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Chapter 4

Influence of widening electrode separation on current steering performance

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Abstract

Objectives: Current steering between adjacent electrodes makes it possible to create more spectral channels than the number of electrodes in an electrode array. With current steering on non-adjacent electrodes, here called "spanning", it could be possible to bridge a defective electrode contact or potentially reduce the number of electrode contacts for the same level of access to the auditory nerve. This study investigates the effectiveness of spanning in terms of the number of intermediate pitches, loudness effects, and linearity of the current weighting coefficient (α) with respect to the perceived pitch.

Design: Twelve post-lingually deafened users of the HiRes90K cochlear implant with HiFocus1J electrode were randomly selected to participate in this study. Electrode contacts were selected at two locations in the cochlea, as determined on multi slice CT (MSCT): 180º (basal) and 360º (apical) from the round window. For both cochlear locations three psychophysical experiments were performed using simultaneous stimulation of electrode contacts. An adaptive staircase based procedure was used. The number of intermediate pitches was assessed with a 3AFC pitch discrimination task, and the extent of current adjustment required when varying the current weighting coefficient (α) was determined with loudness balancing (2AFC). Finally, the pitch of a spanned channel was matched with the pitch of an intermediate physical electrode in a 2AFC procedure to assess the place of the spanned channel on the electrode array.

Results: Spanning required significantly more current compensation to maintain equal loudness than current steering between adjacent electrode contacts. A significant decrease of discriminable intermediate pitches occurred with spanning in comparison with current steering between adjacent electrode contacts. No significant difference was found between the pitch matched current steering coefficient and the theoretical coefficient corresponding a priori with the intermediate physical electrode. No significant difference was found between the data from the apical and the basal sections of the electrode array.

Conclusions: Spanning over wider electrode distance is feasible. With increasing electrode spanning distance, more current compensation is needed to maintain equal loudness and a gradual deterioration in the just noticeable difference for pitch is observed. However, the pitch progression is linear. For a spanned signal with equal proportions of current delivered to both electrodes, pitch is equivalent to that produced by an intermediate physical electrode.

Introduction

Contemporary cochlear implants (CI) contain 12 to 22 intra-cochlear electrode contacts, implying a highly quantized spatial access to the auditory nerve when using standard CI sound processing algorithms. For CI recipients this coarse electrical tonotopy may result in significant difficulties with speech understanding in background noise and appreciating music (Frijns et al. 2003; Shannon et al. 2004). A logical remedy is to increase the resolution of spatial access to the auditory nerve, and thereby hopefully increase the number of distinct pitches a subject can discriminate. Townshend *et al.* (1987) and McDermott and McKay (1994) showed that the perception of pitch can be varied between two adjacent electrodes by delivering the current either simultaneously (Townshend et al. 1987) or non-simultaneously (McDermott and McKay 1994) to both contacts. Recipients systematically reported a single-sound percept with a pitch that was between the base pitches of the individually stimulated contacts. Donaldson *et al.* (2005) were the first to investigate the number of discriminable pitches generated between two adjacent contacts with simultaneous dual-electrode stimulation, also called current steering. Their study concluded that a two- to nine-fold increase in the number of pitches was possible. This was later also found for non-simultaneous stimulation (Kwon and van den Honert 2006). Firszt *et al.* (2007) and Koch *et al.* (2007) extended the study of Donaldson *et al.* (2005) by estimating the number of discriminable pitches (also called spectral channels) that could be generated using current steering. For the whole electrode array, this ranged from 8 to 451 with an average across subjects of 63 spectral channels (Firszt et al. 2007).

A sound processing strategy, called HiRes 120, based on current steering was implemented by Advanced Bionics (Brendel et al. 2008). Several studies (Buechner et al. 2008; Firszt et al. 2009) evaluated this sound processing strategy and found significantly better speech perception for HiRes 120 compared to HiRes. This strategy was also evaluated in a European multi centre HiRes 120 study (Eklöf, reference note 1). Some subjects from the study group at the Leiden University Medical Centre (LUMC) had a non-active electrode (a gap) in their programs. In contrast to the subjects without an electrode gap, this group had poorer speech perception outcomes for the HiRes 120 program than for the HiRes program (Boermans, reference note 2). This led us to consider the possibility that current steering could be used to replace the missing electrodes. Previous research has shown that it is possible to create an intermediate pitch for electrode separation up to and including 4 mm for simultaneous (Saoji, reference note 3) and non-simultaneous (McDermott and McKay 1994) dual-electrode stimulation. We will refer to current steering on non-adjacent electrodes as spanning. If spanning is as effective as current steering on adjacent electrodes, it can be used to bridge, defective contacts. Eventually it could lead to a new electrode design with the same sound perception quality, but with a lower number of physical electrode contacts on an array.

With current steering on adjacent contacts, due to electric field summation, no or very little adjustment of the current is needed to maintain equal loudness (Donaldson et al. 2005; Frijns et al. 2008; Frijns et al. 2009). However, it is not known what happens with current adjustment when increasing the spanning distance. With spanning, there is presumably less overlap between the regions of neural excitation produced by the two electrode contacts, which is comparable with sequential stimulation. With computational modelling has been shown that sequential stimulation needs current adjustment (Frijns et al. 2009). Given the potential importance of spanning in future sound processing strategies, we endeavored to study the amount of current compensation needed to maintain equal loudness with spanning in our subject group.

As a new research element, we intended to study the pitches evoked by spanning in comparison to current steering on adjacent electrode contacts. We focused particularly on the number of intermediate pitches i.e., the possibility of creating the same number of intermediate pitches with spanning as with current steering on adjacent contacts and on the progression of the pitch percept. The number of intermediate pitches can be calculated with a formula, where the just noticeable difference (JND) is used (Firszt et al. 2007; Koch et al. 2007). The latter tests the assumption that, when the current is equally distributed to both electrode contacts and the neural survival is equally distributed, the generated percept is centered exactly between the physical contacts. The question arises whether there is a linear correlation between pitch and the proportion of current going to each of the spanned electrode contacts. One way to look into this issue is to determine the proportion of current that matches the pitch of an intermediate physical contact (linearity of the mapping). This way defective electrodes can be replaced while maintaining exactly the same pitch percept.

