 12 and ID 14 from whom the SRTs without acoustic stimulation were not measurable.

The results show a significant difference between the groups ES,  $EPS_{\sigma=0.375}$ , and EAS determined by a Friedman test ( $p<0.001$ ,  $df=2$ ,  $Z=16.222$ ,  $N=9$ ). Additional post hoc tests revealed significantly lower SRTs for EAS (mean: 4.28 dB, median: 4.8 dB,  $p<0.001$ ,  $Z=1.889$ ,  $N=9$ ) and  $EPS_{\sigma=0.375}$  (mean: 2.5 dB,

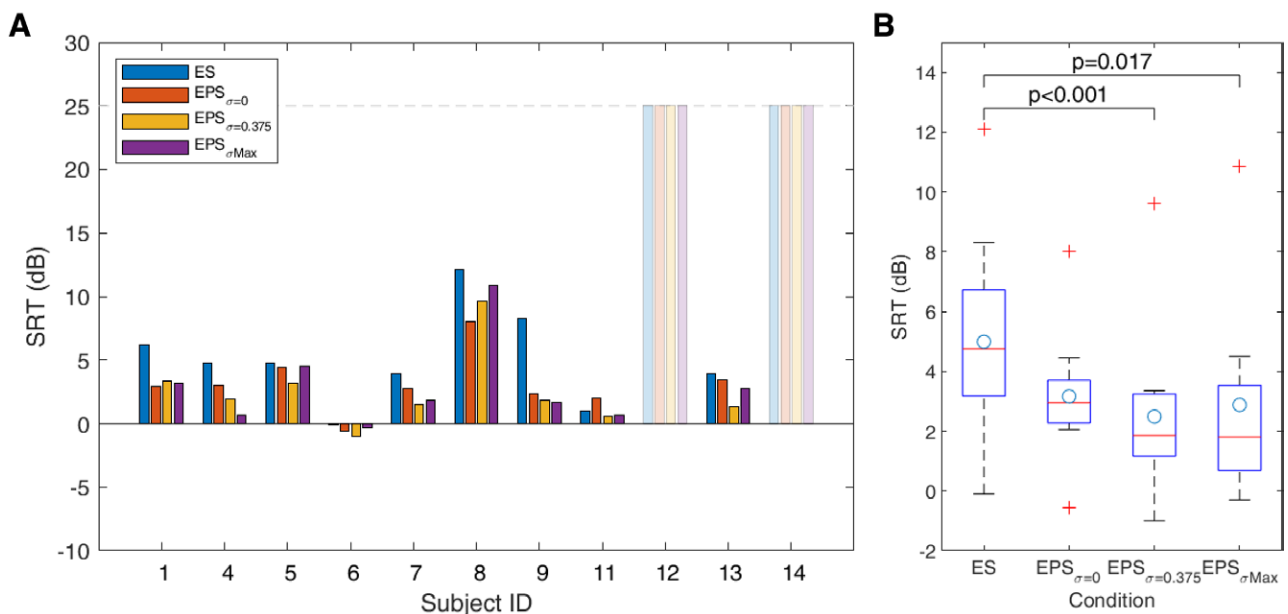


Fig. 6. A, Individual Oldenburger Satztest (OLSA) Speech reception thresholds (SRTs) for electric stimulation (ES) and ES and phantom stimulation (EPS) configured with  $\sigma=0$ ,  $\sigma=0.375$  and  $\sigma_{Max}$ . B, Grouped results of ES and EPS configured with  $\sigma=0$ ,  $\sigma=0.375$  and  $\sigma_{Max}$ . Subjects ID 12 and ID 14 were not considered for the group analysis because the OLSA could not be performed for ES or for at least one phantom condition without reaching the SNR limit of 25 dB (indicated by light shaded bars in panel A).

