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Chapter 2

Spread of excitation and channel interaction in single and dual electrode cochlear implant stimulation

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Abstract

Objectives: To determine how simultaneous Dual-Electrode Stimulation (DES) can be optimized for the individual patient to deliver better sound quality and speech recognition. DES was compared with Single-Electrode Stimulation (SES) with respect to the site of stimulation (X) in the cochlea, the Spread of Excitation (SOE), and channel interaction. Second, it was investigated whether the number of intermediate pitches created with DES can be predicted from SOE, channel interaction measures, current distribution in the cochlea, or distance of the electrode to the medial wall.

Design: Twelve users of the HiRes90K cochlear implant with HiFocus1J electrode were randomly selected to participate in this study. Electrode contacts were selected based on their location in the cochlea as determined by multi slice computed tomography, viz. 120 degrees (basal), 240 degrees (middle), and 360 degrees (apical) from the round window. The number of intermediate pitches with simultaneous DES was assessed with a three-alternative forced choice pitch discrimination experiment. The channel interactions between two single-electrode contacts and two DES pairs were determined with a threshold detection experiment (three-alternative forced choice). The eCAP-based SOE method with fixed probe and variable masker was used to determine the location of the neurons responding to a single-electrode contact or dual-electrode contact stimulus. Furthermore, the intracochlear electrical fields were determined with the Electrical Field Imaging tool kit.

Results: DES was not different from SES in terms of channel interaction and SOE. The X of DES was 0.54 electrode contacts more basal compared with SES stimulation, which was not different from the predicted shift of 0.5. SOE and current distribution were significantly different for the three locations in the cochlea but showed no correlation with the number of perceivable pitches. A correlation was found between channel interaction and the number of intermediate pitches along the array within a patient, not between patients.

Conclusion: SES and DES are equivalent with regard to SOE and channel interaction. The excitation site of DES has the predicted displacement compared with the excitation region induced by the neighboring single-electrode contact. Unfortunately, no predictor for the number of intermediate pitches was found.

Introduction

In the majority of cochlear implant users, the number of electrode contacts required for optimal speech perception is often smaller than the total number of available contacts. Several studies have shown that speech perception in quiet does not improve above about seven electrode contacts (Baskent 2006; Fishman et al. 1997; Friesen et al. 2001; Fu et al. 1998), although a greater number is generally considered beneficial for listening in noise (Frijns et al. 2003; Nie et al. 2006). This asymptote of performance with increasing electrode contact number is thought to be due to channel interactions and limited spatial selectivity of stimulation, which act to limit the degree of spectral discrimination (Fu and Nogaki 2005).

These channel interactions can be divided into two categories, namely electrical and neural interaction. Sequential (non-simultaneous) pulsatile stimulation was initially introduced largely to avoid the electrical interaction that is inevitable with simultaneous stimulation of more than one electrode contact. Nevertheless, even with fast sequential stimulation, interaction still occurs by charge summation on the neural membrane. Because of the wide current spread, the stimuli on several electrode contacts affect an individual neuron. The interaction is somewhat uncontrolled, as it depends on the current spread, influenced for example by electrode location and local tissue conductivity, and the refractory properties of the neuron and the timing between pulses. With simultaneous stimulation, however, current fields can interact by electrical field summation before neural stimulation occurs (de Balthasar et al. 2003; Skinner et al. 1994).

Simultaneous Dual Electrode Stimulation (DES), also known as “current steering”, makes positive use of electrical interaction to enhance the number of spectral channels. DES involves simultaneous stimulation of two adjacent or non-adjacent (spanning) electrode contacts to stimulate intermediate neural populations and thus generate pitch sensations intermediate to those induced by the individual physical electrode contacts (Donaldson et al. 2005; Firszt et al. 2007; Koch et al. 2007; Snel-Bongers et al. 2011; Townshend et al. 1987). The proportion of current delivered to the two stimulated electrode contacts can be varied, potentially leading to several different pitch sensations for any given electrode contact pair.

Simultaneous DES can only be implemented in cochlear implants with at least two independent current sources. At the present time, the principle of DES is implemented commercially in the Advanced Bionics Harmony system, using the HiRes 120 speech coding strategy (Eklöf, reference note 1). Instead of 16 spectral channels generated using the 16 physical electrode contacts, 8 intermediate or “virtual” channels are available per electrode contact pair, giving a total of 120 spectral channels (from 15 available pairs). The expectation is that more spectral channels will result in a more natural sound percept and higher speech perception scores. Although initial results are promising, they vary among different studies (Brendel et al. 2008; Buechner et al. 2008; Firszt et al. 2009) (Boermans, reference note 2).

It is, however, important to note that benefit from DES is likely to be obtained only when the available spectral channels can be discriminated. Firszt et al. (2007) reported that users of the CII and HiRes 90K implants (using the PSP processor) were able to discriminate between 8 and 451 pitch percepts over the entire electrode array, with an average of 63, which suggests that many, although not all, users of these devices may potentially benefit from DES. The use of 120 channels for all patients might be an overestimation of the discrimination potential in the subject group. In approximately 30% of the subjects, the number of discriminable spectral channels is lower than the number of physical electrode contacts on the array (Firszt et al. 2007; Koch et al. 2007). For this group the use of virtual channels will probably not be beneficial and potentially even detrimental. Therefore it would be important to be able to determine in advance whether a patient is able to discriminate between physical contacts and, if so, how many intermediate pitches can be created, so that individual adjustments can be made.

Therefore, there is considerable interest in how current steering in speech coding strategies may be optimized to deliver better sound quality and speech recognition, but to understand what happens with DES, closer investigation is necessary. On the basis of earlier computational modelling of the cochlea (Frijns et al. 2009), it is predicted that low selectivity, high interaction, or a lateral position of the electrode contacts is beneficial to smooth current steering and therefore might correspond with a high number of intermediate pitches. In the present study, we investigated whether the ability of a patient to discriminate intermediate pitches can be predicted by physiological (Spread of Excitation (SOE) and Electrical Field Imaging (EFI)), psychophysical (channel interaction) or radiological (electrode location and distance to the nerve fibers) measurements. In addition to psychoacoustic evaluations, we also investigate objective measures of shifting neural excitation from Single-Electrode Stimulation (SES) to DES (Busby et al. 2008; Hughes and Goulson 2011; Saoji et al. 2009). Of interest are the site of stimulation (X) and SOE of a current steered signal, and the interaction between two current-steered signals.

