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Research Paper

Perceptual changes with monopolar and phantom electrode stimulation

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A B S T R A C T

Phantom electrode (PE) stimulation is achieved by simultaneously stimulating out-of-phase from two adjacent intra-cochlear electrodes with different amplitudes. If the basal electrode stimulates with a smaller amplitude than the apical electrode of the pair, the resulting electrical field is pushed away from the basal electrode producing a lower pitch. There is great interest in using PE stimulation in a processing strategy as it can be used to provide stimulation to regions of the cochlea located more apically than the most apical contact on the electrode array. The result is that even lower pitch sensations can be provided without additional risk of a deeper insertion. However, it is unknown if there are perceptual differences between monopolar (MP) and PE stimulation other than a shift in place pitch. Furthermore, it is unknown if the effect and magnitude of changing from MP to PE stimulation is dependent on electrode location. This study investigates the perceptual differences (including pitch and other sound quality differences) at multiple electrode positions using MP and PE stimulation using both a multidimensional scaling procedure (MDS) and a traditional scaling procedure.

10 Advanced Bionics users reported the perceptual distances between 5 single electrode (typically 1, 3, 5, 7, and 9) stimuli in either MP or PE ($\sigma = 0.5$) mode. Subjects were asked to report how perceptually different each pair of stimuli were using any perceived differences except loudness. Subsequently, each stimulus was presented in isolation and subjects scaled how "high" or how "clean" each sounded.

Results from the MDS task suggest that perceptual differences between MP and PE stimulation can be explained by a single dimension. The traditional scaling suggests that the single dimension is place pitch. PE stimulation elicits lower pitch perceptions in all cochlear regions. Analysis of Cone Beam Computer Tomography (CBCT) data suggests that PE stimulation may be more effective at the apical part of the cochlea. PE stimulation can be used for new sound coding strategies in order to extend the pitch range for cochlear implant (CI) users without perceptual side effects.

1. Introduction

Cochlear implants (CIs) provide people with severe to profound hearing loss the ability to understand speech. The CI is a hearing device which uses intracochlear electrodes to electrically stimulate spiral ganglion cells. Most electrode arrays are designed to be inserted only into the first (basal) 1–1.25 turns into the cochlea (e.g. Landsberger et al., 2015) which represents frequencies of approximately 650 Hz and above along the spiral ganglion of a normal ear (e.g. Stakhovskaya et al., 2007). Both changes in timing and place of excitation are described as changes in pitch. Yet a change in rate and a change in place are perceptually orthogonal (e.g. Tong et al., 1983; Landsberger et al., 2016). Thus, the perceptual differences are described as place and rate pitch. There are limitations on the range of place pitches provided by a CI – such as the length and the insertion depth of the electrode array (e.g. Macherey and Carlyon, 2012). The stimulation depth of the cochlea may be extended using longer electrode arrays (e.g. Schatzer et al., 2014) or by shaping the electrical field towards the apical regions (e.g. Saoji and Litvak, 2010; Macherey et al., 2011). Although apical stimulation of the cochlea through deeply inserted electrodes has been shown to increase the range of place pitches (e.g. Landsberger et al., 2014), it is

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Abbreviations

ALSCAL	Alternating Least Squares Scaling
ANOVA	Analysis of Variance
BEDCS	Bionic Ear Data Collection System
CBCT	Cone Beam Computer Tomography
CI	Cochlear Implant
CL	Cochlear Length
DICOM	Digital Imaging and Communications in Medicine
H	Helicotrema
INDSCAL	Individual Difference Scaling
MDS	Multidimensional Scaling
MP	Monopolar
OC	Organ of Corti
PE	Phantom Electrode
PS	Pitch Shift
PTP	Partial Tripolar Stimulation
RW	Round Window
SG	Spiral Ganglion

unknown whether more apical stimulation through electrical field shaping is able to extend pitch range without changing additional perceptual qualities. This work investigates pitch perception and sound quality produced by extended apical stimulation through electrical field shaping.

The most common stimulation mode used in commercial CI strategies is monopolar (MP) stimulation. In this mode, current flows between an intra-cochlear and a remote extra-cochlear ground electrode. Typically, it is assumed that the pitch elicited by electrical stimulation corresponds to the center of masses (centroid) of the electrical field created by the stimulation mode (Wu and Luo, 2013; Nogueira et al., 2017). In MP stimulation the centroid of the electrical field is near the stimulating electrode. In order to steer the centroid beyond the most apical electrode, electrical field shaping can be used. While the relative order of place pitch is predictable from the tonotopic organization, the absolute pitch corresponding to a place of stimulation is unclear. The position of each electrode can be estimated using various imaging techniques such as X-Rays (e.g. Landsberger et al., 2015) or Cone Beam Computer Tomography (CBCT; e.g. Würfel et al., 2014; Nogueira et al., 2016). Electrode positions can be converted into the corresponding perceived frequencies using the Greenwood function (Greenwood, 1990) or the Stakhovskaya correction (Stakhovskaya et al., 2007). Carlyon et al. (2010) did pitch matches to an acoustic normal hearing ear direct at activation of the CI and found that the pitch elicited by the electrodes could be well predicted by Greenwood's function. Vermeire et al. (2015) found pre-activation pitch matches to be lower than expected by Stakhovskaya. However, the pitch corresponding to a given location shifts towards the frequencies encoded by the electrode with time (e.g. Reiss et al., 2007).

One method to shape the electrical field is phantom electrode (PE) stimulation. In PE stimulation two adjacent electrodes are simultaneously stimulated out-of-phase with different amplitudes (Fig. 1b). The most apical (primary) electrode is stimulated with the current I whereas the adjacent (compensating) electrode is stimulated with $-I^{*}\sigma$. The ratio of the current between the compensating and the primary electrode is defined as σ. The resulting electrical field is pushed away from the most apical electrode (towards the apex) and therefore produces a lower pitch. It has been shown that PE stimulation can achieve pitch shifts equivalent to 0.5 to 2 MP electrodes if applied to electrodes located in the center of the electrode array (Saoji and Litvak, 2010). However, the equivalent pitch shift at the most apical electrode is unknown and had not been previously studied. Additionally, it is unknown whether there are perceptual differences between PE and MP stimulation other than place pitch. PE stimulation may create a narrower spread of excitation in the cochlea relative to MP stimulation (Saoji et al., 2013). This fact may cause differences in timbre or spectral shape perception between MP and PE stimulation. For example, Landsberger et al. (2012) and Padilla and Landsberger (2016) showed that subjective scaling of certain verbal descriptors (Clean/Dirty, Pure/Noisy) correlated with spread of excitation changes caused by shifting from unfocused to focused stimulation.