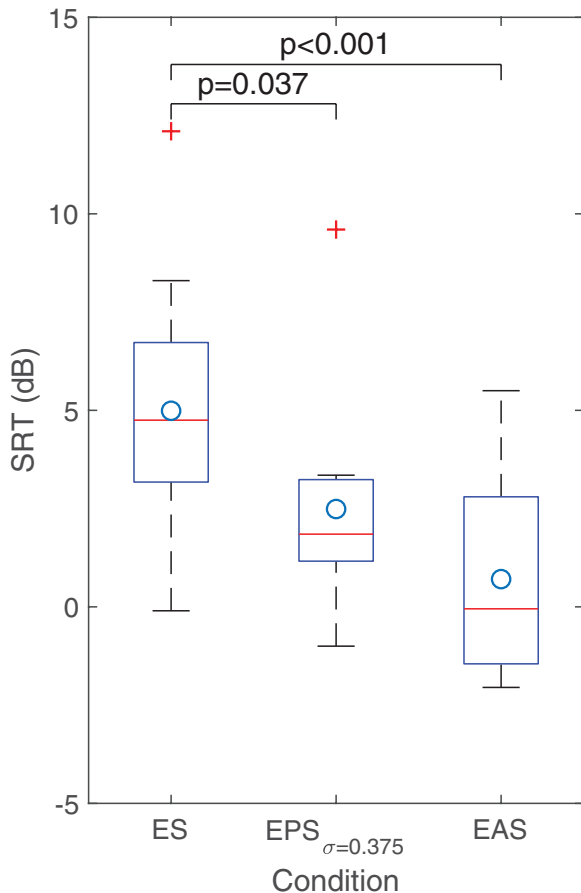


Fig. 7. Speech reception thresholds (SRTs) with electric stimulation (ES), the baseline EPS configuration ( $\text{EPS}_{\sigma=0.375}$ ) and combined electric-acoustic stimulation (EAS). For two subjects (ID 12 and ID 14) ES and  $\text{EPS}_{\sigma=0.375}$  performance could not be measured because the system's limit was reached. Grouped SRTs for the 9 subjects in whom SRTs were measurable without acoustic stimulation.

median: 2.9 dB,  $p=0.037$ ,  $Z=1.111$ ,  $N=9$ ) in comparison to ES. No significant difference between  $\text{EPS}_{\sigma=0.375}$  and EAS ( $p=0.099$ ,  $Z=0.778$ ,  $N=9$ ) was observed. However, the effect size between ES and EAS was large ( $r=0.63$ ) and the effect size between ES and  $\text{EPS}_{\sigma=0.375}$  was medium ( $r=0.37$ ).

### Spectral Overlapped Low-Frequency Speech Information Using Phantom Stimulation

The effect of an extended bandwidth conveyed through phantom for electric stimulation, which overlapped with the bandwidth conveyed through acoustic stimulation, on speech perception with EAS was investigated. For this, the SRT difference between EAS+PS and EAS was analyzed for all subjects tested in these conditions using the OLSA sentence test. Furthermore, the effect of the phantom stimulation configuration in combination with EAS ( $\text{EAS+PS}_{\sigma=0}$ ,  $\text{EAS+PS}_{\sigma=0.375}$ ,  $\text{EAS+PS}_{\sigma_{\text{Max}}}$ , and EAS) on speech perception was investigated. Figure 8A shows the individual, and Fig. 8B shows grouped SRTs for EAS and all tested EAS+PS conditions.