Unlike previous studies, the selection of the electrode contacts in the present study was based on location in the cochlea rather than electrode contact number. There are important differences among subjects regarding insertion angle, size of the cochlea and electrode position, which will likely influence data (Kos et al. 2005; Skinner et al. 2007). Consequently, for standardized comparison between patients in the same study, data of electrode contacts at the same position in the cochlea are preferred. We therefore selected the electrode contacts on the basis of their location in the cochlea, using a computed tomography (CT) scan to determine the exact electrode position (Lane et al. 2007; Skinner et al. 1994; Verbist et al. 2005; Verbist et al. 2010a; Verbist et al. 2010b).

To summarize, the main aims of our study were to investigate to what extent SES is comparable with DES in terms of the SOE, sequential interaction index, and site of stimulation and whether the number of intermediate pitches created with DES can be predicted from the sequential interaction index, SOE, EFI or electrode distance to the medial wall. Furthermore, we investigated whether there is any correlation between these parameters and speech perception measured with SES.

Methods

Subjects

The subjects who participated in this study were 11 postlingually and 1 prelingually (S6) deafened adults who had been implanted with a HiRes 90K device with HiFocus1J electrode (Advanced Bionics, Sylmar, CA) at the Leiden University Medical Centre in 2007. No complications were reported during surgery or the rehabilitation program in any of the subjects. Subject information is provided in Table 1. Written consent was obtained from each subject, and the study was approved by the Medical Ethical Committee of the Leiden University Medical Centre (ref. P02.106.I).

The standard Dutch speech test of the Dutch Society of Audiology, consisting of phonetically balanced monosyllabic (consonant –vowel-consonant) word lists, was used(Bosman and Smoorenburg 1995). The phoneme recognition scores measured during normal clinical follow-up at 6 months were used in this study.

Table 1. *Subject demographics.*

	Gender	Age (years)	Aetiology	Duration of deafness (years)	CI usage (months)	CVC Ph%	Electrodes tested 120°	240°	360°
S1	Female	55	Rubella intra uterine	50	18	66	14	9	5
S2	Female	43	Congenital hearing loss	36	15	86	14	9	5
S3	Male	60	Congenital hearing loss	47	18	69	14	9	5
S4	Male	64	Otosclerosis	23	18	89	14	8	5
S5	Male	61	Congenital hearing loss	55	15	54	13	6	2
S6	Male	62	Meningitis	57	20	38	13	8	4
S7	Female	62	TBC meningitis	44	11	9	14	9	5
S8	Female	55	Congenital hearing loss	46	13	85	14	10	6
S9	Male	49	Meningitis	42	10	68	14	8	4
S10	Female	44	Unknown	39	9	39	13	9	5
S11	Female	70	Congenital hearing loss	21	12	93	14	9	6
S12	Female	42	Congenital hearing loss	27	13	79	14	9	4
Average		56		41	14	65			

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

CVC, consonant-vowel-consonant

Assessment of Electrode Position

The position of the electrode array, and thereby the individual electrode contacts, was determined from a postoperative CT scan, which is part of the clinical CI program. To measure the exact position of the electrodes, a multiplanar reconstruction (MPR) was generated from the CT scan (Verbist et al. 2005). A system of coordinates was placed in the postoperative MPR, using a custom Matlab computer program (MathWorks, Natick, MA). This method has been previously described elsewhere (Snel-Bongers et al. 2011). The angular positions of the electrode contacts used in this study were measured from the round window (Verbist et al. 2010a; Verbist et al. 2010b). Three cochlear locations, basal, middle and apical, were selected for this study at 120 degrees (electrode contact 13-14), 240 degrees (electrode contact 6-10) and 360 degrees (electrode contact 2-6) respectively, (Table 1). Corresponding contacts were determined for all patients.

The influence of the surgeon on the electrode array position in the cochlea was limited, as we concluded from the small range of the selected basal electrode contacts (13 -14). The differences are largely determined by the anatomy of the cochlea, which resulted in apical electrode contacts 2-6 being closest to the 360-degrees position.

The CT-scan was further used to determine the distance from the electrode contacts to the medial wall of the cochlea. After locating the electrode contacts individually, a line was generated from each contact to the centre of the modiolus. The distance to the medial wall was calculated along this line, after identifying the location of the medial wall.

Psychophysical experiments

Two psychophysical experiments were performed: pitch discrimination and measurement of the interaction index (as described in the following sections). These experiments were performed using the research tools BEDCS (Bionic Ear Data Collection System, Advanced Bionics, Sylmar, CA) for the electrical stimulus configuration and PsychoACoustic Test Suite (Advanced Bionics, Niel, Belgium) for the psychophysical tests. Stimuli were bursts of biphasic pulses with phase duration of 32 µs and a rate of 1400 pulses per second. The total burst duration varied among the experiments. Between each burst was a pause of 500 msec.. Dual-electrode stimuli were always delivered simultaneously. The proportion of the total current directed to the more basal electrode contact of the dual-electrode pair is denoted as α. The current steering coefficient varies from $\alpha = 0$, where all current is directed to the apical electrode contact and $\alpha = 1$, where all current is directed to the basal electrode contact. A staircase procedure was used for both experiments. The procedure was that they stopped after 10 reversals (i.e. changes in the direction of the signal level), where the test outcome was calculated over the last six reversals. However, in cases where a downward or upward trend was detected on the last six reversal points by the program (PsychoACoustic Test Suite), the test was extended assuming that either the adaptive procedure had not yet converged to the subject’s discrimination limit or in the latter case lost it again because of, for example, a loss of attention (Reference note 3).

Pitch discrimination

Before starting, most comfortable loudness levels (MCLs) were first determined for each of the six preselected electrode contacts individually. The subject was asked to indicate when the signal sounded most comfortably loud (MCL). All levels were carefully loudness balanced within and across electrode pairs, as in normal clinical practice.

