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Research article

Relationship between electrode position and temporal modulation sensitivity in cochlear implant users: Are close electrodes always better?

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ABSTRACT

Temporal modulation sensitivity has been studied extensively for cochlear implant (CI) users due to its strong correlation to speech recognition outcomes. Previous studies reported that temporal modulation detection thresholds (MDTs) vary across the tonotopic axis and attributed this variation to patchy neural survival. However, correlates of neural health identified in animal models depend on electrode position in humans. Nonetheless, the relationship between MDT and electrode location has not been explored. We tested 13 ears for the effect of distance on modulation sensitivity, specifically targeting the question of whether electrodes closer to the modiolus are universally beneficial. Participants in this study were postlingually deafened and users of Cochlear Nucleus CIs. The distance of each electrode from the medial wall (MW) of the cochlea and mid-modiolar axis (MMA) was measured from scans obtained using computerized tomography (CT) imaging. The distance measures were correlated with slopes of spatial tuning curves measured on selected electrodes to investigate if electrode position accounts, at least in part, for the width of neural excitation. In accordance with previous findings, electrode position explained 24% of the variance in slopes of the spatial tuning curves. All functioning electrodes were also measured for MDTs. Five ears showed a positive correlation between MDTs and at least one distance measure across the array; 6 ears showed negative correlations and the remaining two ears showed no relationship. The ears showing positive MDT-distance correlations, thus benefiting from electrodes being close to the neural elements, were those who performed better on the two speech recognition measures, i.e., speech reception thresholds (SRTs) and recognition of the AzBio sentences. These results could suggest that ears able to take advantage of the proximal placement of electrodes are likely to have better speech recognition outcomes. Previous histological studies of humans demonstrated that speech recognition is correlated with spiral ganglion cell counts. Alternatively, ears with good speech recognition outcomes may have good overall neural health, which is a precondition for close electrodes to produce spatially confined neural excitation patterns that facilitate modulation sensitivity. These findings suggest that the methods to reduce channel interaction, e.g., perimodiolar electrode array or current focusing, may only be beneficial for a subgroup of CI users. Additionally, it suggests that estimating neural survival preoperatively is important for choosing the most appropriate electrode array type (perimodiolar vs. lateral wall) for optimal implant function.

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1. Introduction

Previous studies have suggested that the effective number of channels cochlear implant (CI) recipients can utilize is only up to eight [1–3]. Due to this, CI users rely heavily on the information in the temporal modulation of the electrical pulse trains [1,4]. One measure that assesses CI users' ability to decode temporal modulation of the biphasic pulses is modulation detection thresholds (MDTs). Temporal modulation sensitivity in CI users has been studied extensively in the past (e.g., Refs. [5,6]. MDTs measured in the middle of the array almost perfectly explained the variance in the speech recognition performance across CI users [4]. Subsequent studies [7,8] suggested that thresholds measured in the middle array may not represent modulation sensitivity of the whole ear since MDTs were found to be highly variable along the tonotopic axis. Because the patten of this variability appeared to be ear specific [6], previous studies have attributed the variability to the uneven neural survival along the frequency axis in implanted ears [9–11].

A series of studies were conducted to examine whether avoiding stimulation sites with poor MDTs, which at the time was thought to reflect severe pathology, produced better speech recognition. A significant improvement in speech performance occurred with a map containing ten active electrodes having the best masked modulation versus a map with ten electrodes having the poorest sensitivity [12]. Further, when sites that demonstrated poor modulation sensitivity were turned off, users' consonant and sentence recognition improved in comparison to including all active electrodes; however, their vowel recognition was compromised perhaps due to reduced spectral resolution [6]. Considering the limitations of the previous studies for vowel recognition, along with the fact that sites with poor modulation sensitivity are not evenly spread but converged in specific regions, another approach raised detection threshold (T) levels of poorly performing sites instead of deactivating them which improved participants' speech-reception thresholds (SRTs) [13]. The success of the site-selection [6,12] and site-rehabilitation strategies [13] further highlights the importance of modulation sensitivity for implant function and the gravity of investigating factors contributing to the variation in MDTs.