A significant effect of condition (EAS,  $\text{EAS+PS}_{\sigma=0}$ ,  $\text{EAS+PS}_{\sigma=0.375}$ , and  $\text{EAS+PS}_{\sigma_{\text{Max}}}$ ) was determined by a Friedman's test ( $p=0.005$ ,  $df=3$ ,  $Z=13$ ,  $N=11$ ). Post hoc tests revealed significantly higher SRTs for  $\text{EAS+PS}_{\sigma=0}$  (mean: 1.11 dB, median: 1.3 dB,  $p=0.010$ ,  $Z=-1.727$ ,  $N=11$ ) and for  $\text{EAS+PS}_{\sigma_{\text{Max}}}$  (mean: 0.91 dB, median: 0.55 dB,  $p=0.015$ ,  $Z=-1.636$ ,  $N=11$ ) in comparison to EAS. The effect size was large for  $\text{EAS+PS}_{\sigma=0}$  ( $r=0.52$ ) and medium for  $\text{EAS+PS}_{\sigma_{\text{Max}}}$  ( $r=0.49$ ). A trend toward significance was observed for  $\text{EAS+PS}_{\sigma=0.375}$  ( $p=0.053$ ,  $Z=-1.364$ ,  $N=11$ ). No significant differences were observed between  $\text{EAS+PS}_{\sigma=0.375}$  and  $\text{EAS+PS}_{\sigma_{\text{Max}}}$  ( $p=1$ ,  $Z=-0.273$ ,  $N=11$ ),  $\text{EAS+PS}_{\sigma=0.375}$  and  $\text{EAS+PS}_{\sigma=0}$  ( $p=1$ ,  $Z=0.364$ ,  $N=11$ ) and  $\text{EAS+PS}_{\sigma_{\text{Max}}}$  and  $\text{EAS+PS}_{\sigma=0}$  ( $p=0.869$ ,  $Z=0.091$ ,  $N=11$ ).

Figure 9 shows the SRT difference between EAS+PS conditions and EAS across subjects, as a function of the cutoff frequency or mean EAFD, respectively. A significant correlation between SRT difference and the logarithm of the cutoff

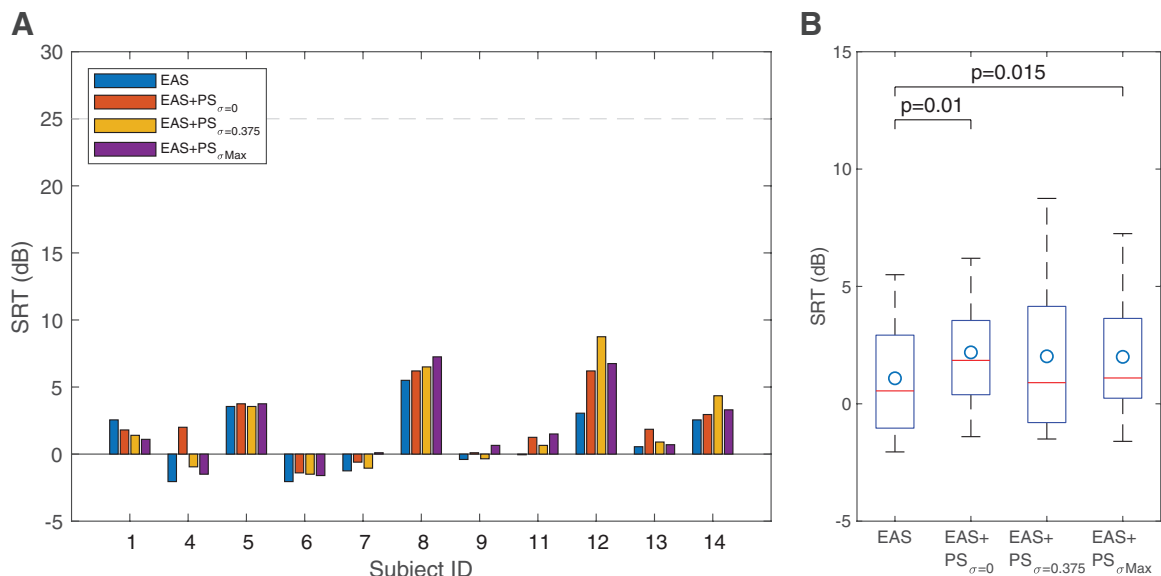


Fig. 8. A, Speech reception thresholds (SRT) for the tested conditions electric-acoustic stimulation (EAS),  $\text{EAS+PS}_{\sigma=0}$ ,  $\text{EAS+PS}_{\sigma=0.375}$ , and  $\text{EAS+PS}_{\sigma_{\text{Max}}}$  for each subject. B, Grouped results ( $N=11$ ) of the SRT for the test conditions EAS,  $\text{EAS+PS}_{\sigma=0}$ ,  $\text{EAS+PS}_{\sigma=0.375}$ , and  $\text{EAS+PS}_{\sigma_{\text{Max}}}$ .