In terms of electrode location several studies have shown that, with current steering, more intermediate pitches can be discriminated in the apical region than in the basal region (Firszt et al. 2007; Koch et al. 2007; Kwon and van den Honert 2006). These studies selected test electrodes based on their rank number on the electrode array. However there are important differences between subjects regarding insertion angle, size of the cochlea and electrode position, which will most probably influence the outcome (Kos et al. 2005; Skinner et al. 2007). Consequently, for standardized comparison, data from electrode contacts at the same position in the cochlea are preferred. We therefore, selected the electrodes based on their location in the cochlea, using a CT-scan to determine the exact electrode position (Lane et al. 2007; Skinner et al. 1994; Verbist et al. 2005).

To summarize, this study investigates whether spanning - up to four electrodes - is as effective as current steering on adjacent electrodes. The following issues are addressed: 1) the extent of current adjustment required to maintain equal loudness due to spanning; 2) the change in number of intermediate pitches with spanning; 3) the linearity of the pitch percept with respect to place; 4) The importance of cochlear location on the psychoacoustic outcomes.

Methods

Subjects

A group of 12 postlingually deafened adults was unilaterally implanted at the LUMC in 2007. Each received a HiRes90K implant with a HiFocus-1j electrode array (Advanced Bionics, Sylmar, CA). No problems were reported during surgery or the subsequent rehabilitation program. Subject information is provided in Table 1. All subjects participated in the first two experiments. Only six of the twelve subjects (S2, S3, S4, S10, S11 and S12) were willing to participate in the third experiment. The average phoneme recognition score of 75 % (range 38-96%), obtained with the standard Dutch speech test of the Dutch Society of Audiology (Bosman and Smoorenburg 1995), is representative for that of the total cochlear implant population at LUMC. Written consent was obtained. This study was approved by the Medical Ethical Committee of the LUMC under number P02.106.J.

Electrode locations

As part of the clinical CI program every CI candidate undergoes a preoperative and a postoperative CT-scan. The latter was used to locate the position of the electrode array. Multiplanar reconstructions (MPR) were made through the cochlea parallel to the basal turn and perpendicular to the modiolus (cochlear view), i.e., in the plane of the electrode array (Vitrea 2 software, Vital Images, Minnetonka, MN).

This procedure was completed using a dedicated Multi slice CT scan data acquisition protocol developed in our center (Verbist et al. 2005).

Table 1. *Subject demographics.*

	Gender	Age (years)	Aetiology	Duration of deafness (years)	CI side	CI usage (months)	CVC Ph%	Electrodes tested 180°	360°
S1	Female	42	Congenital hearing loss	36	right	13	86	11	5
S2	Female	54	Rubella intra uterine	50	right	16	66	11	5
S3	Male	60	Congenital hearing loss	55	right	13	54	9	2
S4	Male	61	Meningitis	57	right	18	38	10	4
S5	Female	47	Progressive hearing loss	15	left	10	80	8	1
S6	Male	74	M. Meniére	24	right	8	74	9	2
S7	Female	54	Congenital hearing loss	46	right	11	85	12	6
S8	Female	69	Congenital hearing loss	21	right	10	93	11	6
S9	Male	48	Meningitis	42	right	8	68	11	4
S10	Female	43	Unknown	39	left	6	39	11	5
S11	Male	63	Otosclerosis	23	right	17	89	11	5
S12	Female	43	Congenital hearing loss	5	right	9	96	10	4
Average		55		34		12	75		

Speech perception scores are given as percentage phonemes correct (Ph%) in phonetically balanced monosyllabic (CVC) words.

To measure the exact position of the electrodes, a system of coordinates was placed in the postoperative MPR, with a custom Matlab computer program (MathWorks, Natick, MA). In this program, the z-axis was placed through the modiolus and the 0^o reference angle was placed through the most lateral point of the lateral semicircular canal. All electrode contacts were marked by an experienced physician. Correction of the angular system to angles measured from the round window was done using the angular position of the round window, as recorded from the preoperative scan of the individual subject. The angles measured from the round window were used in this study, thereby conforming to an international consensus (Verbist et al. 2010). The electrode contact numbering is ascending from apex to base in line with the manufacture's convention. For each subject the electrode contact closest to 360 degrees (apical site, AS) and the one closest to 180 degrees (basal site, BS) were selected (Table1). The average location of these sites was respectively at 354 degrees (+/- 9 degrees) and 181 degrees (+/- 7 degrees). Current steering was conducted between the apical contact (at 360^o or 180^o) and the next four more basal electrode contacts. Throughout this paper a pair, consisting of electrode contacts e and e+i, will be referenced to as 'pair e+i' (with i ranging from 1 to 4).There was no overlap of the two contact groups. The first two experiments took place on both locations, the third experiment was conducted only for the apical site.

Experiments

Experiments were performed with the research tool BEDCS (Bionic Ear Data Collection System, Advanced Bionics, Sylmar, CA) for the electrical stimulus configuration and PACTS (PsychoACoustic Test Suite, Advanced Bionics Europe, Niel, Belgium) for the psychophysical tests. Stimuli were bursts of symmetric biphasic pulses with phase duration of 32 µs, pulse rate of 1400 pulses per second and total burst duration of 300 ms. Between the stimuli was a pause of 500 ms. Dual-electrode stimuli were always simultaneous (i.e., current steering was employed). The proportion of the total current directed to the more basal contact of the dual-electrode contact pair is denoted as α. This coefficient varies from α = 0, where all current is directed to the apical electrode to α = 1, where all current is directed to the basal electrode. The individual loudness growth of each electrode contact was taken into account with linear correction between the two electrode contacts in a pair. Before testing, electrical threshold levels (TL) and most comfortable levels (MCL) were determined for all electrode contacts.

This study consisted of three different experiments; loudness balancing, pitch discrimination and pitch matching. The loudness balancing was conducted first, to determine whether spanning requires current adjustment to maintain constant loudness. These data were used in the other two experiments to equalize loudness between presentations. After each experiment the subject was asked to describe the percepts which they had received. In all experiments a staircase procedure was used (Levitt 1971). The specific type varied between experiments. The procedure required ten reversals (i.e. changes in the direction of the signal level), where the test outcome was calculated over the last six reversals. If the variance (standard deviation) on the last six reversal points was considered too large by the program

(PACTS), determined using an algebraic algorithm (Reference note 4), the test was extended to determine a few (1-12) more reversal points.