To determine the “just noticeable difference” (JND) of α, a three-alternative forced choice, 1-up/2-down staircase procedure was used. The reference stimulus had a value $\alpha = 0$ (all current to apical electrode contact) and the probe stimulus a value of $\alpha > 0$. Both stimuli had a total duration of 300 msec and were presented on MCL. The reference stimulus was presented twice and the probe stimulus once. In each trial, the presentation order of the three stimuli was randomized. The subject was asked to select which stimulus was different in pitch. A loudness roving of 10% (considered to be moderate) was applied to the current levels to avoid any potential bias from loudness cues (Vanpoucke, Reference note 4). The experiment started with probe α of 0.9. Over the 10 reversals, α was altered in steps of 0.1 for the first two, in steps of 0.05 for the second two, and in steps of 0.025 for the remaining six. When a subject was not able to discriminate the probe from the reference (α approaching 1), the test automatically terminated after five attempts.

Channel interaction

The interaction index (*S*) (Boex et al. 2003) can be used as a measure of channel interaction. It compares the detection threshold on a certain channel in the presence of another channel, which is in the present study 2 dB lower than threshold level (TL). In the absence of channel interactions and channel masking, the interaction index is zero.

The formula is as follows:

$$S = (T_p - T_{p+m}) / 2\,(T_m - \mu) \qquad \text{Eq. 1}$$

Where T_p is the TL of the probe alone, T_m is the TL of the masker alone, T_{p+m} is the TL of the masker and probe together, and μ is the amount (the equivalent of 2 dB, in µA) that the masker level is lower than the probe level (see later). Moreover, all other values in Eq. 1 are expressed in µA. When *S* reaches zero, there is almost no interaction, and when *S* reaches 1 or -1, there is a high interaction. A negative value of *S* means that when the probe and masker are stimulated together, more current is needed than when the probe is stimulated alone. A positive value designates the opposite.

For the sequential interaction index, thresholds were determined for the probe, masker and probe + masker condition using a three-alternative forced choice, 1-up/2-down staircase procedure. Two experiments were conducted. In the first experiment, the interaction index of two consecutive single-electrode stimuli was measured. The probe covered electrode contact “e” and the masker electrode contact “e+1” (Figure 1A). The second experiment is a variation in which the interaction index of two current steered channels was conducted. Here, the probe and masker were both a dual-electrode stimulus with α = 0.5. The probe covered

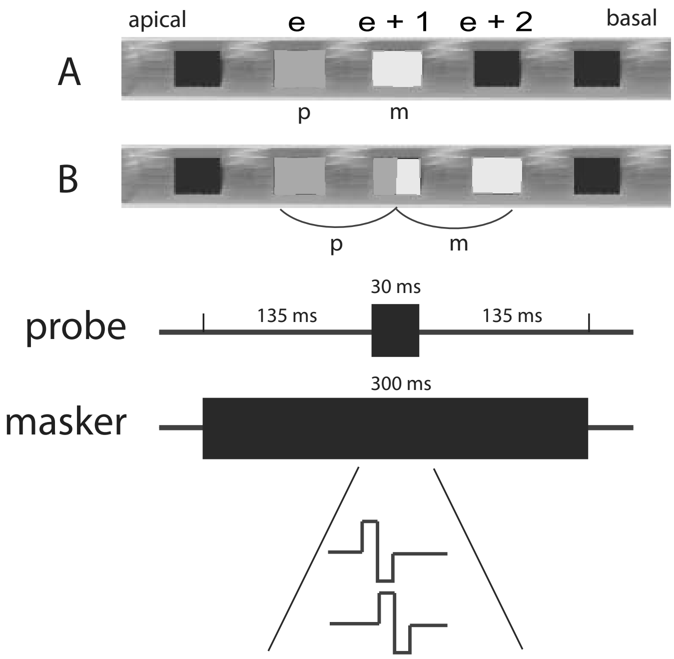

Figure 1. *Electrode contact pairs used in channel interaction experiment for single-electrode stimulation (SES) (A) and dual-electrode stimulation (DES) (B). The most apical electrode contact of a pair is denoted as e and either 120 degrees, 240 degrees or 360 degrees from the round window as selected on the basis of a computed tomography scan. The probe (p), a stimulus of 30 msec, is either e or DES of e and e+1 and the masker (m), a stimulus of 300 msec, is either e+1 or DES of e+1 and e+2. The probe starts 135 msec later than the masker. Probe and masker are presented sequentially, which is shown in the last line, where the probe is the first pulse and the masker the second.*

electrode pair “e” and “e+1” and the masker covered pair “e+1”and “e+2” (Figure 1B).

For both experiments, three thresholds needed to be determined. All the stimuli were presented randomly per part. In the first part, the threshold of the probe alone (T_P) was determined. The probe (the apical electrode contact of the pair) had burst duration of 30 msec (Figure 1) and was presented once in the three alternatives. In the second part, the threshold of the masker alone (T_M) was determined. The masker (the basal electrode contact of the pair) had burst duration of 300 msec (Figure 1) and was also presented once in the three alternatives. In the third part, the threshold of the probe in the presence of the masker (T_{P+M}) was determined. The probe and masker were presented sequentially (in phase) in the test signal, where the probe started 135 ms later than the masker (Figure 1). All trials started with the probe set to most comfortable level (MCL). The masker was presented 2 dB below T_M during the test. The reference stimulus consisted of the masker signal alone (2 dB below T_M) and was presented twice. Following each three-burst sequence, the subject was asked in which interval the signal was heard. The amplitude of the test signal was altered in the first 4 of the 10 steps with 15% and in the remaining 6 steps with 7%.

Objective measures

Electrical field imaging (EFI)
The intracochlear electrical fields exhibit considerable patient variability, depending on factors such as the state of cochlear tissues and the electrode placement and insertion angle. In a patent scala tympani, a wide spread of the current will be observed, whereas in an ossified region, the electrical spread curves are much steeper (Vanpoucke et al. 2004). To identify which intracochlear potential fields were combined with the DES stimuli, we recorded the intracochlear fields with the EFIM (Electrical Field Imaging Measurement) research tool (Advanced Bionics, Niel, Belgium). Each contact along the electrode array is stimulated in monopolar mode, and the EFIM tool then makes an accurate recording of the intracochlear potential induced on each contact along the electrode array. The stimulus used was a 3 kHz sinusoid of 1 msec duration. The spread of the electrical current in the cochlea can be derived from this measurement. To characterize the decay of the intracochlear potential by a single metric, i.e. the width, an exponential line was fitted through the data points separately for the apical and basal side of the expected peak position. The width of the graph was measured at 75% of the peak amplitude and expressed in number of electrode spacings.