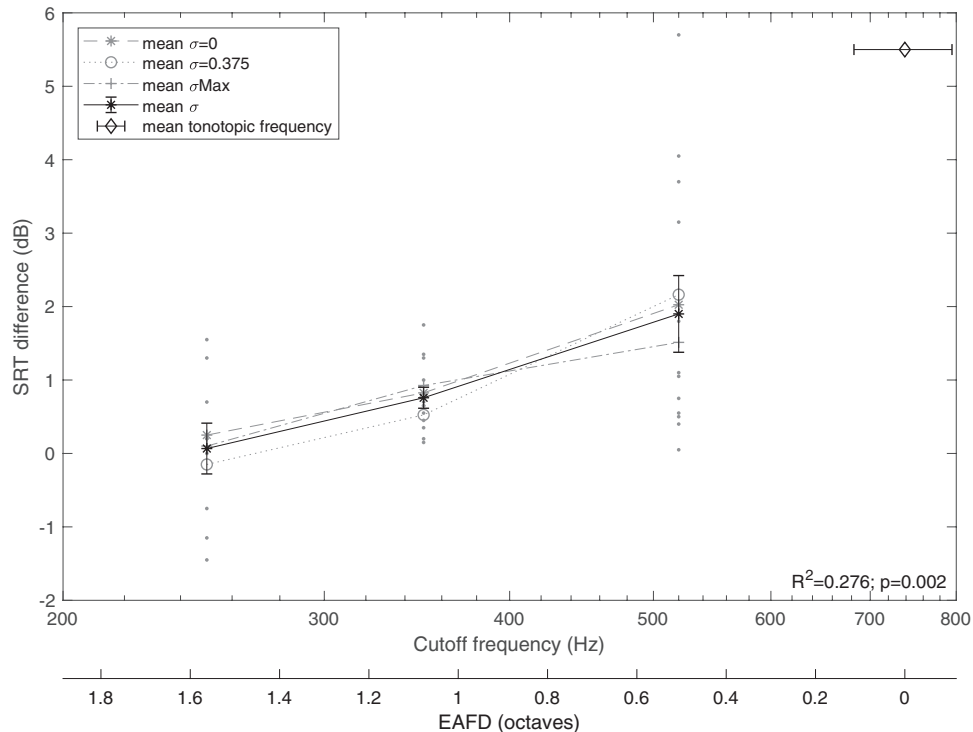


Fig. 9. Speech reception threshold (SRT) difference between the electric-acoustic stimulation (EAS)+PS and EAS conditions as function of cutoff frequency as well as electric-acoustic frequency difference (EAFD). The EAFD is estimated as the difference between the cutoff frequency of acoustic hearing and the tonotopic frequency associated to the most apical electrode across subjects. The SRT difference is shown for each EAS+PS condition using  $\sigma = 0$ ,  $\sigma = 0.375$  and  $\sigma_{\text{Max}}$  and as the mean across the different EAS+PS $_{\sigma}$  conditions. The mean tonotopic frequency was determined from the individual tonotopic frequencies that correspond to the location of the subject's most apical electrode.

frequency or its mean EAFD (Pearson correlation,  $p=0.002$ ,  $R^2=0.276$ ,  $N=11$ ) was observed. However, despite individual insertion angles, the EAFD is significantly correlated with the cutoff frequency (Pearson correlation,  $p=0.021$ ,  $R^2=0.466$ ,  $N=11$ ), and no correlation between the SRT difference and the EAFD at the individual level was observed.