A number of such factors have been identified. Modulation sensitivity improves with stimulation level within the dynamic range [7,14,15], which motivated the site-rehabilitation strategies where T levels were adjusted [13]. Modulation sensitivity also improves by lowering the carrier rate. The effect has been consistently shown in a handful of studies [14–18]. The benefit of low-rate stimulation was attributed partly to the fast loudness growth within a smaller dynamic range. A recent study from our laboratory also demonstrated that in monopolar stimulation mode, MDTs were better on stimulation sites measured with sharper spatial tuning curves [18]. Since low-rate stimulation produces narrower excitation patterns than high-rate stimulation [19], better modulation detection using a lower carrier rate may also be explained by a narrower stimulation pattern.

The mechanism underlying the link between MDT and sharp spatial tuning curves remains unclear. A sharp tuning which defines a good electrode-neuron interface requires local activation of a good neural survival region [20]. Distant electrodes may produce current spread and generate broad tuning patterns, even if the neural survival is good in that region. If the electrodes are close to the modiolus, but in a region of poor neural survival, neural recruitment from the surrounding regions may occur thus resulting in broadened tuning. Although across participants electrode-modiolus distance generally correlated with bandwidth of spatial tuning curves [20], when reexamining this relationship within participants, this relationship was only proven for half of the participants [21]. This is consistent with the idea that electrodes close to the modiolus stimulating few neurons may still produce broad tuning. Thus, it seems reasonable to conclude that the correlation between MDT and tuning curves reported that good modulation sensitivity relies on local activation of a sufficient number of neurons, by close electrodes [18].

In humans with cochlear implants, electrode position varies widely across the length of the array [22–26]. Some of the psychophysical and physiological measures that correlate with the count of spiral ganglion cells in implanted guinea pigs may not necessarily measure local neural conditions in humans, but rather show a strong dependence on electrode-modiolus distance [26]. These measures included electrically evoked compound action potential (ECAP) thresholds, psychophysical detection thresholds, and ECAP amplitude growth functions. Generally, higher thresholds and steeper ECAP growth were correlated with greater electrode-modiolus distance [26]. Recovery from forward masking, a measure that reflects neural health, rather than survival counts per se, was also found to be related to electrode position [27].

The relationship between electrode position and modulation sensitivity has not been previously studied. As discussed above, the across-site variation in MDT has primarily been attributed to the variation in neural survival across the array (e.g., Ref. [6]. Examining the dependence of MDT on electrode position will test the extent to which this assumption is true. Further, it will inform how the selection of array type, perimodiolar versus lateral wall, may affect temporal modulation sensitivity, one of the most important predictors for speech outcomes in implant users. In this study, we used computerized tomography (CT) imaging which has been used to describe the various characteristics of electrode positions in human CI users [22,25,26]; Finley et al., 2008). Expanding from the findings that good modulation sensitivity relies on sharp tuning [18], we aimed to examine, first, how much variation in the tuning curves is explained by electrode position. Based on previous results [21], and the assumption that sharp tuning requires close electrodes stimulating a good neural survival region, we hypothesized that electrode-modiolus distance would account for a moderate amount of variance in the tuning curve slopes. Second, we hypothesized that close electrodes would produce excitation patterns favorable for modulation detection if the quantity of the surviving neurons in that region is sufficient for excitation to remain narrow. Thus, the relationship between MDT and electrode position may depend on individual ears. Ears that have overall better neural survival and measured with good speech outcomes, may show a positive effect of close electrodes on MDTs, whereas a perimodiolar electrode array stimulating an ear of severe pathology may be detrimental for the modulation sensitivity.

2. Methods

2.1. Participants and hardware

Ten postlingually deafened individuals with a minimum of 1 year of implant experience participated in this study. They were all users of the Cochlear Nucleus® (Cochlear Corporation, Englewood, CO) devices. S1, S25, and S37 were bilaterally implanted and both ears were tested. S27 was also bilaterally implanted but was tested only for the right ear. Participant demographic information is shown in Table 1. All participants provided written informed consent to take part in the study. Use of human participants for the following experiments were approved by the Institutional Review Board (IRB) of East Carolina University.