Spread of excitation
A forward-masking method was used to obtain the eCAP with Neural Response Imagining via Research Studies Platform for Objective Measures (Advanced Bionics, Niel, Belgium). For determining the location of the neurons responding to a

stimulus, SOE method with fixed probe and variable masker (Cohen et al. 2001) was measured in awake subjects, both for SES and DES. The masker preceded the probe with an interpulse interval of 398.7 µs, i.e. well below the refractory period, such that fibers recruited by the masker can no longer respond to the probe stimulus. The SOE function was measured using the eCAP method as psychophysical measurements were judged too time consuming. The test started with determining the most comfortable loudness level (MCL) of the probe electrode contact(s), because the test took place at MCL. In the first experiment, the probe was set to a fixed single electrode contact. In the second experiment, the probe was expected to be shifted towards the base by approximately half an electrode contact with DES pitch (α = 0.5). The recording electrode contact was located two electrode contacts apical to the probe electrode contact. The masker, stimulated at MCL determined for the probe, was roved along all electrode contacts apart from the recording electrode contact and was a mono electrode stimulus in both experiments.

The subtraction method (Abbas et al. 2004; Brown et al. 1998) was used to separate the neural activations from the electrical artefacts. The stimulus (probe and masker) consisted of a biphasic pulse with phase duration of 32.3 µs. The gain at the recording contact was set to 300 X and the sampling rate of the stimuli to 56 kHz. The ECAP response was computed by averaging each recorded response 32 times.

To quantify the selectivity or side of stimulation (X) of the probe electrode in a single-width metric, an exponential line was fitted separately for the apical and basal side of the peak position over the graph depicting the response magnitude as a function of masker position (Cohen et al. 2003). The peak was based on the data points of the graph and is not necessarily at the same position as the probe. Selectivity was determined as the graph width at 75% of the peak amplitude expressed as number of electrode contacts (Hughes and Abbas 2006a). The X was determined in two different ways; (i) the position of the peak of the graph (X_p) and (ii) the center point along the 75% line (X_c), both expressed as position along the electrode array.

Statistical Analysis

For the comparisons between SES and DES for SOE and the interaction index, a Student t-test was used. In the other comparisons, there were multiple data points per patient. Therefore, a linear mixed model was used as this method can take several parameters into account in the same analysis. With this method, direct correlation will give a result for the group but not for the individual patient. It is even possible that the overall result can give a positive correlation, whereas all individual patients have a negative correlation of their own data points(Fitzmaurice et al. 2004). The difference between the two methods will be illustrated by additionally using a Pearson's correlation for all the comparisons.

As speech perception cannot be measured on three different locations along the array, the comparison between speech perception and the other parameters was performed using a Pearson's correlation. Differences were considered significant at the 0.05 level. All data were analyzed using the SPSS 16 (Statistical Package for the Social Sciences, SPSS inc. Headquarters, Chicago, IL).

Table 2. *Statistical outcomes of the linear mixed model (LMM) and Pearson correlation for all the measured parameters for the influence of the electrode contact location in the cochlea (180 degrees vs. 360 degrees measured from the round window) and in comparison with alpha.*

	Statistical test		**Alpha**	**Sequential interaction index (SES)**	**Sequential interaction index (DES)**	**Selectivity SES (elec.)**	**Selectivity DES (elec.)**	**EFI**	**Distance medial wall (mm)**
Influence of place	LMM	*p*	0.462	0.869	0.982	0.014 *	0.049 *	0.001 *	0.143
Alpha vs.	Pearson correlation	R^2	-	-0.119	-0.234	0.125	0.080	0.077	0.370
		p	-	0.488	0.197	0.481	0.653	0.657	0.026 *
	LMM	*p*	-	0.026 *	0.375	0.913	0.233	0.859	0.806

For both tests, the p value and the Pearson correlation R^2 are given.

* Differences were considered significant at the 0.05 level.
SES, single-electrode stimulation; DES, dual-electrode stimulation; EFI, electrical field imaging

Results

Electrode position

The LMM can take several indicators into account, of which the electrode location in the cochlea is one. For all the parameters, it was investigated whether the electrode position was of influence on the outcome, of which the *p* values are shown in Table 2 in the first row. Both SOE and EFI show a significant difference for the three locations (p < 0.05). This only indicated that there is a difference between the three locations but not which ones differ from each other.

The differences between the three locations were further analyzed with a standard (two-sided) Student *t*-test, the results of which are shown in table 3. The basal region gives a significantly smaller 75% width of the graph than apical, indicating better selectivity in this region. There was no significant difference between apical and middle and between middle and basal sites. There was, however, a significant difference between apical and basal sites. For EFI, the LMM also showed an influence of the position of the electrode in the cochlea (Table 2). The Student *t*-test (Table 3) calculated a significant difference in width between middle and basal and between apical and basal locations. There was, nevertheless, no difference between the width at apical and middle locations. This indicated more current spread in the apical and middle regions than in the basal region. The other parameters were not different for the three locations (Table 2).

Comparison between SES and DES

The comparison between SES and DES for SOE and sequential interaction index is shown in Figure 2. No difference (p = 0.708) was found between SES (4.32 +/- 2.43) and DES (4.45 +/- 2.36) for the width at 75% of the SOE graph (Figure 2A). Figure 3 shows the results from a typical subject (S3), where the width for SES appears similar to DES, which also demonstrates the similarity between SES and DES. This figure also demonstrates that the exponentials nicely fitted the data points (R^2 between 0.90 and 0.98), which is the case in all subjects (the average R^2 is 0.89 +/- 0.09). The sequential interaction index also showed no difference (p = 0.9) between SES (-0.24 +/- 0.12) and DES (-0.23 +/- 0.14), which is illustrated in Figure 2B.