## DISCUSSION

The present study investigated the use of phantom stimulation in EAS subjects to convey low-frequency information of speech through electric stimulation. The use of phantom stimulation for EAS is relevant for understanding the differences in performance benefit caused by adding low-frequency information through electric or acoustic stimulation and offers further possibilities for the assessment of interactions between both stimulation modalities in terms of speech understanding. The results showed that CI users benefited from low-frequency information provided via acoustic or phantom stimulation when additional bandwidth is provided. Furthermore, the results showed that an overlapped frequency bandwidth presented via simultaneous acoustic stimulation and phantom stimulation led to a significant deterioration in speech perception of EAS users.

### Speech Perception With EAS

Previous research showed that EAS provides significant benefits in speech understanding for subjects with substantial residual hearing (Gantz & Turner 2003; Gstöetner et al. 2008; Skarzynski et al. 2012). Similar effects were observed in the current study, all study participants obtained a benefit

from their ipsilateral residual hearing in combination with the CI (Figure 4). The addition of low-frequency acoustic stimulation provided a significant SRT improvement of 4.31 dB ( $p=0.005$ ) with respect to the ES condition using a limited bandwidth. Furthermore, results from the present study showed that across subjects, the benefit from low-frequency acoustic stimulation correlated with the used cutoff frequency ( $R^2=0.638$ ,  $p=0.003$ ,  $N=11$ ).

For subjects ID 12 and ID 14, the OLSA could not be performed using ES because they reached the maximum SNR at which the test could be conducted. This result may be explained by the large residual hearing of these subjects that may have prevented them to adapt well to ES alone and the fact that the ES condition was measured without providing them with some time for adaptation. Although no significant correlation was found between the ES SRTs and the cutoff frequencies across subjects, it is conceivable that the limited bandwidth using ES alone prevented the subjects ID 12 and ID 14 from completing the OLSA. However, the EAS SRTs of these subjects were in the range of EAS SRTs of the other subjects. This could indicate the largest benefit of low-frequency information for these subjects or even the benefit of acoustic stimulation in comparison to electric stimulation. If these two subjects were considered in the group analysis ( $N=13$ ) assuming an SRT of 25 dB (OLSA system limit) or worse the mean difference between EAS and ES would be  $>7.1$  dB with a  $p$  value of  $p \leq 0.005$ . Their high cutoff frequency of 520 Hz combined with their good hearing thresholds at 125 and 250 Hz (Table 1) may indicate that these subjects rely more on their residual hearing than the other subjects.

### Speech Perception With Electric-Phantom Stimulation

The current study showed that a sound coding strategy that conveyed low-frequency information through phantom stimulation significantly improved speech perception in noise in comparison to ES with a limited bandwidth even if phantom stimulation was activated without giving the subjects an acclimatization phase. It can be assumed that the observed benefit of EPS is caused by the extended bandwidth. However, previous studies could not show an improvement in speech perception by extending the bandwidth towards the low frequencies in ES mode alone (Dillon et al. 2015; Imsiecke et al. 2020; Karsten et al. 2013; Reiss et al. 2012). These previous studies modified the electrode-frequency allocation in ES listening mode. It is possible that the limited acclimatization phase provided to the subjects with the new electrode-frequency allocation was not sufficient to observe a significant difference between the restricted and the extended bandwidth conditions. In contrast, the current study extended the bandwidth through an additional phantom channel which allowed the use of the same electrode-frequency allocation for all other CI channels. Therefore, the subjects of the current study may have been less influenced by acclimatization effects when using the extended and the restricted bandwidth in comparison to the subjects tested in the previous studies of Imsiecke et al. (2020), Karsten et al. (2013), and Reiss et al. (2012). For this reason, we observed significant differences when extending the bandwidth using EPS.