Loudness balancing

TLs and MCLs were determined for each of the ten preselected electrode contacts. The subject was asked to indicate when the signal on the physical contacts was just heard (TL) and also when the signal sounded most comfortably loud (MCL). All levels were carefully loudness balanced within and across electrode pairs, as in normal clinical follow-up. Linear correction then took place between the electrode contacts. Because of the correction for possible differences in MCL, the influence of loudness difference on the outcome of this experiment is reduced to a minimum. Using a two-alternative-forced-choice (2AFC) 1-up/1-down staircase procedure, equal loudness was determined for the intermediate percepts compared to the apical electrode contact of the stimulated pair. Stimulus A, with $\alpha = 0$, was presented at MCL. Stimulus B, with $\alpha = 0.5$, started at 120 percent of MCL. In each trial, the order of presentation of stimulus A and B was randomized. The subject

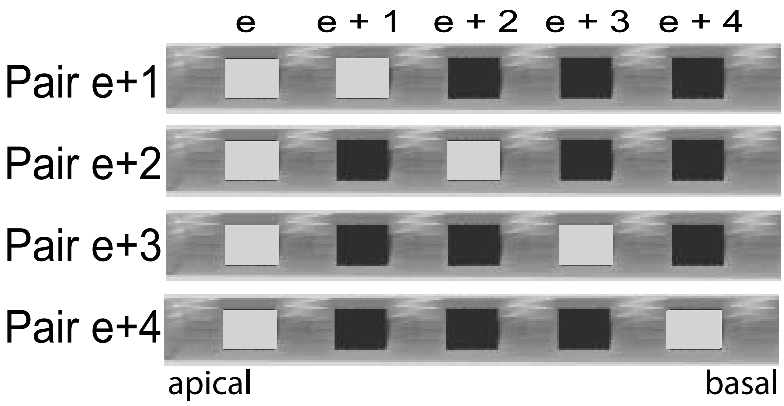

Figure 1. *Electrode pairs used in loudness balancing and pitch discrimination experiments. The most apical electrode of a pair is denoted as e and is either AS (360^o from round window) or BS (180^o from round window) as selected on the basis of a CT-scan. The light gray squares are the stimulated electrode contacts with dual-electrode stimulation in the experiments. A pair consist of e, the apical electrode and 'e+i', the basal electrode, where 'i' varies between 1 and 4.*

was asked which stimulus was louder. Through 10 reversals, the current for stimulus B decreased or increased in 15 percent increments for the first four reversals and in 7 percent increments for the last six reversals. For both cochlear locations (AS and BS), four different electrode pairs with increasing spanning distance (figure 1) were evaluated. The experiment always started with the AS pair e+1, followed by AS pair e+2 and so on.

Pitch discrimination

The just noticeable difference (JND) in current weighting coefficient α was determined with a 3 AFC, 1-up/2-down staircase procedure for the four different spanning pairs at each cochlear location: AS and BS. The reference stimulus had a value $\alpha = 0$ (apical electrode) and the probe stimulus a non-zero α between 0 and 1. The reference stimulus was played twice and the probe stimulus once. In each trial, the presentation order of the three stimuli was randomized. The subject was asked which stimulus was different in pitch. A loudness roving of 10% (considered to be moderate) was applied to the stimulation current in order to avoid any potential bias from a loudness cue (Vanpoucke, reference note 5). The experiment started with $\alpha = 0.9$. Of the ten reversals, the first two were altered in steps of 0.1, the second two in steps of 0.05, and the last six in steps of 0.025 of α. When a subject was not able to discriminate the physical electrode in the pair (α evolving to 1), the test automatically stopped after five attempts.

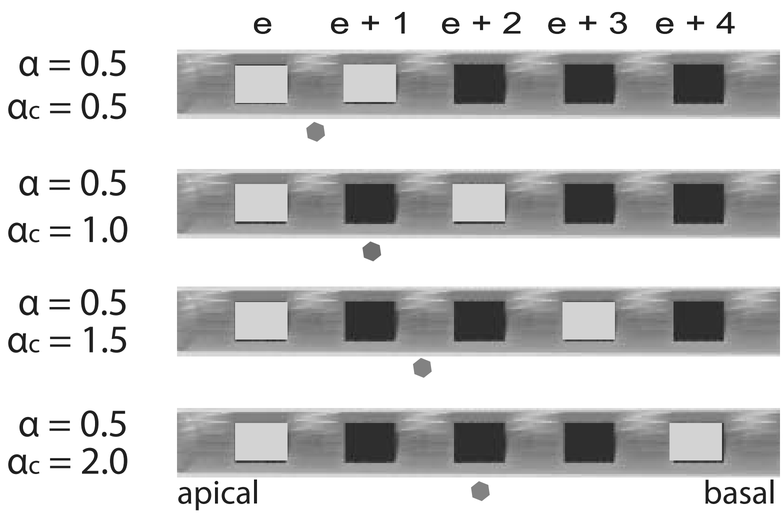

Figure 2. *Explanation of the corrected α (α_c), as defined by Equation 1. The light gray squares are the electrode contacts stimulated with current steering in the pitch discrimination experiment. The dots indicate the location associated with $\alpha = 0.5$, the actual fractions of the current going to the basal contact of the spanned pair. α_c is after computing with Equation 1, expressed in electrode spacing.*

The variable α has a different basis for each spanning distance. To be able to compare the outcome of this experiment between the different spanned electrode pairs, a common scale must be used for the position between the contacts. Using electrode spacing provides this common reference. The position of $\alpha = 0.5$ for adjacent contacts will correspond to a 0.5 electrode spacing measured from the apical electrode of the pair. For $\alpha = 0.5$ with two bridged contacts, pair e+3 will correspond to a 1.5 electrode spacing. Therefore, in the data analysis, normalization was applied expressing all JNDs in terms of the so-called corrected α, α_c, defined as follows (see figure 2). :

$$\text{JND } \alpha_c = \text{JND } \alpha \times (EL_{basal}-EL_{apical}) \qquad \text{(Eq. 1)}$$

With JND α = JND for that specific electrode pair expressed in electrode spacing measured from the apical electrode of the pair, EL_{basal} = basal electrode of the current steered pair and EL_{apical} = apical electrode of the current steered pair.