To determine if there are any perceptual differences other than a place pitch shift, a multidimensional scaling (MDS) test was conducted comparing MP and PE stimulation at multiple electrodes/cochlear locations. MDS is a technique that has been successfully used to investigate perceptual differences between different stimulation rates (Lawless, 1986; Tong et al., 1983) and electrode insertion depths (Landsberger et al., 2014). Using MDS, it can be

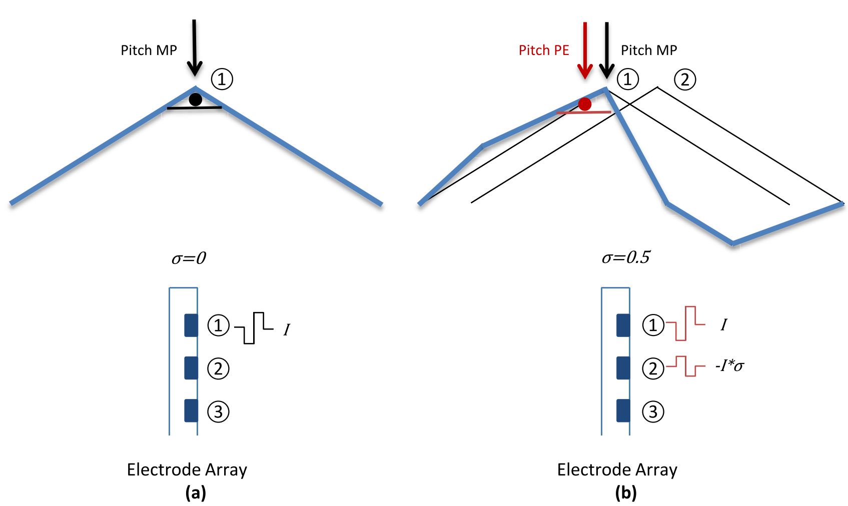

Fig. 1. Schematic illustration of the Phantom effect for σ = 0 (a) and σ = 0.5 (b) on pitch perception adapted from Nogueira et al. (2015). The electrical field is stimulated using triangular functions and assumes linear superposition of the electrical field produced by each electrode. The centroid of the electrical field is assumed to be related to the pitch elicited by the MP stimulation. Using PE stimulation, it is possible to push the electrical field away from the most apical electrode.

determined if the perceptual differences between MP and PE stimulation can be explained by the same perceptual dimension as a change of place (indicating PE stimulation only shifts place pitch) or if there is an additional perceptual dimension that describes the difference. While MDS can describe the magnitude of perceptual differences as well as the number of perceptual dimensions represented by a stimulus set, it cannot explain what perceptual qualities or differences might be associated with a given perceptual dimension. To provide further insight, a second scaling experiment was conducted where the sound quality and the pitch of MP and PE stimulation was scaled. The perceptual changes from the apical to the central part of the electrode array were compared with CBCT data to determine the electrode position and thus the corresponding relative place pitch of the electrodes. Furthermore, the CBCT data were used to indicate the magnitude of place pitch shifts in octave units along the spiral ganglion. Both the Greenwood (1990) and Stakhovskaya et al. (2007) methods were used for the calculation of the corresponding relative place pitch in frequency units.

2. Methods

2.1. Subjects

10 users of the Advanced Bionics CII, HiRes90k or HiRes90k Advantage implants participated in the study. Subjects were bilateral or unilateral CI users without residual hearing on the contralateral ear. For bilateral CI users, only the better ear in terms of speech performance was tested. All subjects provided informed consent in accordance with the ethics committee of the Medical University of Hannover (MHH). Only Advanced Bionics devices were used because of the need to simultaneously stimulate several electrodes in- or out-of-phase, requiring multiple independent current sources.

Table 1 shows the specific subject demographics. Data were collected at the MHH.

2.2. Estimation of the characteristic frequency for each electrode location

The characteristic frequency associated with each electrode can be estimated using the Greenwood equation (Equation (1)) with the correction proposed by Stakhovskaya et al. (2007). This equation transforms the geometrical distance between each electrode and the helicotrema (D_H) into estimated characteristic frequencies:

$$F = A \cdot 10^{a x_H} - k, \qquad (1)$$

where $A = 165.4$, $a = 2.1$, $k = 0.88$ and $x_H = \frac{D_H}{CL}$ as provided by Greenwood (1990).

Electrode location and cochlear length estimation can be obtained from temporal bone CBCT data. CBCT data were collected during CI surgery using a stationary Xoran MiniCat (Ann Arbor, MI, USA) equipped with a 536 × 536 matrix detector resulting in 0.3 mm × 0.3 mm × 0.3 mm isotropic voxels (125 kVp, 7 mA). Multiplanar reconstruction from the Digital Imaging and Communications in Medicine (DICOM) data was performed using OsiriX MD (Pixmeo, Geneva, Switzerland). First, different landmark positions along the cochlea's lateral wall were identified from the round window (RW) to the helicotrema (H) (Fig. 2). Afterwards, these landmarks were used to unroll the cochlea (Fig. 2c) such that the cochlear length (CL) and the electrode locations could be estimated (Würfel et al., 2014). Next, the distance between the RW and each electrode position (D_{RW}) was measured to get the Organ of Corti (OC) distance. The RW was taken as reference because in the unrolled view it is difficult to observe the H. Afterwards the OC distance was projected into the spiral ganglion (SG) distance by

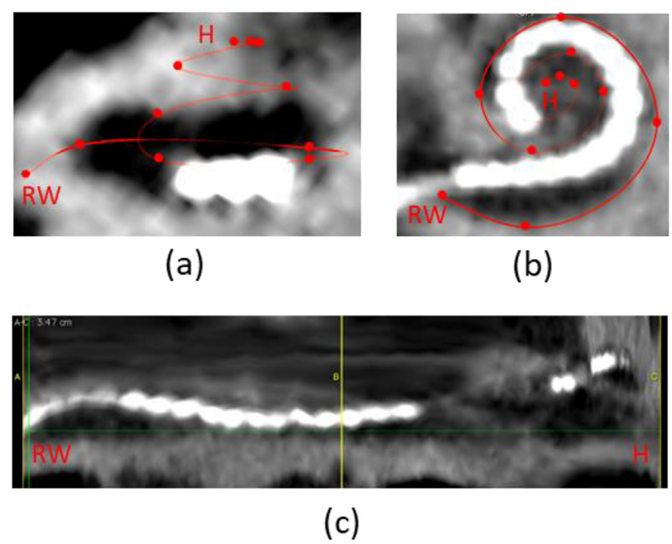

Fig. 2. Method to estimate the electrode position from CBCT. Panels a) and b) show the postoperative scans in the sagittal and axial planes, respectively. The round window is indicated as RW and the helicotrema as H. Additional landmarks along the lateral wall of the cochlea are indicated with circles. The c) panel shows the unrolled cochlea.

Table 1
Subject demographics and performance scores.

Subject	Tested Ear	Contralateral Ear	Age at surgery [years]	Duration of CI use at time of testing [years]	Clinical strategy	Clinically deactivated electrodes	Cochlear length [mm]	Etiology	Implant type
S1	Right	CI	56.1	5.1	Optima	1, 16	40	genetic	HiRes90K Helix
S2	Right	CI	43.0	9.6	Optima	–	38.5	genetic	HiRes90K Helix
S3	Left	CI	44.5	7.9	Optima	–	35.2	unknown	HiRes90K Helix
S4	Left	Deaf	67.2	6.5	Optima	1, 10	–	unknown	HiRes90K Helix
S5	Right	CI	33.8	15.5	Optima	–	–	genetic	CII
S6	Right	CI	62.0	3.6	Optima	–	34.8	unknown	HiRes90k Advantage HiFocus Mid-Scala
S7	Right	Deaf	61.9	6.7	Optima	–	–	acute hearing loss	HiRes90K Helix
S8	Left	CI	41.5	9.5	Optima	–	–	unknown	HiRes90K Helix
S9	Left	CI	43.8	1.8	Optima	–	–	acute hearing loss	HiRes90k Advantage HiFocus Mid-Scala
S10	Right	CI	48.5	6.8	Optima	–	–	skull fracture	HiRes90K Helix

using the following equation:

$$y(x_{Base}) = \frac{100}{1 + \left(B\frac{100}{x_{Base}} + C\frac{x_{Base}}{100} - B - C\right)^2}, \quad (2)$$

where $B = 0.22$, $C = -0.93$, x_{Base} is the relative distance from a given location at the OC of the cochlea to the base of the OC relative to the CL (Stakhovskaya et al., 2007) or $x_{Base} = 1 - x_H$ and $y(x_{Base})$ is the relative distance of the corresponding location along the SG.