A Nucleus Freedom® processor was used in the psychophysical tests controlled by MATLAB programs and the Nucleus Implant Communicator (NIC2) interfacing software. Speech testing used the participants' own processors and their everyday use programs.

2.2. Modulation detection thresholds

The dynamic range (DR) of the MDT stimuli was measured at all active electrodes in random order. Pulse phase duration rather than pulse amplitude was modulated to allow finer resolution in the modulation depth. The MDT stimuli were 300 ms long, delivered at a stimulation rate of 250 pulses per second (pps) in monopolar stimulation mode. The reference phase duration and phase gap were 200 μ s and 8 μ s, respectively. The method of adjustment (MOA) was used to determine T levels and the method of limits was used to determine the maximum comfort levels (Cs) for each electrode. The participants were presented with the options of 25, 5, and 1 clinical unit (CU) buttons to adjust the stimulus level. To measure Ts, the participants were instructed to begin with increasing stimulus level to comfortable audibility to avoid potential confusion caused by any tinnitus sensation, after which they were asked to decrease the level to determine the just detectable stimulus level. They were advised to utilize finer step sizes when approaching the threshold. To measure Cs, the participants were instructed to slowly raise the stimulus level to a maximum level they could tolerate for a long duration, restricting the use of 25-CU step size to avoid overstimulation.

To measure MDTs, the stimuli were presented at 50% DR of the respective electrodes. The modulated signal (10 Hz) was placed randomly in one of the intervals of the 4-alternative-forced-choice (4AFC) paradigm and the remaining three stimuli were not modulated. The task of the participants was to identify the interval containing the modulated signal. Modulation depth (m) started at 50% and was adapted using a 2-down 1-up approach based on the participant's response. Two consecutive correct responses from the participant resulted in a decrement, while a single incorrect response resulted in an increment in modulation depth. For the first and second reversals, the step sizes were 6 dB and 2 dB, respectively, and all of the remaining were 1 dB. MDTs were calculated by averaging the m values of the last eight reversals and were quantified as dB re 100% modulation depth.

2.3. Psychophysical tuning curves

A subset of seven ears (S1L, S1R, S4L, S19L, S22R, S25L and S25R) were measured for spatial tuning curves. For each ear, two electrodes with relatively high versus low 80-pps thresholds were selected as probe locations. Measuring low-rate threshold is a quick way to estimate width of neural excitation across the stimulation sites [28]. For S1R, four electrodes, two with relatively high, and two with relatively low 80-pps thresholds were measured. The spatial tuning curves were measured using forward masking. Each probe had seven maskers, one at its own position and 3 each on the apical and basal side of the probe location, when spatially allowed. DRs were estimated, using methods described above, for each of the 7 maskers and the probe stimuli using biphasic pulse trains of 25 μs phase duration, 8 μs phase gap, and a stimulation rate of 900 pps. The stimulus lengths for masker and probe stimuli were 300 ms and 20 ms, respectively, with a probe delay of 10 ms. Probe thresholds were measured again adaptively (3AFC) using the 2-down 1-up rule. The probe threshold was defined as the average level of the last six reversals out of a total of ten reversals. The above procedure was repeated, and the two thresholds were averaged. The probe level was then set at 2 dB above its threshold.

To measure spatial tuning, the masker level required to just mask the probe was measured for each of the seven maskers in a 3AFC

Table 1
Participant demographic information.

Participant	Gender	Age (years)	CI Experience (years)	Electrode Type	Processor
S1L	M	82.3	19.2	CI24R (CS)	CP910
S1R	M	82.3	13.2	CI24RE (CA)	CP810
S4L	F	62.1	9.7	CI24RE (CA)	CP810
S7R	F	75.6	10.4	CI24RE (CA)	CP810
S19L	F	74.5	13.9	CI24RE (CA)	CP1000
S22R	F	76.4	8.8	CI24RE (CA)	CP920
S25L	F	64.1	13.6	CI24RE (CA)	CP900
S25R	F	64.1	12.8	CI24RE (CA)	CP900
S27R	M	61.7	15.3	CI24RE(CA)	CP920
S31L	M	71.6	5.8	CI422	Kanso
S36L	M	81.6	2.8	CI522	CP1000
S37L	M	76.2	6.8	CI422	CP920
S37R	M	76.2	18.3	CI24R (CS)	CP920