On average, phantom stimulation ( $EPS_{\sigma=0.375}$  and  $EPS_{\sigma_{\text{Max}}}$ ) yielded significantly improved SRTs with respect to ES alone. No significant differences between  $EPS_{\sigma=0}$  and ES,  $EPS_{\sigma=0}$  and  $EPS_{\sigma=0.375}$ , as well as between  $EPS_{\sigma=0}$  and  $EPS_{\sigma_{\text{Max}}}$  were observed. It could be hypothesized that the improvement in SRT by adding additional bandwidth in comparison to ES, only observed for  $EPS_{\sigma=0.375}$  and  $EPS_{\sigma_{\text{Max}}}$  and not for  $EPS_{\sigma=0}$ , may be associated to an increased pitch discriminability elicited by phantom stimulation using higher values of  $\sigma$  with respect to the most apical HiRes Optima channel. This hypothesis is supported by the lack of pitch discrimination observed in subject ID 11 who was not able to discriminate between the most apical HiRes Optima channel and phantom stimulation for  $\sigma=0$  (Table 4). Moreover, this subject obtained worse SRTs using  $EPS_{\sigma=0}$  ( $\sigma=0$ ) in comparison to ES. However, it is important to mention that increasing the value of  $\sigma$  increments the likelihood of unpleasant sound sensations (Table 4) or pitch reversals for some subjects (Saoji and Litvak 2010; Lamping et al. 2020).

### Speech Perception With EAS and With EPS

The current study showed that SRTs can be improved due to low-frequency information conveyed through EAS as well as EPS. Moreover, no significant differences in SRT between EAS and EPS ( $p=0.099$ ,  $N=9$ ) were observed. However, the two subjects ID 12 and ID 14 excluded from the analysis were not able to perform the OLSA without acoustic stimulation or with phantom stimulation which shows the limitation of conveying low-frequency information through phantom stimulation. If these two subjects were considered in the group analysis ( $N=11$ ) assuming a SRT of 25 dB or worse for the conditions where no speech perception was measurable, the differences between the groups ES, EPS, and EAS would still be significant (Friedman's test,  $p<0.001$ ,  $N=11$ ). Furthermore, there would be a significant difference between EPS and EAS SRTs (mean difference

$\geq 5.45$  dB and  $p<0.043$ ). As mentioned before, one reason why subjects ID 12 and ID 14 exceeded the OLSA's system limit without acoustic stimulation could be that they relied more on acoustic stimulation and were not accustomed to electric stimulation alone because of their good residual hearing.

There is evidence that the encoding of low-frequency acoustic information in EAS improves speech understanding performance. This low-frequency information includes acoustic features of speech such as the temporal fine-structure, the fundamental frequency and linguistic cues, including voicing and lexical boundaries (Brown and Bacon 2010). The benefits of encoding low frequencies through EAS motivated the design of sound coding strategies that also encode low-frequency information through phantom stimulation for regular CI users (e.g. Carlyon et al. 2014; Nogueira et al. 2015). However, these studies found no benefit (Carlyon et al. 2014) or limited benefit of these strategies after one month of use (Nogueira et al. 2015) in terms of speech understanding. The results from these studies may indicate that the perception of acoustic features conveyed through low-frequency phantom stimulation is subject to similar limitations as regular electric stimulation. In contrast to Carlyon et al. (2014) and Nogueira et al. (2015), the current study investigated the use of phantom stimulation in subjects that received a limited bandwidth through ES. Therefore, more benefit through phantom stimulation was to be expected for EPS in comparison to the studies of Carlyon et al. (2014) and Nogueira et al. (2015). Furthermore, in contrast to Carlyon et al. (2014) and Nogueira et al. (2015), the tested subjects were EAS users that have more experience using low-frequency cues. It is possible that the tested subjects received more benefit from EPS than CI users without residual hearing.

Although acoustic stimulation and phantom stimulation were individually matched in loudness to electrical stimulation, it cannot be excluded that there were some differences in loudness between EAS and EPS conditions that may have influenced the results. However, both acoustic stimulation as well as phantom stimulation were fitted to elicit a comfortable loudness perception in combination with the HiRes Optima strategy. Therefore, it can be assumed that if there were differences in loudness between EAS and EPS, these differences were relatively small.