In order to change the reference landmark from the RW to the H, the D_{RW} is substracted from the CL ($D_H = CL - D_{RW}$). Finally, the D_H distance is normalized with respect to the CL and introduced in Equation (1) to estimate the characteristic frequency associated with each electrode (F_{el}). The relative frequency differences between each pair of electrodes can be given in Hz or in octaves.

2.3. Experiment 1: MDS: $PE_{\sigma=0.5}$ vs MP

2.3.1. Stimuli

All stimuli were composed of trains of charge-balanced, symmetric, anodic leading, biphasic pulses. The electrode attached to the case of the device on the implant was used as the distant ground. The stimuli consisted of MP and PE pulse trains (phase duration = 194 μs) presented by default on electrodes 1, 3, 5, 7 and 9 at a rate of 1000 pulses per second (pps). A total of 10 stimuli (5 electrodes x 2 modes) were used in the experiment. If there were patients with any of the listed electrodes deactivated, the measured electrodes were shifted by one electrode towards the base. For PE, σ was set to 0.5. This value was chosen because in Nogueira et al. (2015) this configuration of PE elicited a lower pitch sensation than MP stimulation in all subjects without causing a pitch reversal. A long phase duration was used to ensure comfortable loudness could be achieved for all stimuli and for all subjects without exceeding the maximum compliance voltage of the device. All pulse trains had a duration of 500 ms. All stimuli were delivered using the Bionic Ear Data Collection System (BEDCS) 1.17 and custom software. The BEDCS software has been used in previous studies, e.g. Carlyon et al. (2010, 2014), Macherey and Carlyon (2012) and Landsberger et al. (2012).

2.3.2. Procedure

MDS describes the magnitudes of perceptual differences between all stimuli in a stimulus set. A typical MDS analysis, such as ALSCAL (Young and Lewyckyj, 1979) determines the best fit of the distances between all of the stimuli in an N-dimensional space from a matrix consisting of the perceptual differences between all stimuli. MDS includes a set of techniques that can be used to display the information contained in a distance matrix created by rating the subjective perception elicited by stimuli presented in pairs. MDS transforms the distances between these pairs of stimuli in an N-dimensional space such that the distances between all pairs of stimuli used in the experiment are preserved as well as possible. In the N-dimensional space each object is located by coordinates. Kruskal and Wish (1978) proposed that the number of dimensions which should be used for MDS analysis is equal to the number of stimuli divided by four. In this experiment 10 different stimuli were used and for this reason the number of dimensions used to analyze the MDS was fixed to two. Typically, if a horse-shoe shape is observed in the two-dimensional scatter plot it is assumed that the distances between the stimuli can be explained by a single dimension. A MDS procedure was used to measure the perceptual dissimilarity between PE and MP stimulation at different electrode locations. Prior to the MDS, all stimuli were loudness balanced. The loudness balancing procedure consisted of two steps. First, the MP and the PE sounds were presented at 0 μA and the amplitude was gradually increased in 10 μA steps until the subject indicated that the sound was perceived as "comfortably soft". Next, the step size was reduced to 2 μA until "the comfortably loud level" was reached. A scale from 1 to 10 in which 1 was equivalent to "just noticeable", 5 was equivalent to "comfortably soft", 7 was equivalent to "comfortably loud" and 10 was equivalent to "very loud", was used. In the second step, four consecutive stimuli ordered from apex to base were presented sequentially at the "comfortably loud level" (e.g. MP_{el1}, PE_{el1}, MP_{el3}, PE_{el3}) and the subject was asked which stimuli differed in loudness. Next, the loudness of the corresponding stimuli was re-adjusted and the same question was repeated until the subject reported that the 4 stimuli were equally loud. The procedure was then repeated removing the two most apical stimuli and including two new stimuli towards the base (e.g. MP_{el3}, PE_{el3}, MP_{el5}, PE_{el5}). In this new procedure, only the level of the two new stimuli could be re-adjusted.

After loudness balancing, all the stimuli were presented in series to the subjects to familiarize them with the range of stimuli in the experiment. Before the familiarization, subjects were informed that they would have to rate any difference between the sounds they heard (except differences in loudness) and that all the possible sounds would be presented to them during the familiarization process. However, the specific terms on how to scale the sounds were not explained to the subjects in advance. After familiarization, the main experiment began.

In a given MDS trial, two stimuli were randomly selected and presented with a 500 ms inter-stimulus-interval (ISI). Subjects had to scale how different the two stimuli were perceived by using the computer mouse to click on a bar on the screen (see Fig. 2 from Landsberger et al., 2016). The bar represented "most similar" on its left extreme and "most different" on its right extreme. The subjects were able to select any location on the bar. These clicks were converted into numerical values ranging from 0 ("most similar") to 100 ("most different"). The location of the bar was randomly changed after each trial. This prevented the subject from repeatedly clicking at the same location. In a block of trials, each possible pair from the 10 stimuli was compared, resulting in 100 comparisons. Each comparison was repeated 5 times, resulting in 500 trials.

2.4. Experiment 2: pitch shift and sound quality scaling: $PE_{\sigma=0.5}$ vs MP

2.4.1. Stimuli

Stimuli were pulse trains of PE or MP delivered to the same electrodes with the same rate, amplitude and pulse duration as described in the previous experiment.

2.4.2. Procedure

In a single trial, subjects were presented one randomly selected single pulse train in MP or PE stimulation mode on any tested electrode (usually 1, 3, 5, 7 or 9) using a method similar to Landsberger et al. (2012). All stimuli were loudness balanced from Experiment 1. Subjects were asked to scale "How high is the sound?". As in Experiment 1, subjects used a computer mouse to click on a bar on the screen. The range of the bar represented "not high at all" (corresponding to 0) on the left extreme to "very high" (corresponding to 100) on the right one. The subjects were able to click the mouse on any position of the bar. Again, the location of the bar changed between trials to ensure that the subject had to move the mouse to make a new selection for every trial. Each sound was scaled 15 times, totaling 150 trials.

The same scaling procedure was repeated with the same stimuli to scale the question "How clean is the sound?". The bar on the screen now represented "not clean at all" on the left extreme and

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"very clean" on the right one.

3. Results

3.1. Experiment 1: MDS: $PE_{\sigma=0.5}$ vs MP

Fig. 3 presents the individual and the combined MDS results using the alternating least squares scaling (ALSCAL) and the individual difference scaling (INDSCAL) algorithm (Young and Lewyckyj, 1979).

The individual ALSCAL plots have similar shapes and show r^2-values varying from 0.7 to 0.89 and stress values varying from 0.19 to 0.3. The inputs of the INDSCAL analysis are the individual distance matrices of all subjects. The r^2 and the stress values for the INDSCAL were 0.90 and 0.17 respectively, indicating a good fit to the data. The INDSCAL was also computed for three and four dimensions but the stress of the model only decreased marginally. An analysis in three dimensions revealed also a horse-shoe shape which projected onto two dimensions was very similar to the result presented in Fig. 3 (grey background panel).

Fig. 3 shows that although there is a great deal of variability across subjects, most subjects perceptually organize the different electrode locations and stimulation modes in a horse-shoe shape. The outputs of an MDS experiment are typically organized in such a horse-shoe shape when the data can be explained by just one dimension. The reason for this shape is that the magnitude of small perceptual differences is normally overestimated and large differences underestimated, causing the single-dimensional perceptual space to bend (Kendall, 1971).