paradigm. The masker level started at 20% of its DR. The masker-plus-probe stimulus was presented randomly in one of the three intervals and the remaining intervals were maskers only. The participants were instructed to select an interval ending with a "chirp." The masker level adapted using a 2-down 1-up rule. The minimum masker level to mask the probe was determined as an average of the last six reversals out of ten for each masker location. The masker level in CU was then converted to % of its respective DR. The above procedure was repeated, and the results were averaged across the runs. A linear slope was fit to the apical and basal sides of the tuning curve. The two slopes were averaged and quantified as % DR/electrode.

2.4. Speech recognition

The speech testing was performed in a double-wall sound-attenuated booth in which the sentences were played via loudspeaker positioned at a distance of 1 m from the participants' head at 0-degree azimuth. The participants' task was to repeat, to the best of their ability, the sentences that they heard. Ear plugs were used in the non-implanted ear of unilaterally implanted participants to eliminate speech audibility in the non-implanted ear. Bilateral participants wore the processor only on the ear being tested.

Participants' SRTs (speech reception thresholds) were measured to estimate the amount of noise that they could tolerate relative to the signal (signal to noise ratio, SNR) to perceive speech with 50% accuracy. The City University of New York (CUNY) sentences were presented at a fixed level of 65 dBA in the background of an amplitude modulated (4 Hz) noise. The level of the noise started at 45 dB to maintain an initial SNR (signal-to-noise ratio) of 20 dB and was adapted based on participants' responses in 2 dB step sizes using a 1-down 1-up protocol. The process continued until 12 reversals were observed, and then SNRs for the last six reversals were averaged. The procedure was repeated and the final SRT was averaged across the two runs. If the two thresholds were not in agreement (within 2 dB of each other), a third run was obtained.

Two participants were measured with extremely high SRTs, i.e., >25 dB (S19L, S27R), which raises the question of whether their thresholds can be ranked with the rest of the group. Thus, a second speech test was implemented, where perception of the AzBio sentences presented at a fixed SNR of 15 dB was measured. The participants performing poorly on the SRT test were expected to achieve scores below 50%. The AzBio sentences were presented to the participants at 65 dBA in a background of 10-talker babble. The percentage of words identified correctly per list of 20 sentences was calculated and the scores from two such lists were averaged.

2.5. Computerized tomography

Post-operative CT scans were performed using a Siemens CT scanner at the Heart Institute of East Carolina University. Whenever pre-operative CT images were available, they were used with the post-operative CT to construct a composite image. The pre-operative CT image voxel space was optimized for anatomical details of the ear, while the post-operative image was optimized for resolution of the electrode. The electrode lead wires and contacts were identified and segmented from the post-operative images and aligned onto the pre-operative voxel space (ANALYZE software, Mayo Clinic, Rochester, MN, USA, Robb 2001). This composite image allows for maximum resolution of the electrodes as well as visibility of the anatomy. When pre-operative images of the implanted ear were not available, CT images from the contralateral non-implanted ear were used based on the assumption that anatomy of the two ears from the same person would be similar.

Second, the composite image was aligned with one of ten high resolution cochlear atlases to infer the location of the fine and soft tissue structures within the cochlea that were not resolved by the CT. The visualization of the soft tissue structures (for example, the basilar membrane) makes it possible to define the scala positions of the electrodes. One of the atlases is based on an orthogonal-plane, fluorescence optical sectioning (OPFOS) microscopy scan [29] and the others are μCT scans of cadaveric donors with normal cochlear anatomy. These μCT scans illustrate details of both the soft tissue and bony structure of the cochlea. For participants with bilateral CIs and no pre-operative CT available (S1, S25, S27 and S37), the cochlear wall in the composite image is that of the aligned high resolution cochlear atlas.