Table 3. *Statistical outcomes of the standard (two-sided) Student's t-test for selectivity SES and DES and EFI.*

	Selectivity SES	Selectivity DES	EFI
120 degrees vs. 240 degrees	0.161	0.218	0.005 *
120 degrees vs. 360 degrees	0.004 *	0.015 *	< 0.001 *
240 degrees vs. 360 degrees	0.077	0.168	0.233

The three different locations are compared with each other, because of the significant influence found with the linear mixed model (see table 2 first row). The p-values are shown.
** Differences were considered significant at the 0.05 level.*
SES, single-electrode stimulation; DES, dual-electrode stimulation; EFI, electrode field imaging.

The last comparison between SES and DES was for the X (the site of stimulation). The peak of the SOE graph (X_p), determined using the intercept of the fitted lines, and the center of the excitation area (X_c, half way along the 75% line) are used as measures of X; both X_p and X_c are expressed in electrode contact number. The dashed line in Figure 3 indicates X_p and the arrow in Figure 3B indicates X_c., which are both hypothesized to be identical to the number of the probe contact. With DES, this can be a fractional number, e.g. 6.5 when DES on contacts 6 and 7 with α = 0.5 is used for the probe. Figure 4 shows X_p (A) and X_c (B) between SES and DES for the three locations separately (triangle (120^0), square (240^0) and dot (360^0)). The expected place of X_p and X_c for DES is indicated by a dashed gray line (at 0.5). Note that the SES on the apical contact of the pair was used as a reference stimulus and is indicated by the horizontal solid line at zero. The bars represent the average

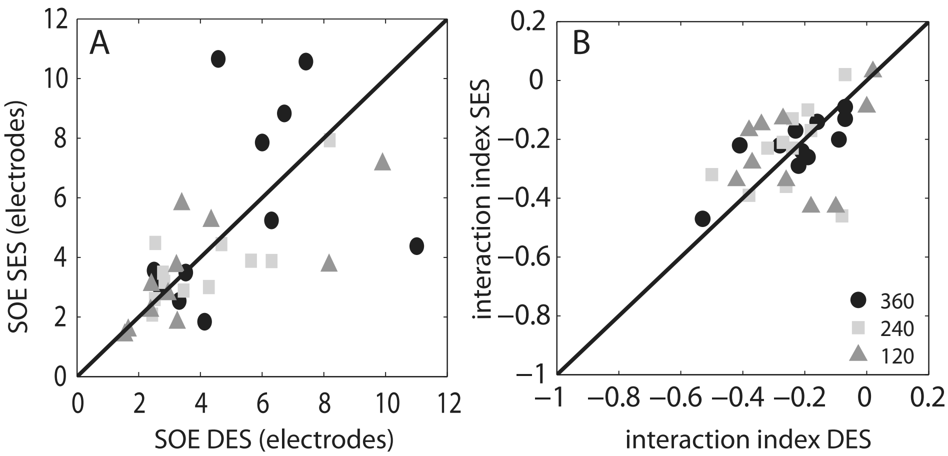

Figure 2. *The comparison between single-electrode stimulation (SES) on the y axis and dual-electrode stimulation (DES) on the x axis for spread of excitation (SOE) (A) and channel interaction (B). The dot represent the data derived from apical (360 degrees), the square the data from middle (240 degrees) and the triangle the data from basal (120 degrees).*

shift per electrode location. Despite the wide spread of the individual data points, the averages of X_p along the array are not significantly different from the electrode contact number of SES (p = 0.99) or the predicted location of DES (p = 0.744). In comparison with SES on the apical contact of the DES pair, an average shift of 0.54

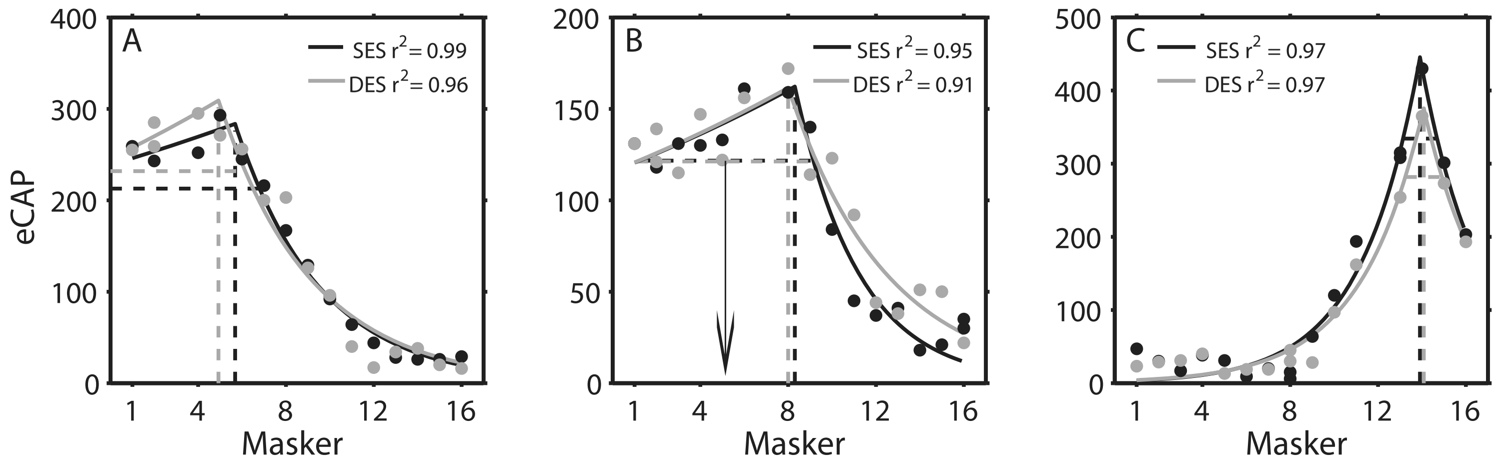

Figure 3. *The spread of excitation curves from S3 for the three locations in the cochlea, 360 degrees (A), 240 degrees (B) or 120 (C). The black dots and line represent the data from single-electrode stimulation (SES) and the grey dots and line represents the data from dual-electrode stimulation (DES) on adjacent electrode contacts. The vertical dashed line denotes* X_p *of the graph on the electrode array, and the horizontal dashed line denotes the width of the graph at 75% of the peak amplitude. The arrow in (B) denotes* X_c.