Pitch matching

This pitch matching experiment was conducted to compare the pitch of a monopolar physical electrode contact with the pitch of a spanned stimulus. As described above, it is presumed that $\alpha = 0.5$ with three bridged contacts (pair e+4), will correspond to 2 electrode spacing, which is equal to the position of physical electrode e+2. Similarly, $\alpha = 0.33$ with two bridged electrode contacts (pair e+3) will correspond to 1 electrode spacing and is equal to physical electrode contact e+1. With a 2 AFC, 1-up/1-down staircase procedure, α was determined for a dual-electrode contact pair for six different pair combinations (shown in figure 3) at the AS cochlear location only. Similar loudness roving (10%) as for 'pitch discrimination' was used. The reference stimulus A was given through a monopolar physical electrode contact lying between the electrodes contacts comprising the spanning pair. The test stimulus B was a spanned signal using one of the spanning pair. In each trial, stimuli A and B were presented in random order. The subject had to determine which of the two stimuli sounded higher in pitch. The staircase procedure converged on the value of α that best matched the pitch of the reference stimulus. For the ten reversals, α was altered in steps of 0.1 during the first two, in steps of 0.05 during the second two, and in steps of 0.025 during the remaining six. The experiment started alternating with $\alpha = 0.1$ and $\alpha = 0.9$, both tested twice for all six electrode pairs presented randomly. The averaged was calculated of these four outcomes per pair.

Statistical Analysis

All data were analyzed with the SPSS 16 (Statistical Package for the Social Sciences, SPSS inc., Chicago, IL) statistic software package. For loudness balancing and pitch discrimination experiments a linear mixed model (Fitzmaurice et al. 2004b) was used. In the pitch matching experiments, the Student's t-test was used to compare the mean α with the expected α, corresponding to the intermediate physical electrode. Differences were considered significant at the 0.05 level.

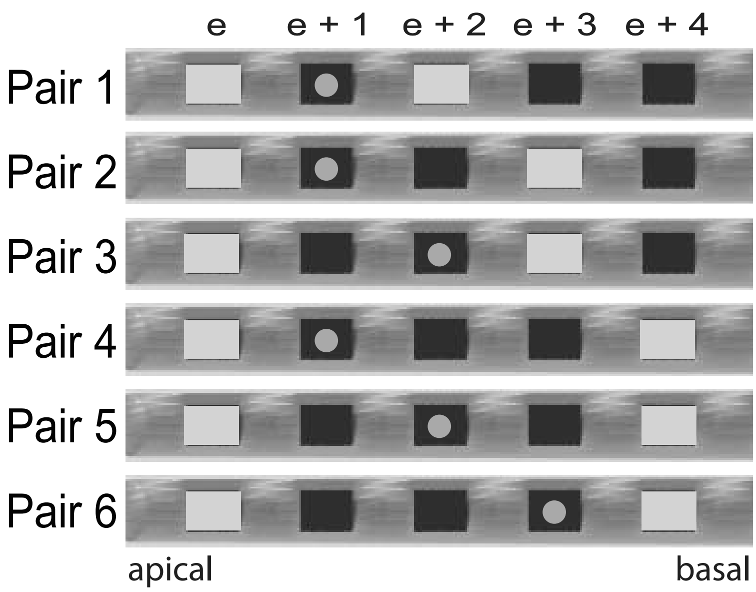

Figure 3. *Electrode pairs used in pitch matching experiments. The light grey squares are the stimulated electrodes with dual-electrode stimulation. The dots correspond to the intermediate electrode contact i.e., the physical reference contact.*

Results

Loudness balancing

The group results are shown in figure 4. Stimulation currents ($I_{MCL}(\alpha)$) are normalized such that the current needed for MCL as measured for α = 0, was set at 100%. The results are shown for both cochlear locations, AS and BS (dot and triangle resp.). There was no significant difference between apical and basal locations ($p = 0.7$). The results of the individual subjects differed substantially, which is illustrated by the large standard deviations. In general, current adjustment needed to create the same loudness for different electrode pairs, increased significantly ($p = 1.0 \times 10^{-6}$) with increasing spanning distance. The current compensation ranged from 103% (0.2 dB)

the other pairs. However, using a statistic spline model (Fitzmaurice et al. 2004a), significance could not be confirmed ($p = 0.06$) at this point. Looking at the individual results (Figure 5) several differences among the subjects are shown. First, across subjects there is an alternation between AS and BS for which required the largest amount of current adjustment. Second, a decrease in current on e+1 is