A few characteristics of the electrode positions were analyzed based on the composite image, including the radial distance of the electrode from the medial wall (MW) of the cochlea, distance of the electrode from the middle axis of the modiolus (MMA, middle modiolar axis; a location more medial than the MW), electrode insertion angle, and the scalar location of the electrodes. The scala locations were categorized into scala tympani (ST), scala vestibuli (SV), and the medial region (M). The location was categorized as M when the electrode fell into an ambiguous region when the resolution of the CT was unable to determine whether the electrode was in ST or SV. Location of M does not necessarily indicate that the electrode was in scala media. For S36L, the three most apical electrodes were folded over; it is unclear how this might have affected the conduction of current and neural excitation, but they certainly represented an anomaly and thus the three electrodes were excluded from further analysis.

2.6. Statistical procedures

First, linear correlations were performed between the slopes of the tuning curves and the distance measures. These data were from 2 to 4 electrodes measured in 7 ears, thus the across-participant variation in these data were first removed. This was achieved by normalizing both measures to the ear's mean. For each ear, MDTs were also correlated with the two distance measures. Lastly, The MDT-distance correlation coefficients were used to correlate with the participants' speech recognition performance. For all the above tests, Pearson's correlations were used. To control for family-wise type 1 error, Bonferroni corrections were performed by dividing the P value (0.05), by the number of tests. All statistical analysis were performed using the SPSS software (IBM SPSS 26).

3. Results

Fig. 1 shows the composite CT volume rendering of the participants' lateral cochlear wall and electrode array viewed along the MM axis. The last panel shows the location of the 0° insertion angle line and the MM point. Fig. 2 shows the variation in the MW and MMA distance measures across the electrode array with respect to insertion angles. The two distance measures were not independent measurements, which prevented further statistical analysis. Nonetheless, visual inspection of the two distances revealed that the two curves were not parallel to each other. The difference between the MW and MMA distance was the greatest at the basal end and gradually decreased towards the apex, as the volume of the scala reduces and the distance between the medial wall of the cochlea and the mid axis of the modiolus also reduces. Although the two distances were not perfectly correlated with each other, the general patterns were similar. For most ears, the curves follow a far-close-far-close pattern. Participants implanted with the straight arrays (see Table 2) had the greatest distance measurements.

In Fig. 2, specific electrode locations are denoted by their respective symbols based on their scalar location within the cochlea. For each ear, the mean and variance of each distance measure, a count of electrodes in each of the scala tympani (ST), the scala vestibule (SV), and the M region, as well as the insertion angle of the most apical electrode are described in Table 2. For two ears (S25R and S27R), all electrodes were in ST. For S19L and S25L, all electrodes were in SV. The remaining ears had electrodes in all three regions of the cochlea. As mentioned in the Methods section above, for S36L, the tips of the three most apical electrodes which were translocated to SV were also folded over. Across participants, the proportion of electrodes in the three spaces are: ST: 51.4%, SV: 25.5%, and M region: 23.1%. S4L and S37R had the deepest (635°) and shallowest (248°) insertion depths, respectively, among all ears.

Fig. 3 shows the relationship between the normalized slopes of tuning curves and the normalized distance measures. Analysis showed that there was a moderate but significant negative correlation between the normalized slopes of the tuning curves and normalized MW distance (Pearson's R, $r = -0.49$, one tailed $p = 0.027$). Correlation with the MMA distance was not significant (Pearson's R, $r = -0.38$, one tailed $p = 0.073$), but a similar trend can be observed. Using an adjusted criterion significance level of 0.025 (Bonferroni correction) to control for family type I error, correlation between the tuning slopes and the MW distance became nonsignificant. The MW distance explained 24% of the total variance in the slopes of the tuning curves.