S4 and S6 were the only subjects not showing the regular horse-shoe shape. S4 was excluded from the combined INDSCAL analysis because this participant did not rate physically identical sounds as similar. For this subject, the average difference between two identical stimuli was 41 units, whereas the average difference for all other subjects was 6 units (0 units corresponds to "most similar" and 100 to "most different"). S6 however, rated two identical sounds with an average of 14 units suggesting that this subject conducted the task correctly. This subject was the only participant for whom the ALSCAL analysis does not show such a horse-shoe shape.

It is interesting to note that the INDSCAL analysis presented in Fig. 3 shows that the perception elicited by MP5 and PE5 is very similar. Note that most of the subjects show clear differences between PE5 and MP5 in the ALSCAL plot, but these differences are smoothed in the INDSCAL because the relative order of appearance in the horse-shoe shape is reversed from subject to subject. To a lesser extent, the same happens for the pair MP1-PE1.

In summary, the INDSCAL results are organized in a horse-shoe shape, indicating that the perceptual differences between electrode locations and stimulation modes can be explained by a single dimension. Most probably the single dimension is related to place pitch because the horse-shoe shape is organized by electrode. The following experiments have been designed to confirm whether the single dimension is indeed pitch.

3.2. Experiment 2: pitch shift and sound quality scaling: $PE_{\sigma=0.5}$ vs MP

Fig. 4 presents the individual and trimmed mean responses for the scaling procedure to assess how clean the sound is perceived for different electrode locations and stimulation modes. For each subject, stimulation mode, and electrode position, the 20% trimmed mean was calculated. Trimmed means were used to reduce the effects of asymmetric tails in the distribution that are likely to occur as a result of floor and ceiling effects created by a restricted response range (e.g. Aronoff et al., 2011; Wilcox et al., 1998).

A two-way repeated measures analysis of variance (ANOVA) revealed no significant effect of electrode location ($F(1.5,11.9) = 3.72$, $p = .066$), stimulation mode ($F(1,8) = 3.58$, $p = .095$) or the interaction between both ($F(1.7,14) = 0.12$, $p = .858$) on how clean the sound is perceived.

Fig. 5 presents the results for the pitch height scaling experiment. Note that the analysis of the pitch scaling results assumes equal pitch distance along the whole scale from 0 to 100.

A two-way repeated measures of ANOVA indicated a significant effect of stimulation mode ($F(1,8) = 9.36$, $p = .016$), electrode location ($F(1.6,12.9) = 57.35$, $p < .001$) and their interaction ($F(4,32) = 4.24$, $p = .007$) on pitch height perceived. Although the p-values for all pairs being compared, except the pairs (MP5-PE5 and MP7-PE7), are all 0.05 or less (MP1 vs. PE1, $t(8) = 2.71$, $p = .027$; MP3 vs. PE3, $t(8) = 2.48$, $p = .038$; MP5 vs. PE5, $t(8) = -0.36$, $p = .728$, MP7 vs. PE7, $t(8) = 2.21$, $p = .058$ and MP9 vs. PE9, $t(8) = 7.01$, $p < .001$), all the results except the result for the pair MP9-PE9 are not statistically significant after using Rom's method (Rom, 1990) to correct for family-wise type-I error. These results indicate a trend towards a lower pitch perception elicited by PE in contrast to MP stimulation at any electrode location. It is interesting to note that the small differences in the pairs PE1-MP1 and PE5-MP5 have been not only observed in the pitch height but also in the MDS results.

Fig. 6 presents the pitch shift calculated from the traditional pitch scaling procedure. The pitch shift is estimated using the following equation:

$$PS_i = MP_i - PE_i, \tag{3}$$

where PS is the pitch shift and i the electrode number.

3.3. Estimation of the pitch shift produced by PE stimulation from MDS results

The MDS analysis has shown that a single dimension can explain the perceptual differences between stimulation modes and electrode locations. The scaling experiments suggest that this dimension is most likely pitch. For this reason, the MDS perceptual differences along the horse-shoe curve can now be re-interpreted as pitch differences. The magnitude of the pitch differences between PE and MP stimulation from the MDS results presented in Fig. 3 is estimated using the following equation:

$$PS_i = 2 \cdot \frac{|P(PE_i - MP_i)|}{|P(MP_{i-2} - MP_i)|}, \tag{4}$$

where PS is the pitch shift in electrodes, i indicates the electrode location of the main electrode and P represents the perceptual difference elicited by two stimuli obtained from the MDS scaling procedure. Note that Equation (4) assumes a linear distribution of pitch across electrodes. This assumption is based on the Greenwood equation which linearly relates cochlear location in mm with frequency in octaves.

In Equation (4), a factor of 2 was introduced because the distance between two MP stimuli in the denominator corresponds with 2 electrodes. Equation (4) can only provide information about the magnitude of the pitch shift but not about its direction, i.e. towards the base or towards the apex. The estimated pitch shift for each electrode location averaged for all study participants is presented in Fig. 7.

A one-way repeated measures ANOVA detected a significant effect of electrode location on the magnitude of the pitch shift produced by PE stimulation ($F(4,32) = 4.99$, $p = .003$). A post-hoc

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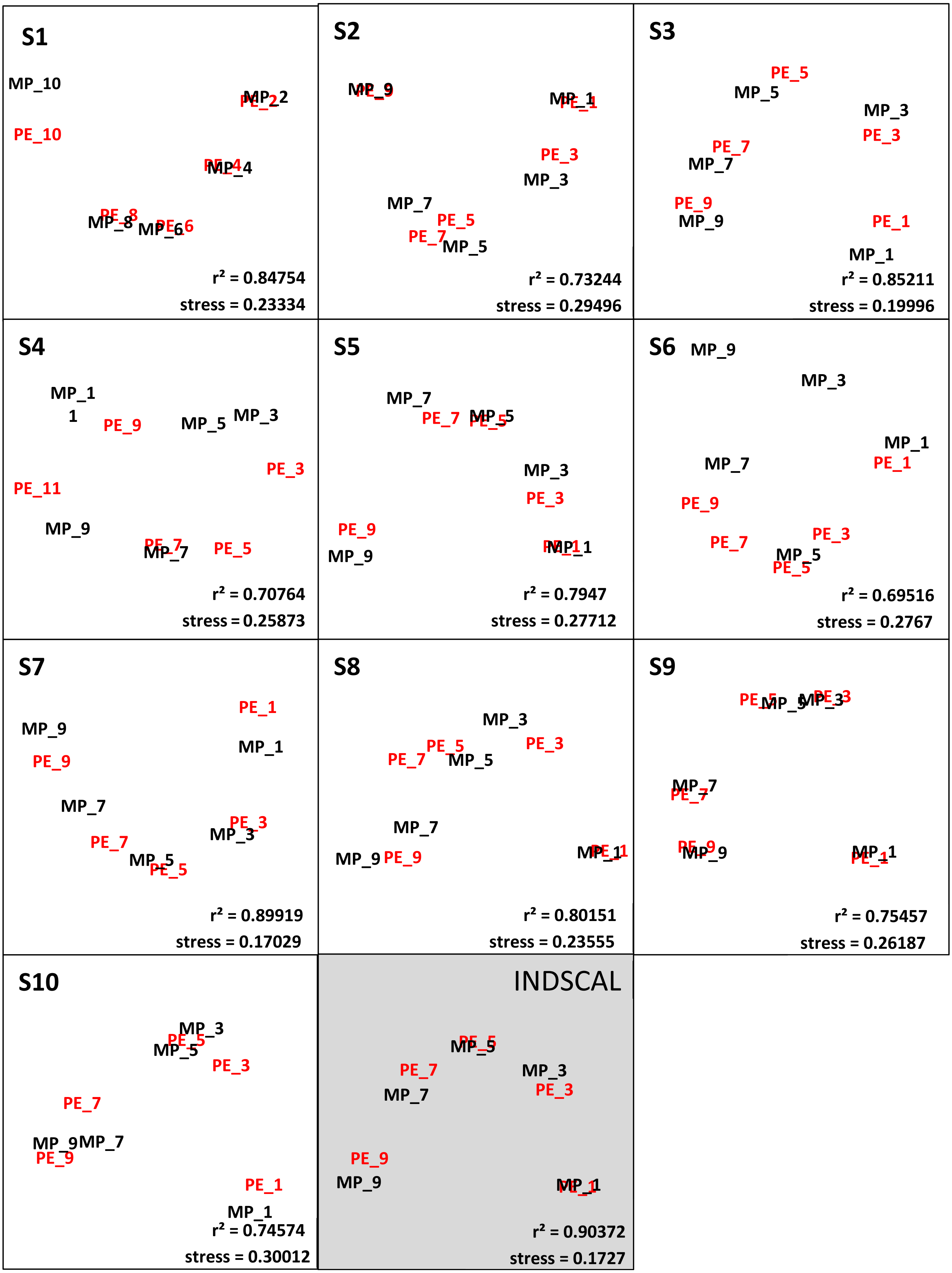