(+/- 0.77) electrode contacts to basal was shown for DES (with α=0.5), which is highly significant (p = 0.0002) and completely in line with expectations. This shift is also illustrated in Figure 3 for subject S3. In contrast, the averages of X_c are significantly different from the electrode number of SES (p = 0.003) or the predicted location of DES (p < 0.001). The location along the array for SES is 0.69 (+/- 1.3) electrode contacts more apical to the electrode number of the probe, which is demonstrated in figure 3B. The average difference of X_c between SES and DES (with α=0.5) is 0.57 (+/- 1.2) electrode contacts (X_c for DES being more basal), which is a significant one (p = 0.007) of the expected size and direction (Figure 4B).

Predictors of pitch discrimination and speech recognition

To be able to predict JND α from the other measures, at least one parameter must correlate significantly with it. As shown in Figure 5 A-D and listed in Table 2 in the second row, only the electrode contact distance to the medial wall showed a significant, but rather weak (R^2 = 0.370, p = 0.026) correlation with JND α. None of the other measured parameters (interaction index, selectivity and EFI) seemed to correlate with JND α. However, as argued before, a Pearson's correlation is not the correct way to address this issue, and a LMM is more appropriate here. First, the relationship between the different cochlear locations and the measured parameters was determined. As described above and listed in Table 2 in the first row, only SOE an EFI differed for the three locations.

The LMM was applied on JND α with all the other parameters (Interaction index, SOE, EFI and distance to the medial wall). For SOE and EFI, the electrode contact location was embedded in the test. Unlike the Pearson's correlation, a significant relationship between JND α and the sequential interaction index was found (p = 0.032). There was no significant correlation for the electrode distance to the medial wall (p = 0.806). The former result implies that lower channel interaction typically occurs with a lower JND α. The difference between the correlation and the LMM for channel interactions can be explained with the individual results shown in Figure 5F. Five of the 12 subjects (S1, S3, S4, S5 and S10) showed a decrease in JND α together with less interaction. The other parameters were too diverse and showed no relation with JND α (table 2).

For the comparison with speech perception scores, the average of the three values from the different locations for all parameters for each subject was used. Only one apparent relationship was observed (Figure 5E): JND α showed a significant correlation with the speech perception score (R = -0.6, p = 0.038).

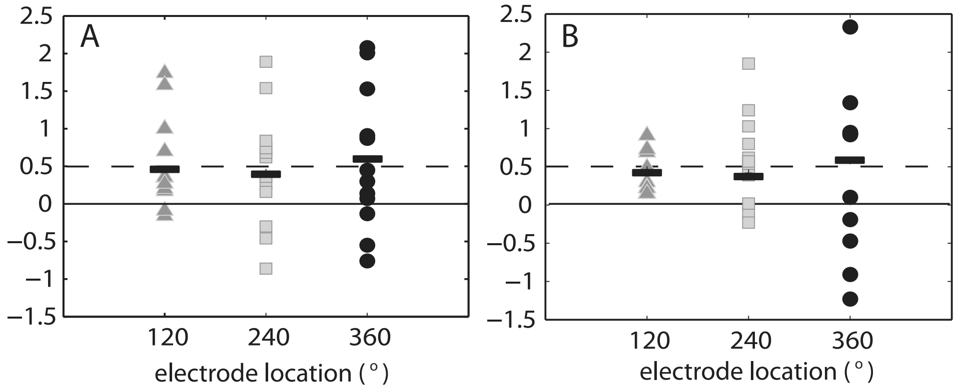

Figure 4. *The difference X between single-electrode stimulation (SES) and dual-electrode stimulation (DES) for* X_p *(a) and for* X_c *(b), where SES is made equal to zero. The y axis represents the place on the electrode array expressed in electrode number. The horizontal dashed line represents the expected shift of 0.5 for α = 0.5. The solid black bars are the average of all the data points for that location. The symbols demonstrate the individual data.*

Discussion

The main goal of this study was to examine whether DES exhibits the same characteristics as SES for SOE, sequential interaction and the site of stimulation (X). The former two parameters were indistinguishable for SES and DES, which implies that a “software electrode” behaves similarly to a real physical electrode contact. This implies that DES can be used in a strategy similar to continuous interleaved sampling (CIS) (Wilson et al. 1991) and if this is true it is likely that DES produce similar speech recognition scores to SES. Moreover, these results are consistent with previous studies (Busby et al. 2008; Saoji et al. 2009).

If DES can be used to improve tonotopical resolution, this could result in improved speech perception in general and possibly also in improved speech perception in noise and better music perception. Indeed, some studies have indicated that an increased number of electrode contacts is beneficial to speech in noise (Nie et al. 2006). Firszt et al. (2009) compared HiRes (SES) with HiRes120 (a DES implementation, theoretically delivering 120 channels) in CII and 90K cochlear implant users. They found a significant improvement in speech recognition with HiRes 120 compared with HiRes for words in quiet and sentences in noise as well as