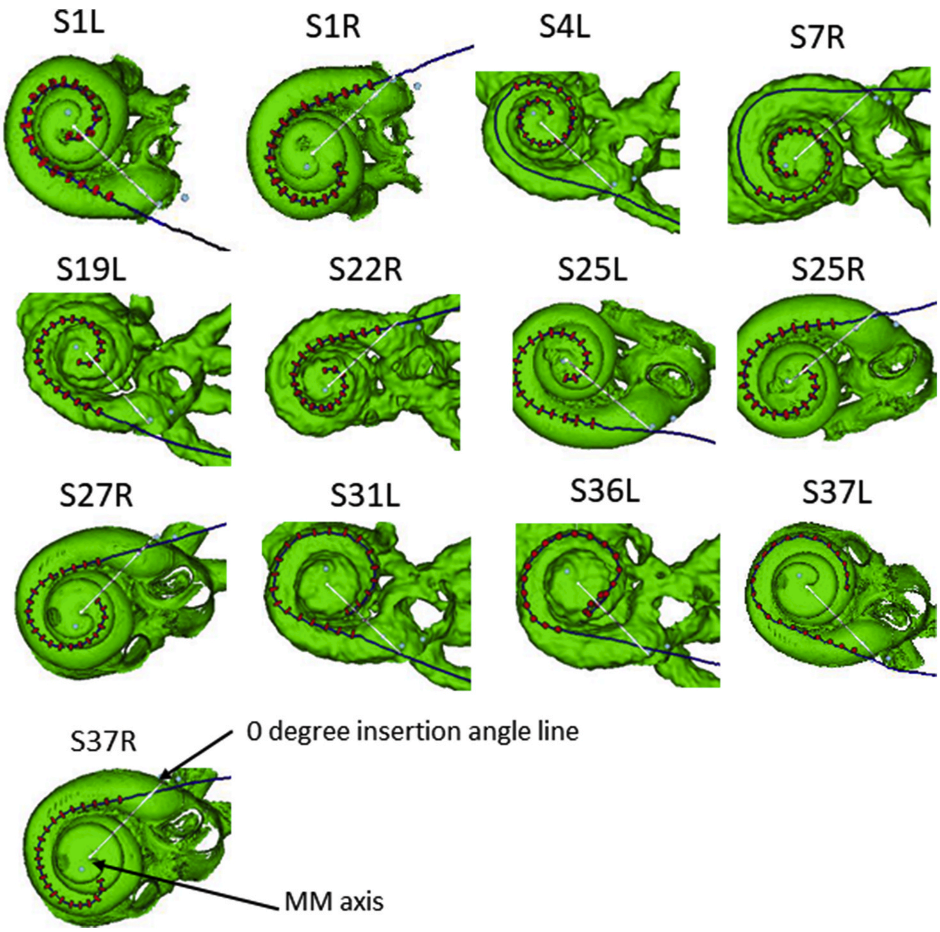

Fig. 1. Composite CT volumes including electrode array for individual ears. For S37R, 0° insertion angle line and MMA are shown.