Fig. 3. MDS results comparing PE and MP stimuli at electrodes 1, 3, 5, 7, 9 (except for subject S1 and S4 for whom the electrodes were shifted basally by one and two electrodes respectively). The 10 panels with white backgrounds show the individual results for each subject and for each electrode location and stimulation mode. Moreover, for each plot the r^2 and stress fit is specified. The panel with the gray background includes an INDSCAL plot illustrating the best perceptual space fit for 9 subjects. S4 was excluded because that subject did not indicate that identical stimuli sounded similar.

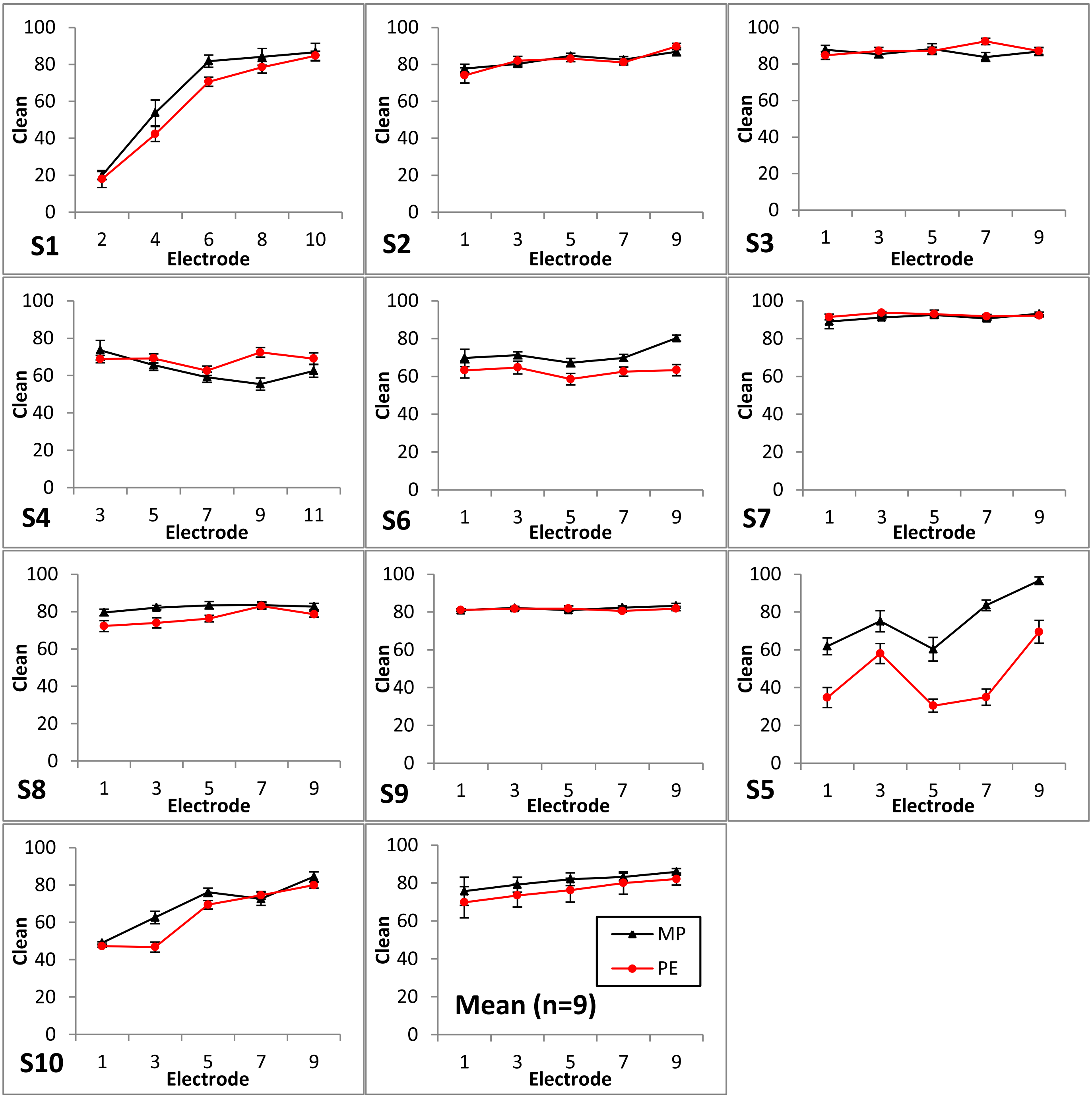

Fig. 4. Results of the scaling procedure for the question "how clean is the sound?" with MP and PE stimulation mode at electrode locations 1, 3, 5, 7 and 9. For S1 and S4 the most or the two most apical electrodes were disabled. For this reason, the electrode locations were set to 2, 4, 6, 8, 10 or 3, 5, 7, 9, 11. For S1 the results were averaged with the other subjects shifting the results by one electrode, i.e. electrode 2, 4, 6, 8, 10 was averaged with electrode 1, 3, 5, 7, 9 from the other subjects respectively. Error bars graphically represent the variability of data (standard deviation) and were used to indicate the error or uncertainty of a measurement.

paired *t*-test was used to compare the pitch shifts across each pair of electrode locations. Using Rom's method (Rom, 1990) to correct for family-wise type-I error, only the PE pitch shift pairs PE3-PE7 ($t(8) = 3.08$, $p = .015$) and PE3-PE9 ($t(8) = 3.65$, $p = .007$) were found to be significant. No significant differences were detected for the other pairs (PE3-PE5, $t(8) = 1.56$, $p = .157$, PE5-PE7, $t(8) = 0.82$, $p = .439$, PE5-PE9, $t(8) = 1.85$, $p = .102$ and PE7-PE9, $t(8) = 1.80$, $p = .110$). The mean estimated pitch shift across subjects and electrode locations produced by PE with respect to MP stimulation was 0.7 electrodes ranging from 0.08 to 2.01 electrodes.