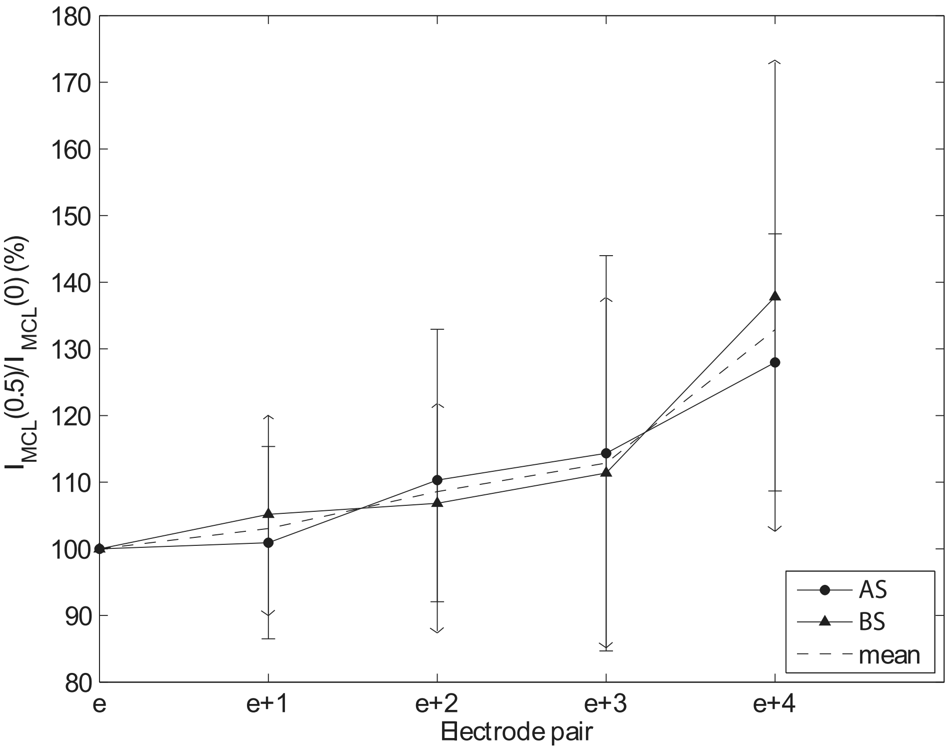

Figure 4. *Average data of the loudness balancing experiment, for AS (dot), BS (triangle) and the mean (dashed line). The current at most comfortable level (MCL) measured on e (I_{MCL} (0)) was set at 100%, the other currents (I_{MCL} (0.5)) are expressed in percentages of this value. The electrode pairs are denoted on the horizontal axis.*

shown in subjects S1-BS, S2-AS, S3-AS, S4-BS and S11-both. Some subjects (S7-BS, S10-BS and S12-AS) demonstrate an increase on e+1 and then a decrease on e+2.

Subject S5-AS, S7-AS, S8-BS and S9-BS needed less current at pair e+3. The remaining subjects illustrate a gradual increase in current over all the pairs, which is consistent with the mean shown in figure 4. An exception was subject S6, whose data deviated for both locations. No correct current could be measured for electrode pair e+4 on the BS while the AS showed a large decrease of current for pair e+4. This subject's data were excluded from further analysis, because this subject perceived two separate pitches (for pair e+2, e+3 and e+4) instead of one and was therefore, not able to complete the experiment.

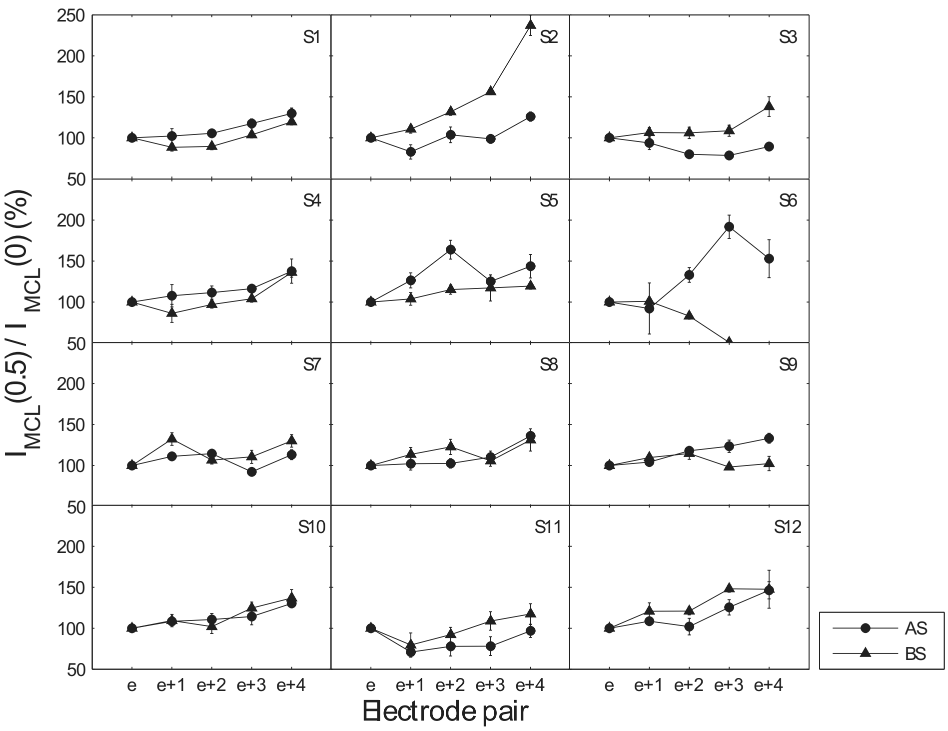

Figure 5. *Individual results for the twelve subjects (S1-12) of the loudness balancing experiments, presented in the same way as the group results in Figure 4. The dots represent the data of the AS of the array and the triangles the BS of the array.*

Pitch Discrimination

The JND for pitch, expressed in α_c, averaged over all subjects is plotted in figure 6 as a function of spanning distance. No significant difference was found between the two cochlear locations ($p = 0.6$). The average α_c for e+1 was 0.83 and for e+4 it was 1.75. This is approximately a doubling, which represents in a significant loss of intermediate pitches ($p = 3.6 \times 10^{-7}$). JND α_c increased approximately by 0.3 per contact distance (1.1 mm) spanned. Using the formula by Firszt et al (2007), $N_{channels} = 2 + (1/JND-1)$, the number of spectral channels (intermediate pitches plus the 2 electrodes) can be calculated. This results in $N_{channels} = 2.2$ for e+1, which is much lower than the results of Firszt et al. (2007) and Koch et al. (2007) (7.1 and 5.0 resp.)