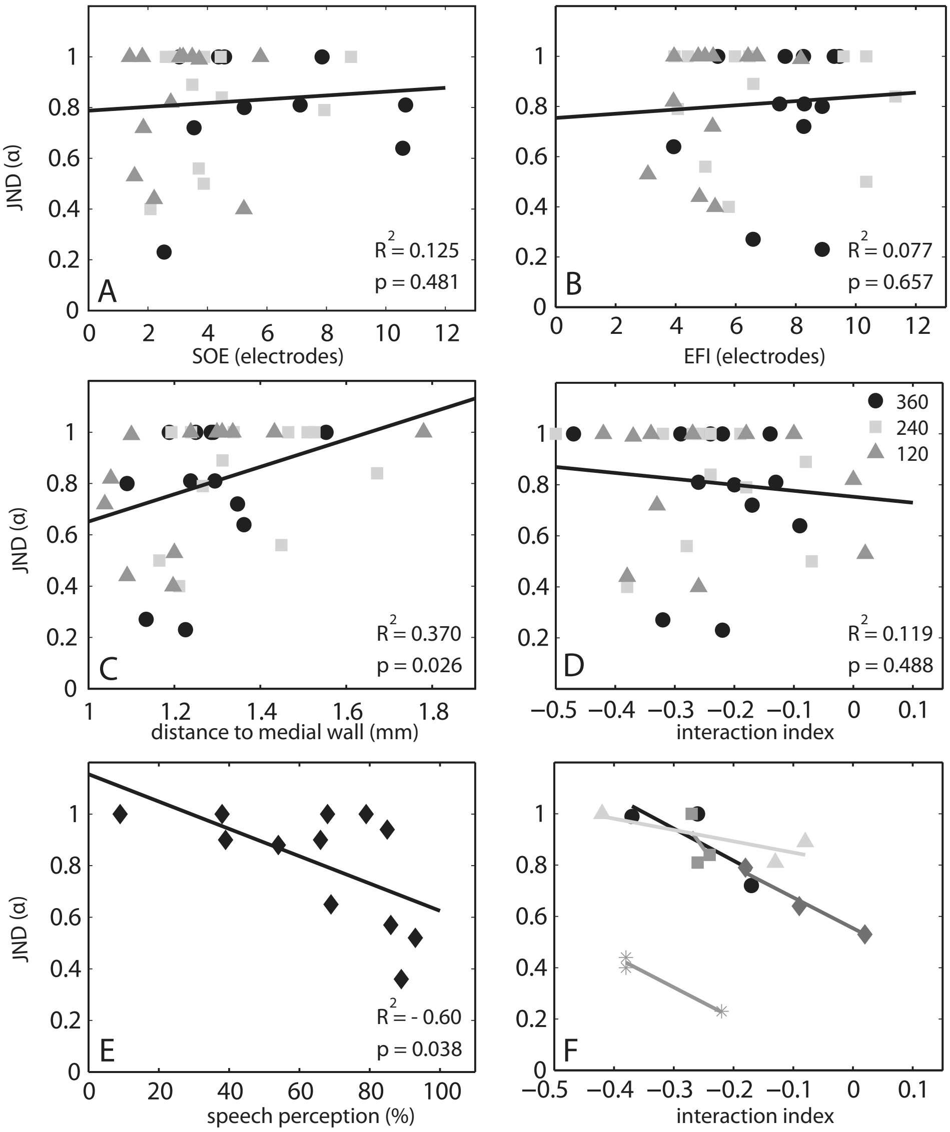

Figure 5. *The first four graphs show the correlation between just noticeable difference (JND) α and spread of excitation (A), electrical field imaging (EFI) (B), electrode distance to the medial wall (C) and channel interaction (D). The dot represent the data derived from apical (360 degrees), the square the data from middle (240 degrees) and the triangle the data from basal (120 degrees). The correlation between JND α and speech perception (E) and the individual results or the channel interaction experiment for 5 of the 12 subjects (F) are also shown.*

music ratings of pleasantness and instrument distinctness. This suggests that use of DES results in significant improvement of performance, although this improvement may be modest. On the contrary in a recent study, Donaldson et al. (2011) found no difference between the two strategies, HiRes or HiRes 120, for speech perception with or without background noise. Some subjects had better speech perception with HiRes 120, but there were also subjects who exhibited initial decrements. The subjects who participated in the present study did not use HiRes 120, and so a direct comparison between the studies is not possible, but the subjects who participated in this study had a relatively high JND α compared with subjects in other published studies (Donaldson et al. 2005; Firszt et al. 2007; Koch et al. 2007; Townshend et al. 1987). When using the formula used in former studies (Firszt et al. 2007; Koch et al. 2007) to calculate the number of spectral channels per electrode array, an average of 20 spectral channels for the whole array applies to our subject group with a range from 8 till 46. It is therefore not clear whether the subjects in the present study would benefit from HiRes 120. It may be that individual allocation of the number of spectral channels implemented using DES, based on the JND α determined for a couple of electrode contact pairs, could optimize the speech coding strategy for individual users.

The SOE produced by current steering has been investigated previously. Saoji et al. (2009) compared the SOE of a simultaneously spanned signal with that produced by an intermediate physical electrode contact in Advanced Bionics CI users (e.g., comparing the SOE produced by electrode contacts 3 and 5 stimulated simultaneously with that produced by electrode contact 4 alone). In line with the findings at the present study, they found that both configurations produced comparable areas of excitation. Busby et al. (2008) determined whether there were any consistent differences between the electrophysiological SOE functions produced by simultaneous DES and SES for subjects with the Nucleus Freedom cochlear implant. They also found that dual-electrode SOEs were similar to those for single electrodes with respect to SOE width. The latter outcomes could, however, have been influenced by impedance differences between the two contacts, as electrode coupling was used to divide the current over the contacts. Hughes and Goulson (2011) used subjects with either an advanced bionics CI or a nucleus Freedom CI and compared physical contact with virtual channels for three different ECAP responses, threshold and slope of the input/output function, measure of refractory recovery and relative location of SOE. They found no difference between a physical contact (SES) and a virtual channel (DES) for all their measures and the location of the SOE from a virtual channel was situated between the two flanking physical electrode contacts.

Classically, uncontrolled channel interaction has been identified as a phenomenon that easily degrades speech perception with CI. Speech perception outcomes generally improved after the introduction of sequential stimulation, such as was first used by the CIS strategy (Wilson et al. 1991), which results in less channel interaction. Boëx et al. (2003a) measured the interaction produced by sequential and simultaneous stimulation and confirmed that sequential biphasic stimuli on different contacts produce lower interactions than simultaneous stimuli. With DES, controlled channel interaction is exploited in a favorable way to produced additional pitch percepts. In line with this, the present study could not demonstrate any difference in terms of sequential electrical interaction or width of SOE between SES and DES. This means that DES channels in many respects behave like physical contacts and could be implemented as such in the CIS strategy, without negative effects due to channel interaction.