Fig. 7 presents data estimating and quantizing the pitch shift produced by PE stimulation in electrode contact units for different electrode locations. However, it is possible that the same electrode shift at different positions of the cochlea results in different frequency shifts in octaves. The SG map predicts that a fixed change in mm along the lateral wall will produce a fixed change in octaves. However, the projected distance between adjacent contacts along the lateral wall may change across the electrode array as the

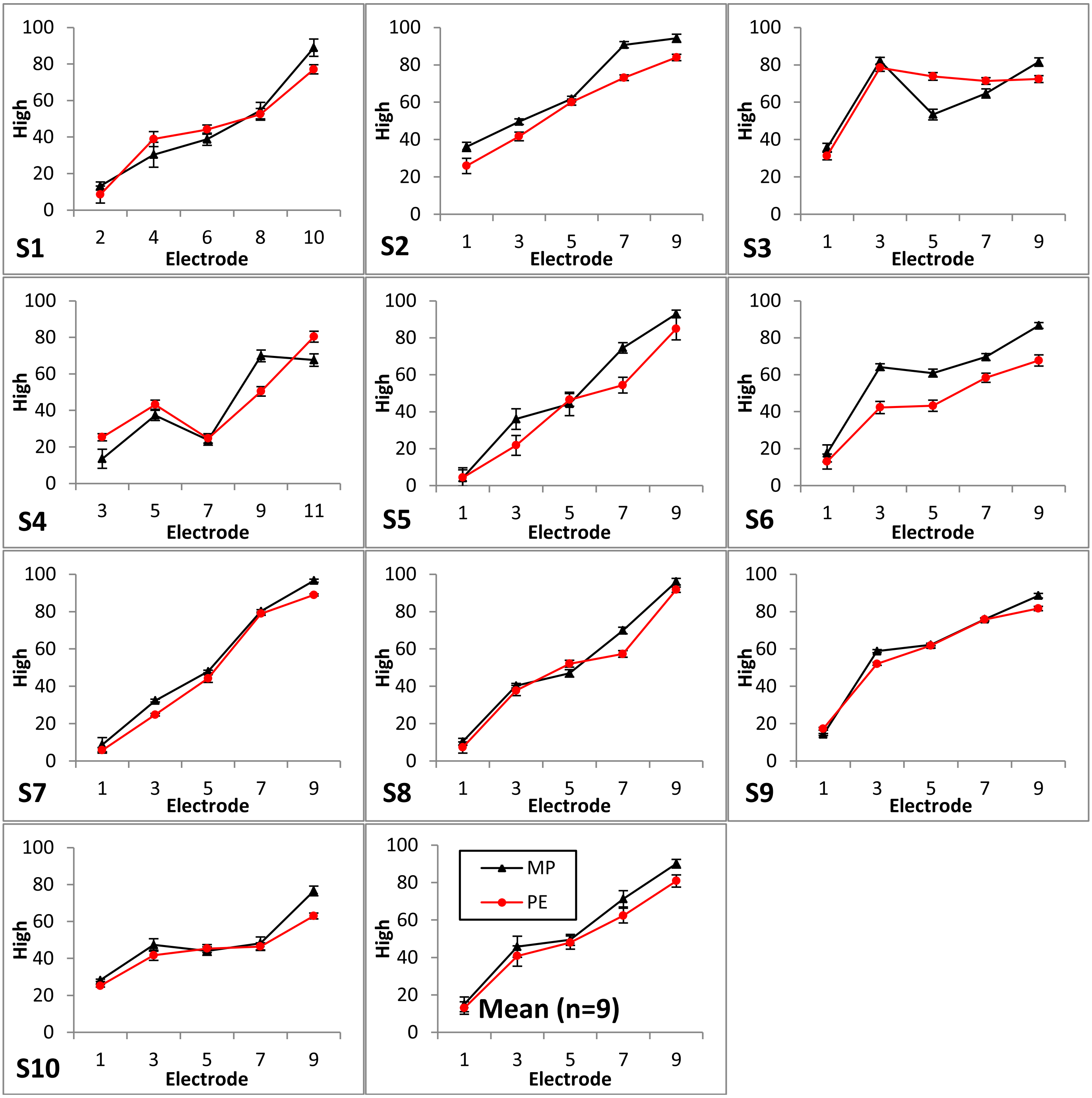

Fig. 5. Pitch height perception with MP and PE stimulation at electrode locations 1, 3, 5, 7 and 9. Again, for S1 and S4 the most or the two most apical electrodes were disabled. For this reason, the electrode locations were set to 2, 4, 6, 8, 10 or 3, 5, 7, 9, 11. For S1 the results were averaged with the other subjects shifting the results by one electrode, i.e. electrode 2, 4, 6, 8, 10 was averaged with electrode 1, 3, 5, 7, 9 from the other subjects respectively. Error bars graphically represent the variability of data and were used to indicate the error or uncertainty of a measurement.

distance between contacts and the lateral wall may change across the electrode array. Furthermore, the relative trajectory between the electrode array and the lateral wall may differ across subjects. Therefore, although the spacing between contacts is fixed in mm, the spacing in distance along the SG may not be fixed in mm causing differences in pitch shifts for each electrode contact and subject.

For the analysis of the CBCT scans the electrode positions were projected onto the lateral wall. The reanalysis in octave units was achieved adapting Equation (4) to account for pitch shift in octave units. The factor 2 in Equation (4) was replaced by a factor β that depends on the estimated frequency difference in octaves elicited by the two electrode contacts *i* and *i*-2 as follows:

$$PS'_i = \beta_{i-2,i} \cdot \frac{|P(PE_i - MP_i)|}{|P(MP_{i-2} - MP_i)|}, \quad (5)$$

where PS' is the pitch shift in octaves and $\beta_{i-2,i}$ is the frequency

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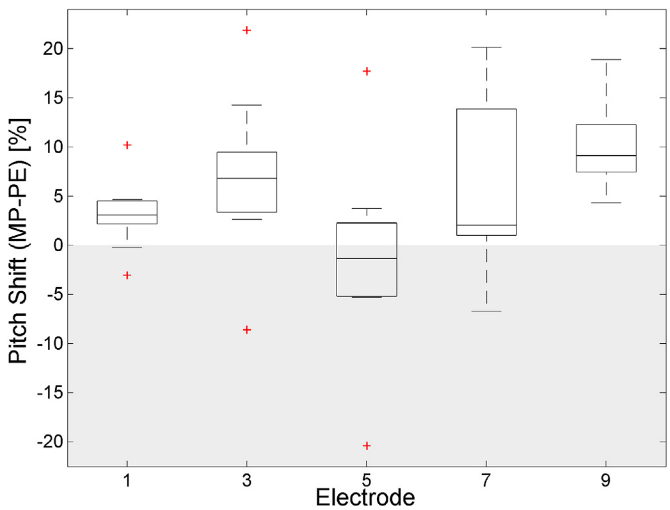

Fig. 6. Pitch shift (MP-PE); The shift has been calculated from the results of the traditional scaling procedure based on the question "how high is the sound?". Results lower than 0 (grey area) indicate that PE stimulation sounds higher than MP stimulation and values higher than 0 (white area) indicate that PE stimulation sounds lower than MP stimulation.