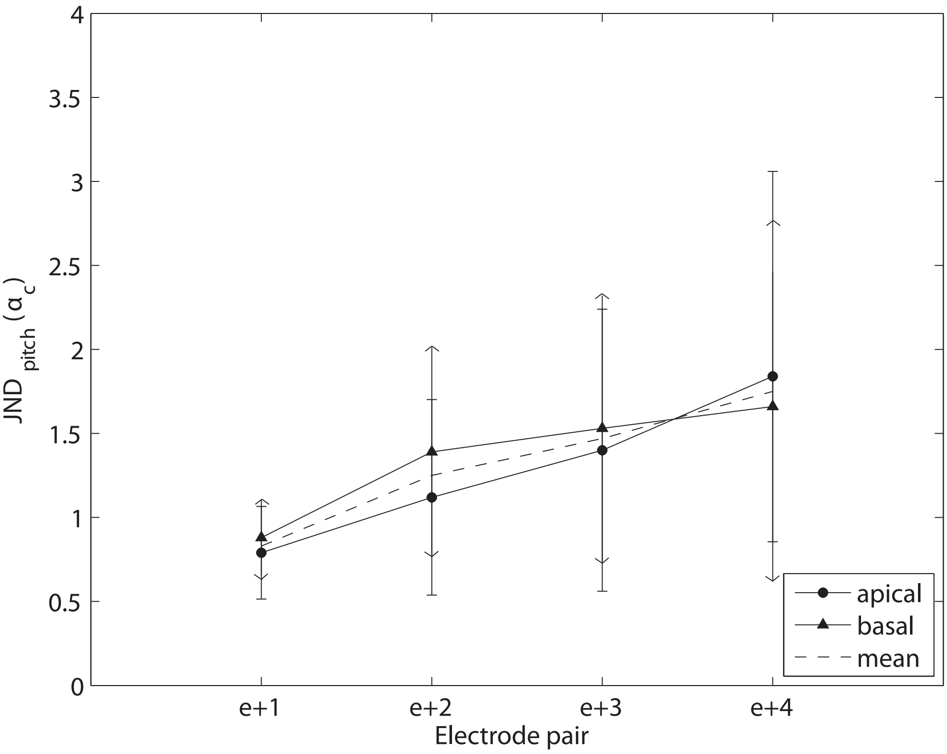

Figure 6. *Average data of the pitch discrimination experiment, for AS (dot), BS (triangle) and the mean (dashed line). The vertical axis denotes the JND of the* α_c *(*JND_{pitch} *(*α_c*), calculated on the basis of Equation 1, while the electrode pairs are denoted on the horizontal axis.*

Four of the twelve subjects (S4, S7, S9 and S12) were not able to distinguish between two adjacent electrode contacts (pair e+1). In that situation the test aborted at α = 1.0. The JND α expressed in electrode spacing could therefore, be higher, which might influence statistics and could lead to a decrease in intermediate pitches. However, when leaving pair e+1 out the linear mixed model, the loss of intermediate pitches is still significant (p = 0.002).

The individual pitch discrimination data are shown in figure 7, demonstrating large inter-individual variability. For a number of subjects, the just noticeable pitch difference could be maintained with increasing spanning distance (e.g. S1-BS, S3-AS, S5-BS, S10-AS, S11- and S12-AS), for others (S1-AS, S2, S3-BS, S4, S5-AS, S6, S7, S8 and S9) the JND increases significantly with increasing spanning distance.

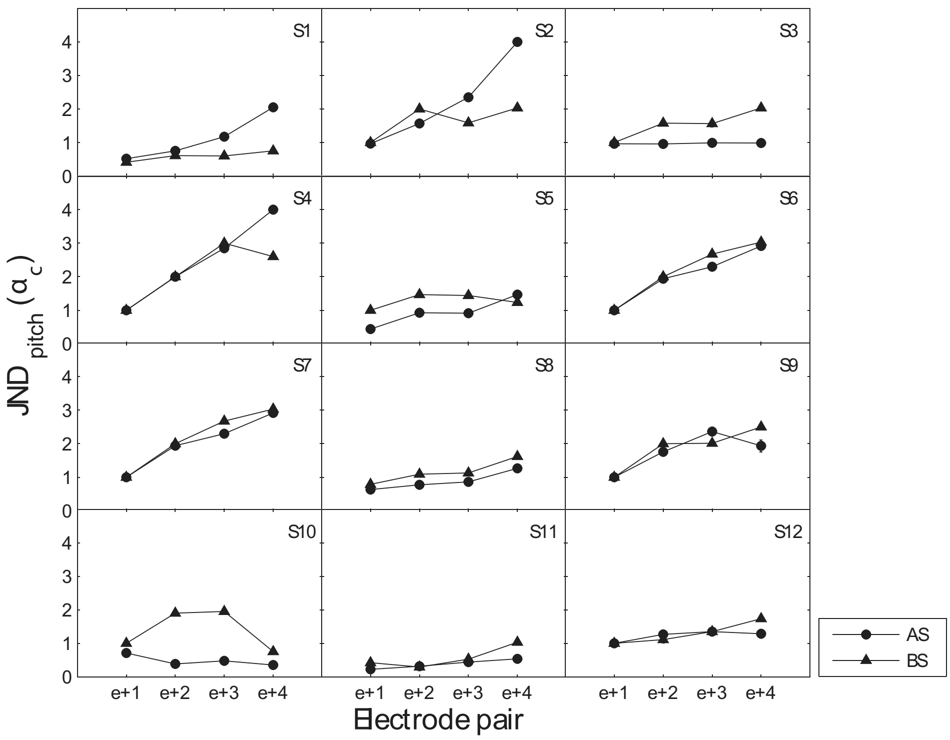

Figure 7. *Individual results for the twelve subjects (S1-12) of the pith discrimination experiments, for AS (dot) and BS (triangle), presented in the same way as Figure 6.*

Pitch matching

In figure 8 the average α per electrode pair (the triangle) is shown. The horizontal solid bars represent the physical contacts used in the spanning pair and the arrow is pointing to a filled square at the place of the theoretically expected value of α. The individual data are presented with light gray dots. These dots represent the average of the four measurements per subject, two times started at 0.1 and two times at 0.9. The standard deviation for these data points varied, with an average of 11.7. There was a significant difference between the data obtained with starting point $\alpha = 0.1$ or $\alpha = 0.9$ ($p = 0.005$). The data from $\alpha = 0.1$ was mostly indicated