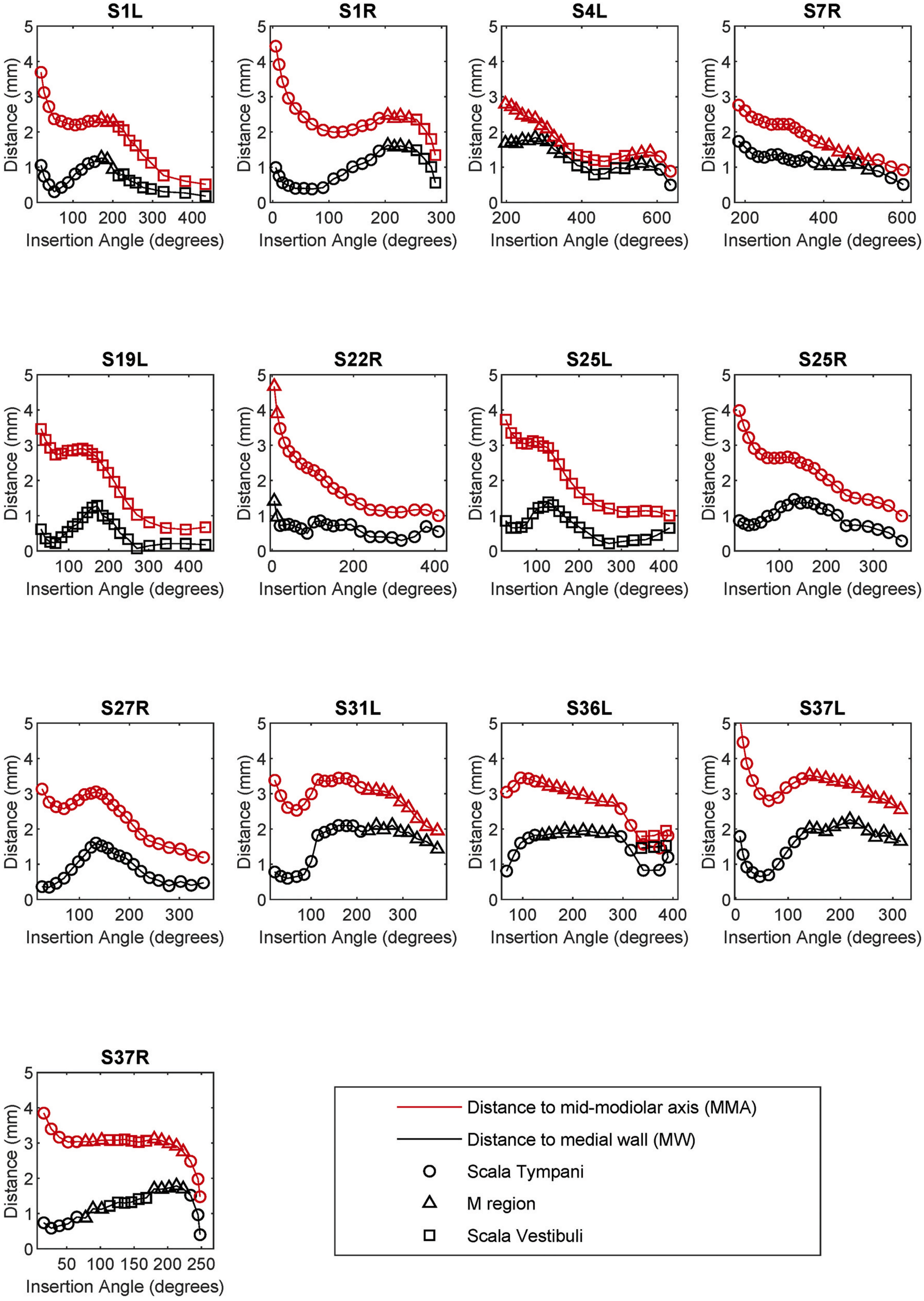

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Fig. 2. Insertion angle, distance from the medial wall (MW), and mid-modiolar axis (MMA) of each electrode for individual ears. Panel labels are displayed as titles above each panel. Electrode locations in terms of scala tympani (ST), scala vestibuli (SV), or M region are represented by different symbols. Black and red represent MW and MMA patterns, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Mean and variance of the Medial wall (MW) and mid-modiolar axis (MMA) distance measure for each ear; the correlation between MDT and distance measures. Asterisk denotes folded-over electrodes (for S36L).

Participant ID	Distance to Medial Wall (MW) (mm)		Distance to Mid-modiolar axis (MMA) (mm)		Number of electrodes in			Maximum insertion angles (degrees)	Correlations between MDTs and MW measure	Correlations between MDTs and MMA measure
	Mean	Variance	Mean	Variance	ST	M	SV			
S1L	0.7	0.11	2.01	0.6	10	3	9	433	r = 0.069, p = 0.77	r = 0.56, p = 0.011
S1R	0.97	0.2	2.43	0.48	14	4	4	289	r = 0.75, p < 0.001	r = 0.082, p = 0.72
S4L	1.29	0.16	1.76	0.35	2	13	7	635	r = 0.55, p = 0.0077	r = 0.74, p < 0.001
S7R	1.16	0.07	1.85	0.28	16	6	0	602	r = 0.11, p = 0.62	r = 0.072, p = 0.75
S19L	0.58	0.14	2.19	0.86	0	0	22	442	r = −0.31, p = 0.2	r = −0.74, p = 0.00029
S22R	0.67	0.06	2.09	1.04	20	2	0	409	r = 0.15, p = 0.5	r = 0.48, p = 0.028
S25L	0.75	0.13	2.2	0.86	0	0	22	413	r = 0.26, p = 0.29	r = 0.17, p = 0.5
S25R	0.95	0.1	2.32	0.58	22	0	0	360	r = 0.52, p = 0.016	r = −0.065, p = 0.78
S27R	0.88	0.19	2.34	0.42	22	0	0	348	r = −0.54, p = 0.012	r = −0.51, p = 0.018
S31L	1.6	0.32	2.94	0.2	13	9	0	375	r = −0.74, p < 0.001	r = −0.088, p = 0.7
S36L	1.58	0.15	2.67	0.44	10	9	3*	390	r = −0.71, p = 0.00062	r = −0.25, p = 0.31
S37L	1.61	0.26	3.32	0.34	10	12	0	315	r = −0.58, p = 0.0071	r = −0.26, p = 0.26
S37R	1.19	0.17	1.95	0.22	8	8	6	248	r = −0.7, p = 0.00089	r = −0.074, p = 0.76