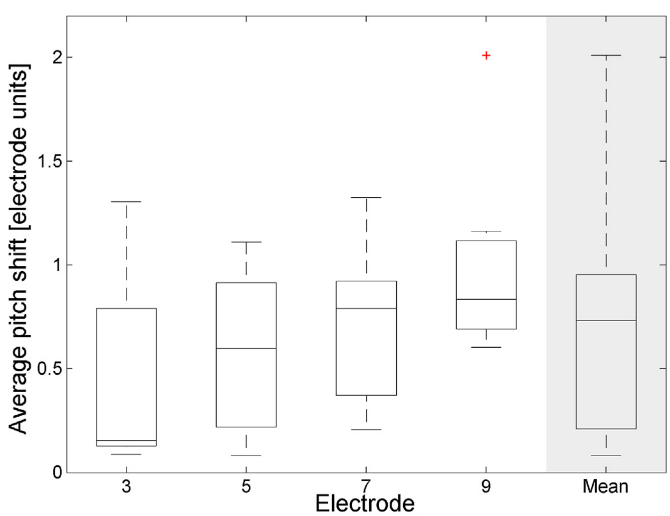

Fig. 7. Average pitch shift (in electrode units) – In the white shaded area the means across subjects for the different electrode locations are displayed. In the grey shaded area the total mean across all subjects and electrodes is presented. Equation (4) was used to calculate the average pitch shift. Box plots indicate the median (horizontal line) and the inter-quartiles (box). The upper whisker represents the distance from the first quartile to the smallest non-outlier whereas the lower whisker represents the distance from the third quartile to the largest non-outlier. Outliers are marked in red color. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

difference in octaves related to electrodes *i*-2 and *i*. The division in Equation (5) assumes linear distribution of pitch across electrodes. This linear assumption is compensated by the β factor.

Fig. 8 presents the mean estimated pitch shift in electrodes and Fig. 9 the mean estimated shift in octaves using the Greenwood Equation (without Stakhovskaya correction) and with Stakhovskaya correction for the 4 subjects for whom CBCT scans were available (S01, S02, S03 and S06). The difference between Figs. 7 and 8 is the number of subjects being included, because the CBCT scans were not available for all subjects.

As indicated in Fig. 7 ($n = 9$), the pitch shift achieved by PE stimulation is larger at the middle than at the apical part of the electrode array. When examining a subset of the subjects ($n = 4$) for whom CBCT data was available, the same trend is observed (Fig. 8). However, when the data for the subjects with CBCT data is converted into octave units, pitch shift seems to increase towards the apex of the cochlea. This is true when using either the Greenwood or the Stakhovskaya correction for electrodes 5, 7 and 9. Indeed, a one-way repeated measures of ANOVA revealed no significant effect of electrode location on pitch shift estimated in electrode units ($F(3,9) = 1.34$, $p = .321$), while a significant effect on pitch shift in octaves using the Greenwood equation ($F(3,9) = 7.56$, $p = .008$) and an almost significant effect of electrode location on pitch shift in octaves estimated with Stakhovskaya correction ($F(3,9) = 3.518$, $p = .062$) was observed.

The mean pitch shift across the 4 subjects and the different electrode locations was 0.7 electrode contacts corresponding with 0.5 and 0.7 octaves with and without Stakhovskaya correction respectively. Note that the correction introduced by Stakhovskaya

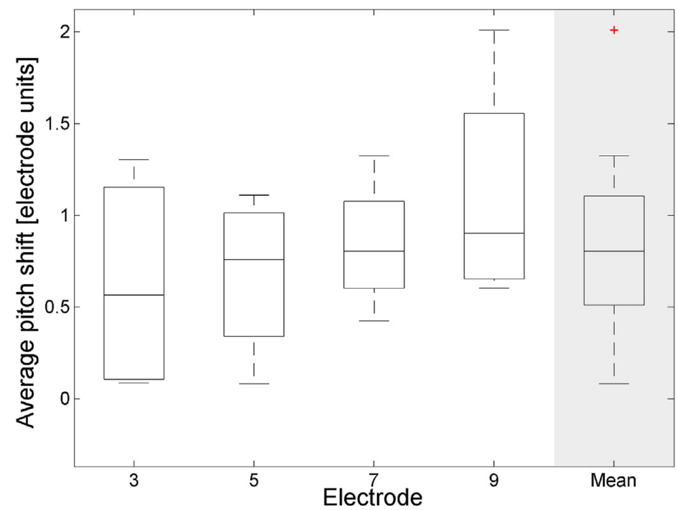

Fig. 8. Average pitch shift (in electrode units) for the 4 participants with available imaging data. The grey area includes the mean data across electrodes and subjects. The definition of the box plots is given in Fig. 7.

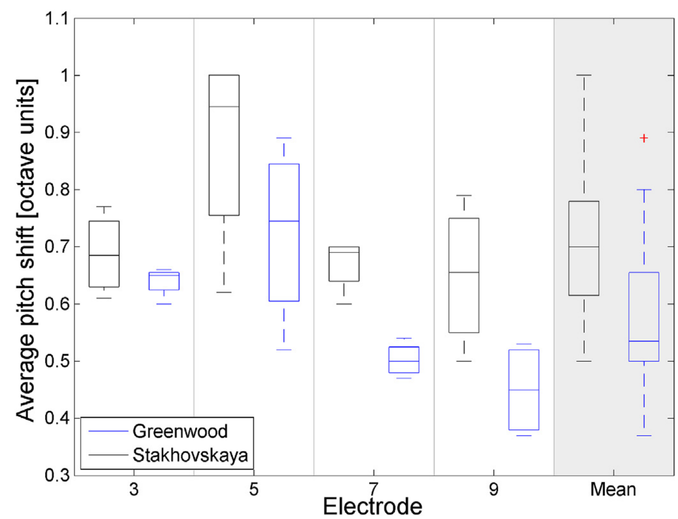

Fig. 9. Average pitch shift (in octave units) in blue calculated using the Greenwood equation without and in black with Stakhovskaya correction for the 4 participants with available imaging data. The grey area includes the mean data across electrodes and subjects. The definition of the box plots is given in Fig. 7.

et al. causes an expansion of the estimated pitch shift with respect to the Greenwood estimations, especially at the central part of the cochlea.

4. Discussion

The current study investigated perceptual differences between MP and PE stimulation using both multi and single dimensional scaling procedures. MDS in 9 CI users suggest that the perceptual differences between MP and PE stimulation can be described by a single dimension because the MDS results were organized in a horse-shoe shape for both the single subject ALSCAL and the overall INDSCAL analysis.

The traditional scaling experiment measured two perceptual quality attributes: cleanness and pitch height. The clean scaling results detected no significant effect of electrode location, stimulation mode or the interaction between them in sound quality. However, the pitch scaling results demonstrate a significant effect of electrode location, stimulation mode and the interaction between both factors on pitch perception. From these results, it can be concluded that the single dimension being responsible for the perceptual differences between MP and PE stimulation is most probably related to place pitch perception.

The reason to choose the attributes cleanness and pitch height was based on the findings that PE stimulation causes a narrower spread of excitation (Saoji et al., 2013) and that narrower spreads of excitation are consistently described as "cleaner" whereas broader spreads of excitation were consistently described as "noisier" (Landsberger et al., 2012; Padilla and Landsberger, 2016). Based on these previous studies, it was hypothesized that the conversion from MP to PE stimulation causes a perceptual difference in quality (such as cleanness) in addition to the difference in place pitch.

Brightness, which is an attribute of timbre perception, can be confused with pitch by both CI users (Lamping et al., 2016) and normal hearing listeners (Allen and Oxenham, 2014). Because of this, it is possible that pitch height and brightness were interchangeably used by CI users in the current pitch scaling experiment. However, according to the present results only one dimension was used to rate the differences in electrode location and stimulation mode, suggesting that the observed perceptual differences were not influenced by brightness. Therefore, and because of time constraints, no brightness scaling experiment was conducted.