The lack of significant differences between EPS and EAS for subjects who could perform the OLSA using ES alone may be explained by the fact that the OLSA was performed using stationary background noise. There is evidence that the advantage of EAS becomes more prominent when speech understanding is measured in a competing talker situation (e.g., Gantz et al. 2005; Turner et al. 2004), for example, because EAS users obtain improved speech perception with better access to the fundamental frequency difference between a target and a masking speaker (Carroll et al. 2011; Auinger et al. 2017). Therefore, one can speculate that the difference in speech understanding between EAS and EPS may become larger if measured under non-stationary noise or in a competing talker situation. As shown by Luo and Garrett (2020), phantom stimulation with a dynamic  $\sigma$  (varying  $\sigma$  over time) can be used to convey time-varying pitch contours (flat, rising and falling) in CI users. Therefore, it would be conceivable to encode low-frequency speech cues using a dynamic  $\sigma$  in EPS to further enhance speech perception, maybe even under non-stationary noise conditions.

It still remains unclear whether EPS could provide further benefits after a long acclimatization time in comparison to current



sound coding strategies that convey the full frequency range electrically. However, EPS could potentially be used to substitute the acoustic component in EAS users without requiring a change in their accustomed electrode–frequency allocation. Specially, the current study showed an acute benefit due to low-frequency information when the conveyed frequency bandwidth was extended through phantom stimulation for those subjects who obtained measurable SRTs with ES. As shown by Büchner et al. (2009), SRTs in noise were significantly deteriorated if EAS users switched from a fitting with separated bandwidths for electric and acoustic stimulation to a fitting that used the full frequency range of a CI (approximately from 200 to 7000 Hz) through electric stimulation only. Furthermore, Imsiecke et al. (2020) investigated the effect of frequency bandwidth conveyed through electric stimulation in EAS users and reported that only some users tolerated the electrode–frequency allocation change caused by bandwidth extension delivered through ES. For this reason, Imsiecke et al. (2020) limited the bandwidth extension for ES to two octaves. However, that study could not observe a significant benefit for ES alone even after an acclimatization phase of approximately 4 weeks. In these situations, phantom stimulation could be used to convey the low frequency bandwidth without changing the accustomed electrode–frequency allocation and obtain an acute improvement for EAS users with a deactivated acoustic component.

### Speech Interaction With Electric-Acoustic Stimulation

The current study showed that low-frequency information conveyed via phantom stimulation significantly improved SRTs with respect to ES, but worsened SRTs in combination with EAS (EAS+PS). Averaged across subjects, EAS+PS led to significantly deteriorated SRTs of 0.99 dB in comparison to EAS alone, with a maximum of 5.7 dB at the individual level. These findings confirmed the results from previous studies (Imsiecke et al. 2020; Karsten et al. 2013; Vermeire et al. 2008) and show that EAS users with low frequency residual hearing performed better when they used a spectrally separated frequency bandwidth fitting in comparison to a spectrally overlapped fitting. Furthermore, the current results supplemented previous findings (Imsiecke et al. 2020; Karsten et al. 2013; Vermeire et al. 2008) showing that a spectrally overlapped bandwidth between electric and acoustic stimulation led to a deterioration of SRTs in comparison to spectrally separated fittings even if the electric extended frequency bandwidth conveyed by phantom stimulation improved the speech understanding performance using ES only.

The deterioration in SRT observed with EAS+PS is supported by the results from previous studies by Karsten et al. (2013) and Imsiecke et al. (2020) that compared non-overlapping fittings with overlapping fittings. This deterioration was observed after an acclimatization period of approximately 4 weeks. The acclimatization period was provided because the overlapping fitting required a change in the electrode–frequency allocation. In the current study, it can be speculated that performance with EAS+PS could improve if an acclimatization period would have been given because the EAS condition was very similar to the subject's familiar listening mode, whereas EAS+PS could be considered as an unfamiliar listening mode. However, we hypothesize that this potential familiarization effect may be rather small. Reasons for this are: (1) The addition of phantom stimulation in the EAS+PS condition did not change the electrode–frequency allocation table; (2) most subjects obtained an acute benefit from low-frequency information

conveyed through phantom stimulation in the EPS condition with respect to the ES condition.