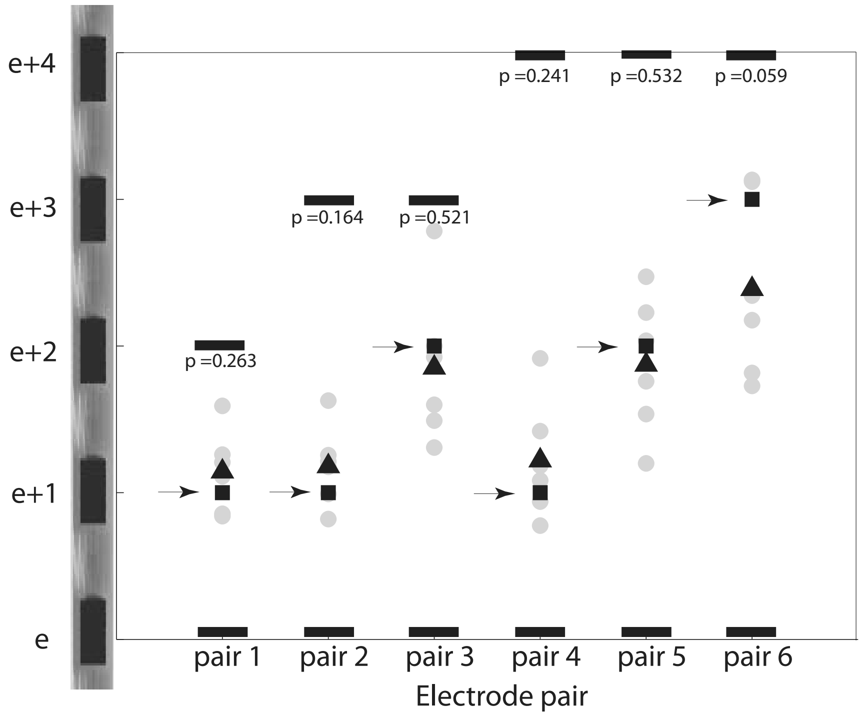

Figure 8. *Average and individual data of pitch matching at AS for six different electrode pairs (horizontal axis). On the vertical axis the position along the electrode array is plotted. The thick horizontal bars represent the places of the spanned electrode pair on the electrode array. The squares marked by an arrow represent the physical reference contacts, the triangles represent the average αs. The light gray dots represent the individual data. The p-values (Student's t-test with null-hypothesis that the triangles and the squares have the same position on the graph) are shown under the horizontal bars for each electrode pair.*

lower than expected and the data from α = 0.9 higher than expected (Carlyon, reference note 6). The average per electrode pair shows no significant difference between the place of the spanned signal and the physical electrode both expressed in electrode spacing, although pair 6 seems lower.

Discussion

Loudness balancing

Our results show a consistent pattern. At larger spanning distances simultaneous dual electrode stimulation is still possible, but precision in addressing the auditory nerve is reduced. For example, for the reference situation of current steering on adjacent electrodes our finding that no current compensation was needed to maintain equal loudness is consistent with the literature (Donaldson et al. 2005; Frijns et al. 2008; Frijns et al. 2009).Gradually, with increasing distance, an approximately linear current adjustment (0.52 dB/mm) is required to maintain loudness.

In a recent study Frijns *et al.* (2009) demonstrated that sequential dual electrode stimulation requires current correction to maintain constant loudness with varying α on adjacent electrodes. On the basis of computational modelling they inferred, that in sequential dual electrode stimulation, current compensation serves to fuse two separate excitation areas to a single one. They also concluded that simultaneous current steering between adjacent contacts provides a single area of excitation. The fact that current compensation is also needed with simultaneous spanning is an indication that with increasing electrode separations the electrical field summation reduces and that two separate excitation areas exist around each electrode contact of the pair.

To illustrate this reasoning further, figure 9 shows intra cochlear potentials for a subject (not from this study) in our centre, measured with the EFIM (Electrical Field Imaging Method) research tool (Advanced Bionics, Niel, Belgium). These electrical potentials are measured along the electrode array, and therefore are only an approximation of the electrical potentials at the location of the auditory nerve. However, this approximation is good enough to illustrate the effect of increasing spanning distance. The thin grey lines denote the potentials applied by the individual electrode contacts. The dotted horizontal line denotes the hypothetical threshold of neural excitation. Nerve fibres in the zone with a potential above this threshold are assumed to react to electrical stimulation, while those below this

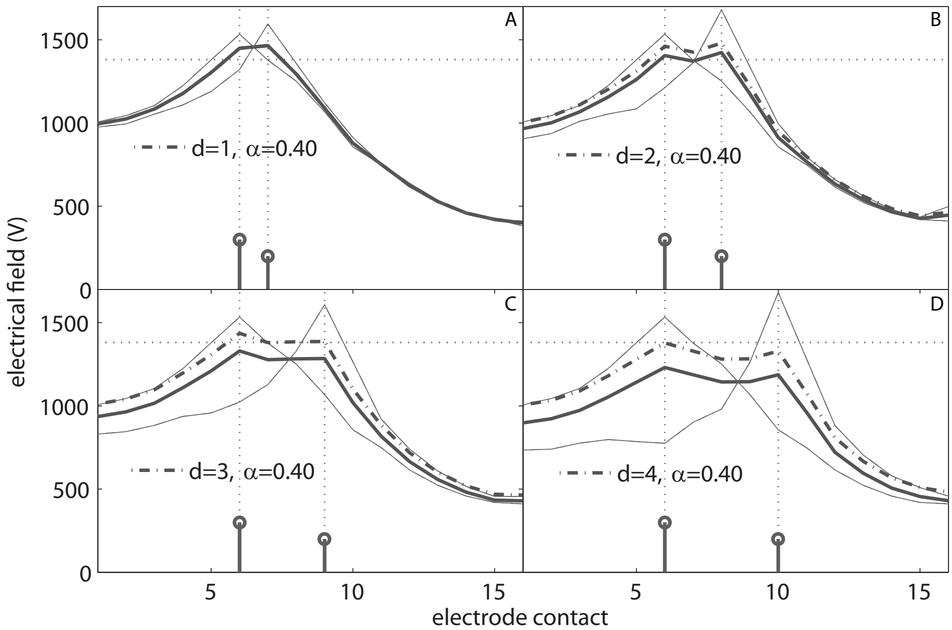

Figure 9. *Intracochlear potentials with a spanned field for a coefficient α = 0.4 and four inter-electrode distances (1.1 (A) – 4.4 mm (D)). The thin grey lines denote the potentials generated by the individual electrode contacts, as measured with Electrical Field Imaging in a patient for a HiRes90K implant with HiFocus1j electrode array. The dotted horizontal lines denote a hypothetical threshold of neural excitation. The thick line denotes the situation when no current compensation is applied. The dash-dot line denotes the situation with the addition of 4% extra current per additional contact distance spanned.*

threshold would not respond. When dual electrode stimulation is applied without current compensation, the summed field (in bold) is created. The figure shows the spanned field for a coefficient α = 0.4 and four inter-electrode separations (1.1 (A) – 4.4 mm (D)). The graphs differ in height and width; these differences are the consequence of the conductance change of the surrounding tissue as can be clinically found in patients. For increasing spanning distance essentially two phenomena are observed: (1) the peak of the spanned field decreases leading to perceivable loudness effects (cf. Figure 4) – the stimulation level potentially becoming sub-threshold (panels C and D) and (2) the width of the electrical field broadens. The dash-dot line denotes the situation with 4% additional current per additional (1.1 mm) electrode distance. This compensation current, intended to ensure constant loudness of the percept, elevates the potential over a broader region and thus adds fibres to the zone with assumed electrical stimulation, thereby fusing the regions of excitation around each electrode contact.