The current study could not detect any significant difference on how clean the sound is between PE and MP stimulation although PE stimulation produces a narrower electrical spread of excitation than MP stimulation (Saoji et al., 2013). This aspect could cause differences in sound quality between MP and PE stimulation. For instance, Padilla and Landsberger (2016) showed a significant correlation for "Pure/Noisy" and "Clean/Dirty" ratings with spread of excitation measured by a forward-masking paradigm with different configurations of focusing using partial tripolar (PTP) stimulation. No significant correlation was found for other quality indices such as "Full/Thin" or "High/Low" or "Flute-like/Kazoo-like". The difference between the study of Padilla and Landsberger (2016) and the results presented in the current study may be explained by the fact that PE stimulation was configured with $\sigma = 0.5$ which may not narrow down the field as much as PTP stimulation with a compensation coefficient of 0.75. According to Padilla and Landsberger (2016) it is expected that increasing σ, i.e. narrowing the electrical field produced by PE stimulation, will cause a cleaner sound than MP stimulation.

Several studies show that PE stimulation implemented in a sound coding strategy to transmit low frequency information has a significant effect on sound quality (e.g. Munjal et al., 2015; Nogueira et al., 2015; Caldwell et al., 2017). Munjal et al. (2015) found out that the use of PE stimulation when listening to music has a positive effect in the ability to detect alterations in low frequency or bass content in music. This is consistent with the improved balance between high and low frequencies observed with a PE sound coding strategy observed by Nogueira et al., (2015). The benefit of adding low frequency information has also been observed in CI users with electric and acoustic stimulation combined in one ear (e.g. McDermott, 2004; Gifford et al., 2010; Gfeller et al., 2007; Dorman et al., 2007) and in MED-EL long electrode array users where low frequencies are transmitted through deeply inserted electrode arrays (e.g. Roy et al., 2016). The current study demonstrates that PE stimulation with a σ of 0.5 leads to a pitch shift of 0.7 [0.08 to 2.01] electrode contacts towards the apex of the cochlea. Therefore, PE stimulation can be used to virtually extend the length of the electrode array. This deeper electrode stimulation combined with the quality benefits observed in combined electric and acoustic stimulation as well as deeply inserted electrodes may explain the effects in sound quality observed when using PE in a sound coding strategy. Note that in these studies higher σ values of 0.63–0.75 were used.

Another aspect of electrical stimulation that could have an impact on cleanness of the sound is the rate of stimulation in relation to the location of stimulation in the cochlea. Landsberger et al. (2016) showed with 10 MED-EL CI users having a 31-mm electrode array that high stimulation rates (above ~400 pps) sound clean at all cochlear locations, whereas low stimulation rates (below ~400 pps) sound cleaner at the apical than at the middle or the basal part of the cochlea. The current study was performed stimulating different cochlear locations at rates of 1000 pps. This relatively high stimulation rate may explain the fact that the cleanness of the sound was not significantly different across electrode locations, including extended apical regions through PE stimulation, and that the overall ratings were closer to the clean range. If lower rates were used, there may have been an effect of location on clean sound quality.

The MDS results indicate that the perceptual dimension describing a change in place also describes the difference between MP and PE stimulation. For this reason the perceptual differences between MP and PE stimulation rated during the MDS were reinterpreted as pitch differences in order to estimate the magnitude of the pitch shift achieved by PE stimulation. However, the MDS experiment provides information about the magnitude and not about the direction (i.e. towards the base or towards the apex) of the pitch shift because subjects were only asked to rate the magnitude of the difference between the two presented stimuli in the MDS experiment. The current study, for simplicity, estimates the pitch shift caused by PE stimulation assuming a linear distribution of pitch across electrode locations. This assumption is based on the Greenwood equation, which linearly relates cochlear location in mm with frequency in octaves. The observed pitch shift, when specified in electrode units, was larger at the central than at the apical part of the array. In contrast, for the subset of subjects with CBCT data ($n = 4$), the pitch shift estimated in octave units (using either Greenwood or the Stakhovskaya correction) seems to increase towards the apex of the cochlea ($n = 4$).

Pitch shifts in electrode units assume that the physical distance between adjacent electrode contacts when projected into the lateral wall (Greenwood) or the modiolar wall (Stakhovskaya) is the same at all electrode locations (basal, middle and apical) and for each study participant. However, the projected distance can vary within subjects because of variations in surgical placement of the array as well as large inter-subject variability in size and morphology of the cochlea (e.g. Würfel et al., 2014). These projections may be different across the cochlea and the same electrode array can have highly variable insertion depths across individuals (Landsberger et al., 2015). For this reason, the effect of electrode location on pitch shift may be different if estimated in electrode number units or in octaves from CBCT data.

The current study has shown that the average electrode shift between PE and MP stimulation ranged from 0.08 to 2.01 electrodes in 9 CI users. In 4 subjects for whom CBCT data were available it was estimated that the mentioned electrode shift corresponds with 0.7 octaves. These results are in agreement with the work of Saoji and Litvak (2010) who studied PE stimulation in the central part of the electrode array. They revealed a lowering of the pitch perception equivalent to 0.5 to 2 electrode contacts for a PE stimulus in comparison to MP stimulation with an average σ value of around 0.63 using the same configuration of PE stimulation as in the present study.

In the current study PE stimulation has been configured with a compensation coefficient σ of 0.5. Previous studies investigating PE stimulation have shown that an optimal σ would be 0.75 in order to produce the lowest pitch sensation (Macherey and Carlyon, 2012). Nogueira et al. (2015) showed that a σ value of 0.62 in the PE configuration delivered the lowest pitch sensation in 9 of 12 participants, however for 2 subjects this value of σ produced a pitch reversal with respect to MP stimulation. For this reason, in the current study a σ value of 0.5 was used to minimize the risk of a pitch reversal. Note that the use of a larger value of σ could have increased the magnitude of the pitch shifts observed and perhaps even the effect on other perceptual changes.

There is a great interest in using PE stimulation in a sound coding strategy as it can be used to stimulate cochlear regions more apical. This deeper stimulation of the cochlea could therefore produce lower pitch sensations. Although Carlyon et al. (2014) could not show a benefit of PE stimulation in speech performance in an acute measurement, in Nogueira et al. (2015) it was shown that a sound coding strategy based on PE stimulation is a promising technique to improve speech intelligibility in noise after one month of use as well as music perception. It was hypothesized that the main reason for the improvements observed is the more balanced sound perception between low and high frequencies delivered by PE stimulation. The results of the current study support the application of PE stimulation, at least with a σ of 0.5, because it produced the desired effect of shifting pitch perception without any other effect on additional perceptual dimensions. This is important because if there are no other effects on additional perceptual dimensions, the virtual PE electrodes may sound very similar to a physical electrode.

5. Conclusions

Perceptual differences between MP and PE stimulation can be explained by a single perceptual dimension which is most probably related to pitch. No other dimensions influencing perceptual differences between PE and MP were observed. The pitch shift between PE and MP stimulation was larger at the medial part of the cochlea than at the apical part when quantized in electrode units. Reanalyzing this shift in octave units it seems that the shift is equal or even larger at the apex than at the medial part of the cochlea. The consideration in octave units could correlate better with the reality than the analysis in electrode units. Therefore, PE stimulation, with a σ of 0.5, is a promising technique that can be incorporated in a sound coding strategy to extend the pitch range for CI users without perceptual side effects.

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