The decrease in performance observed with the EAS+PS condition in comparison to the EAS condition can be interpreted as an interaction between electric and acoustic stimulation caused by both, spectral and/or spatial effects (Karsten et al. 2013; Imsiecke et al. 2020). For example, Karsten et al. (2013) reported worse speech understanding performance with EAS using spectrally overlapped fittings. However, they reported no psychoacoustic or electrophysiological interaction, which may be explained by the short electrode arrays and the limited residual hearing of the tested subjects. Therefore, the observations by Karsten et al. (2013) may be explained by spectral interaction rather than spatial interaction. However, psychoacoustic EAS masking studies (Imsiecke et al. 2018; Kipping et al. 2020; Krüger et al. 2017; Lin et al. 2011) showed increased masking when the electric and the acoustic stimulation were delivered to similar spatial locations in the cochlea. Furthermore, Imsiecke et al. (2020) showed a correlation between EAS masking and the deterioration of SRTs using overlapped with respect to non-overlapped fittings. In contrast to Karsten et al. (2013), their result could indicate a contribution of spatial interaction.

In the current study, EAS speech interaction increased with spectrally expanded residual hearing indicated by an increased cutoff frequency, which led to decreased EAFDs and therefore could also indicate that EAS speech interaction is related to psychoacoustic EAS masking as shown by Imsiecke et al. (2020). Moreover, Saoji et al. (2018) showed that phantom stimulation, similarly to a physical electrode contact, masked acoustic pure tones. Therefore, phantom stimulation caused more psychoacoustic masking compared to monopolar stimulation. The authors argued, the spatial distance between electric and acoustic stimulation could be decreased due to shifting the electrical field by the use of phantom stimulation, which led to an increase of psychoacoustic masking (Saoji et al. 2018). Consequently, it could be assumed that both spectral and spatial effects may contribute to the observed deterioration in SRT comparing EAS+PS to EAS. The amount of spatial interaction could be increased by adding phantom stimulation in the apical cochlear regions, although modifying the amount of overlap location through different  $\sigma$  did not result in significant differences in speech understanding interaction. However, in the current study, the separated examination of spatial effects caused by the EAFD or the amount of spectral overlap is restricted by the correlation between both. Therefore, the current study cannot conclusively answer to what extent the proportion of spectral or spatial effects are responsible for the observed deterioration of SRTs with the EAS+PS condition and further investigation are is required.

### Potential Clinical Applications

For CI, users who no longer benefit from their residual hearing, phantom stimulation could be used as an acute treatment to reduce the adaptation time to electric stimulation alone and therefore to compensate for their potential decrease in speech perception performance. For example, it would be possible to gradually increase the bandwidth assigned to the phantom channel to treat EAS users with progressive hearing loss after implantation. In case of a defective acoustic component, phantom stimulation could bridge the time to the next technical or clinical appointment.

## CONCLUSIONS

The current study showed that CI users with low acoustic residual hearing benefit from low-frequency information conveyed in combined EAS. Furthermore, EAS users obtained advantages of low-frequency information conveyed through phantom stimulation that otherwise is usually conveyed through acoustic stimulation. For subjects who's SRT was measurable with electric stimulation alone, no significant difference in speech perception was observed between low-frequency information conveyed through acoustic or phantom stimulation. However, two subjects were not able to perform the OLSA test without using acoustic stimulation. Moreover, the results from the current study showed that speech perception was deteriorated by the simultaneous presentation of low-frequency information through acoustic and phantom stimulation indicating interaction between electric and acoustic stimulation.

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