Pitch discrimination

In the present study the number of intermediate pitches observed for spanning is reduced by approximately 0.3 per electrode contact distance (1.1 mm) spanned. The widening of the spanned electrical field is assumed to be the root cause for this gradual loss of pitch discrimination observed with increasing spanning distance. Nevertheless, in the present paper current steering on adjacent electrodes also had a low number of intermediate pitches in comparison with previous research (2.2 vs. 7.1 and 5.0) (Firszt et al. 2007; Koch et al. 2007). Although the experimental setup was comparable with these earlier two studies, some minor differences can be listed, which are not likely the cause of the differences in outcome. First, the difference in electrode selection (same position in the cochlea vs. same contact number) might influence the number of spectral channels. Secondly, our definition of α is different. In the above- mentioned studies, $\alpha = 0$ accounts for all current on the basal electrode, where $\alpha = 0$ in this study indicates the apical contact (in line with the definition used by Donaldson et al. (2005)). Thirdly, the experimental set-up differed i.e., a 3AFC 1up/2down procedure in this study, versus a 2AFC 1up/3down in the previous ones. Fourthly, our experiment included loudness roving, while previous experiments did not. Considering these four items, the last item seems the most plausible cause of the difference between the studies. In the present study a considerable variation in performance existed among the subjects. Other studies in our clinic with good performers showed similar results to Firszt et al (2007) and Koch et al (2007). In line with this observation, also the good performers in the present study also tended to have a smaller JND α than the

poorer ones. The subjects (S1, S5, S7, S8, S11 and S12) with a speech perception score > 75%, had a significantly ($p = 0.017$) lower JND α (0.70) than the subjects with a speech perception score < 75% (0.97).

Furthermore, not every subject was able to discriminate between the pitches of two adjacent physical electrode contacts, which is consistent with previous research (Donaldson et al. 2005; Firszt et al. 2007; Koch et al. 2007). Some subjects in our study were not even able to discriminate between contacts several millimetres apart. In theory, this leads to fewer spectral channels than physical electrode contacts. Consequently, the number of spectral channels as described in the studies of Firszt *et al.* (2007) and Koch *et al.* (2007) may be overestimated for subjects, who were not able to discriminate between two adjacent electrode contacts.

The pitch discrimination performance measured for adjacent contact current steering and spanning varies widely among subjects. Some of the inter subject variability is likely due to differences in the intra cochlear electrical fields electrode placement and neural survival. Therefore, it would be interesting to investigate whether these or other parameters are able to predict the JND of α.

Pitch matching

In the present study we used pitch matching between a spanned pair and intermediate physical electrode contact to assess the relationship between the pitch and α. We expected, e.g., that the pitch of monopolar coupled electrode contact e+2 would be the same as that for α=0.5 in pair 5 (spanned pair e+4). This expectation was confirmed. None of the electrode contact pairs showed a significant difference between the place pitch of the physical electrode and the pitch of the corresponding spanned stimulus. Based on this result, spanning is believed suitable for replacing a defective electrode contact with a comparable signal. Saoji et al. (2009) also compared a spanned signal with an intermediate physical electrode, but used spread of excitation instead of a psychophysical experiment. Their outcome was not expressed in electrode place on the electrode array. They also concluded that the centre of gravity was comparable for a spanned signal and the signal of a physical electrode contact.

Although the average data were not significantly different, the individual data were not close to the expected value for every subject (figure 8). The exact stimulation site between the two electrode contacts could be influenced by the asymmetry of the electrical fields due to the tapering of the cochlea. Also, the shape of the cochlea, the arrangement of the nerve fibers (Sridhar et al. 2006), or the survival of the nerve fibers could influence outcome (Briaire and Frijns 2006), since they can differ between subjects. Which of these factors is of greatest influence on the variance between the subjects is not clear? This will be examined in the near future in our computer model of the cochlea (cf. Frijns et al. 2009). If it turns out that the shape of the cochlea has any systematic influence, it must also be taken into account in the clinical setting, when determining the number of intermediate pitches to be incorporated in future current steering based speech processing strategies. In our opinion, such an approach is likely to be an improvement over the method that is currently used in the HiRes 120 strategy.

Electrode location

All experiments were performed at two different locations on the electrode array viz., a basal- and an apical site (at 180° and 360° from the round window, respectively). In contrast with previous research (Firszt et al. 2007; Koch et al. 2007), for current steering between adjacent electrode contacts we found no significant difference in the number of intermediate pitches between basal and apical sites. An explanation for this dissimilarity could be the difference in the way electrodes were selected (same position in the cochlea vs. same contact number). In the present study, the number of the reference apical contact (e) varied between 1 and 6. Similarly, a range of between 8 and 12 was used for the basal contact (Table 1). These selections were required to compensate for anatomical and surgical variability. Electrode selection based upon location in the cochlea, on the basis of a CT-scan, is a reliable and standardized method. We prefer this approach since it allows comparison of comparable parts of cochleae across subjects.

General conclusion

Our results indicate that with current steering spanning is possible at larger electrode contact separations. With increasing electrode spanning distance, more current compensation is needed to maintain equal loudness. Moreover, a gradual deterioration in the JND for α_c is observed, which implies that the total number of intermediate pitches decreases when increasing the spanning distance. Nevertheless, spanning provides a potential opportunity to fill in gaps in the tonotopic map for subjects with defective electrode contacts. This is likely a better solution than skipping regions of the cochlea. In that respect, the spanning results are promising and therefore, spanning should be implemented in future speech coding strategies.

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