This study demonstrates that eCAP forward-masking curves, which are mostly used to determine the SOE of a single-electrode contact, are an appropriate method for distinguishing the stimulation site for DES and SES. In line with our findings, Saoji et al. (2009) concluded that the "center of gravity" was comparable for DES and SES. Of course, one would also expect that there are differences between DES and SES at the edges of the region of excitation, but we are not aware of any evidence in the literature in this respect. Snel-Bongers et al. (2011) used a pitch matching experiment that used spanned electrode contacts to find the actual X produced by DES. Again, in that study, a current steered signal was compared with an intermediate physical electrode contact. They found that equal current distribution (α = 0.5) corresponded with a physical electrode contact exactly in between the driven contacts. In the present study, the excitation area was determined by using eCAP-based SOE curves. For the site of the neural excitation zone, a difference of 0.5 electrode contacts between SES and DES was predicted. A significant shift in X_p of 0.54 electrode contacts towards the base relative to the X_p of the probe with SES was observed, which was not significantly different from the expected value of 0.5. So, the maximal X for α = 0.5 is situated half way between the two driven electrodes contacts, just as predicted and in line with the study of Snel-Bongers et al. (2011). However, this was not the case when the centre of gravity was used as a measure of excitation site, i.e., the middle of the 75% width line. Here, the shift differed significantly from the expected shift of 0.5. In line with this, for SES also, the centre of gravity of the 75% SOE width was shifted apical relative to the stimulating contacts. It is not equivocally clear which of the two methods is the most appropriate. A theoretical advantage of the first method (X_p) is that it does not require or assume symmetry, whereas the second method does. Among others, Briaire et al. (2000) showed that there is no symmetry in the current pathways in the cochlea. The current distribution to basal is larger than to the apical region, which results in an asymmetry in the SOE curves (van de Beek, reference note 5). A limitation of the first method is that it depends on the fit of an exponential curve to the data points, which is not per se correct. However, the correlation coefficient of the fitted line is high in all cases tested here.

Two studies already mentioned above (Saoji et al. 2009; Snel-Bongers et al. 2011) have tried to identify X of DES by making use of spanning, i.e. current steering between nonadjacent electrode contacts. The question arises whether eCAP forward-masking curves give the same results for spanning as was found in the present study with neighbouring contacts. This will be subject of future investigation. The initial outcomes suggest that the findings can be extended to spanned electrode pairs.

The location of the electrode array is influenced by the surgical insertion and by the anatomy of the cochlea. As shown in Table 1, the electrode contact closest to 120 degrees from the round window was quite constant in our subjects, ranging from 13 to 14. This means that in this population, the insertion position of the electrode contact was constant. Nevertheless, there was a wide range in contact number for the electrode contact used at the apical (360 degrees) position (which is between contacts 2 and 6), demonstrating that the insertion angle varies considerably among individuals for outer wall electrodes like the HiFocus J. This is most likely a result of the variable anatomy (especially size) of the cochlea, which means that the actual location of any particular electrode contact may vary widely among subjects when it is defined by electrode contact number as is done in many studies. In the present study, however, all measured parameters were correlated with the electrode contact location rather than number: EFI and SOE however, showed significant differences between the three locations in the cochlea. The EFI recordings showed more current spread in the apical region and, accordingly, the eCAP SOE measures yielded broader spatial selectivity curves in the apex. This was previously predicted by Briaire and Frijns (2006) in a computer model of the cochlea but has, to our knowledge, not yet been demonstrated in patients. Previous studies investigating the influence of the location on SOE (Hughes and Abbas 2006a; van Weert et al. 2005) found no difference between apical, middle or basal electrode contacts. However, their selection of electrode contacts was based on contact number instead of more precise electrode location.

One of the principal aims of this study was to find a parameter that predicts the ability of a subject to discriminate intermediate pitches. Using a Pearson's correlation, only the electrode distance to the medial wall showed a significant correlation with JND α. However, a Pearson's correlation is not the optimal method when a subject has more than one data point with the same experiment because, in this situation, an individual might show a significant correlation, while the group does not. With a LMM, the individual and other different parameters can be taken into account. Using this approach, only the sequential interactions index showed a significant correlation with JND α but only on a per-patient basis. Therefore, the sequential interaction index in itself is not a useful predictor for JND α.

As mentioned earlier, four subjects reach floor performance, i.e. they have a JND α = 1. Three of these four subjects (S6, S8 and S9) also participated in the study of Snel-Bongers et al. (2011), where spanning offered the possibility to measure JND α above 1. If their smallest JND α from that study (2.85, 1.94 and 1.76, respectively) is included in the statistics of the present paper a significant correlation with the distance to the medial wall is found (R^2 = 0.649, p = 0.043). This means that a lateral placement of the electrode array would lead to a higher JND α, which is in contrast with our initial hypothesis. Further studies in larger patient groups have to elucidate this.

As an addition, all the parameters from the present study were compared with the speech perception of the subjects measured at 6 months after implantation. JND α showed a significant correlation with speech perception. Subjects who are good at discriminating intermediate pitches tend to have high scores in speech understanding, which is in contrast with the findings from Firszt et al. (2007). The other parameters of the present study showed no correlation with speech perception, which is in line with previous studies (Cohen et al. 2006; Hughes and Abbas 2006b; Hughes and Stille 2008).

An explanation for finding better pitch discrimination with higher speech perception scores could be that these subjects have better or more evenly distributed neural survival (Briaire and Frijns 2006). If some neurons are missing in a crucial cochlear location for a given pitch, it is logical that a subject will not be able to discriminate between two signals which stimulate that area. This would suggest that current steering is only beneficial for subjects who have optimal conditions for speech perception from the outset. Contrary to this hypothesis, Firszt et al. (2009) report that they could not predict the benefit from current steering on the basis of performance with HiRes, Donaldson et al. (2011) do not analyze this explicitly, but from the data they present, it is not evident that better performance with HiRes would predict more benefit from HiRes120.

In summary, the results of the present study showed that SES and DES are equal with regard to SOE and channel interaction, which indicate that DES channels could be used in a CIS strategy. The excitation site of DES has the predicted displacement compared with the excitation region induced by SES measured with SOE. Furthermore, the variation in number of intermediate pitches created with DES along the array is correlated with channel interaction.

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