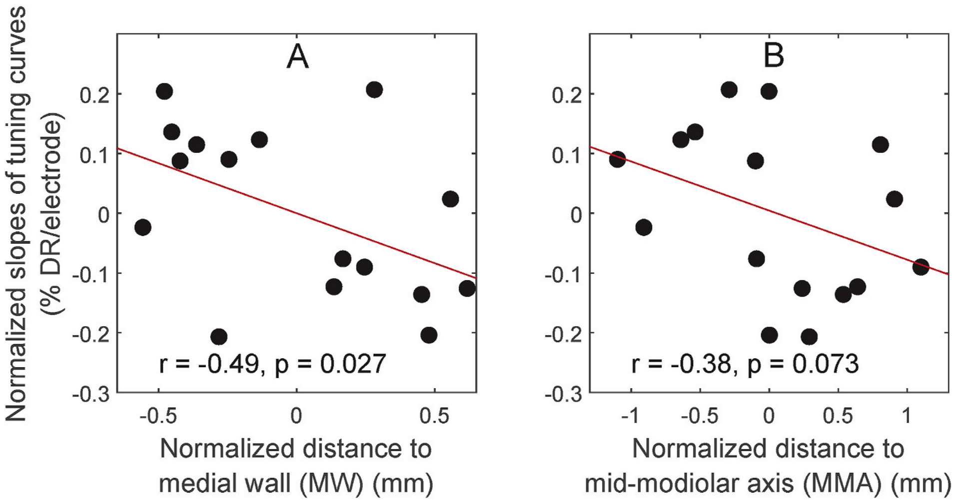

Fig. 3. Relationship between normalized slopes of tuning curves and normalized distance to the medial wall (MW, panel A); mid-modiolar axis (MMA, panel B). The correlation coefficients and corresponding p-values are included at the bottom of each panel.

To investigate if close electrodes were always beneficial for modulation sensitivity, a correlation analysis between modulation detection thresholds (MDTs) and each distance measure was conducted for each ear. The correlation coefficients and the corresponding p values are given in Table 2. The scatter plots are shown in Fig. 4. A regression line was fit if the correlation was significant (two tailed, $p < 0.05$). The direction of the correlation between MDTs and distance was ear specific. MDTs showed statistically significant positive correlations with MW distance for S1R and S25R, MMA distance for S1L and S22R, and both distance measures for S4L. These ears showing a positive correlation between MDT and the distance measure demonstrate that they benefit from close electrodes for the modulation sensitivity. There was a significant negative correlation between MDT and the MW distance measure for S31L, S36L, S37L, and S37R, a significant negative correlation between MDT and MMA measures for S19L, and negative correlations with both distances for S27R. The ears with the negative MDT-distance correlations represent an opposite scenario of close electrodes being detrimental for modulation sensitivity. For S7R and S25L, neither the MW nor MMA measure was related to the MDT. The above analysis held true after applying Bonferroni corrections for all of the cases except for S22R: the positive correlation between MDT and MMA measure became marginally significant (p-value slightly greater than 0.025). In summary, there were five ears showing positive correlation with at least one distance, six ears showing negative correlation with at least one distance, and two ears showing no

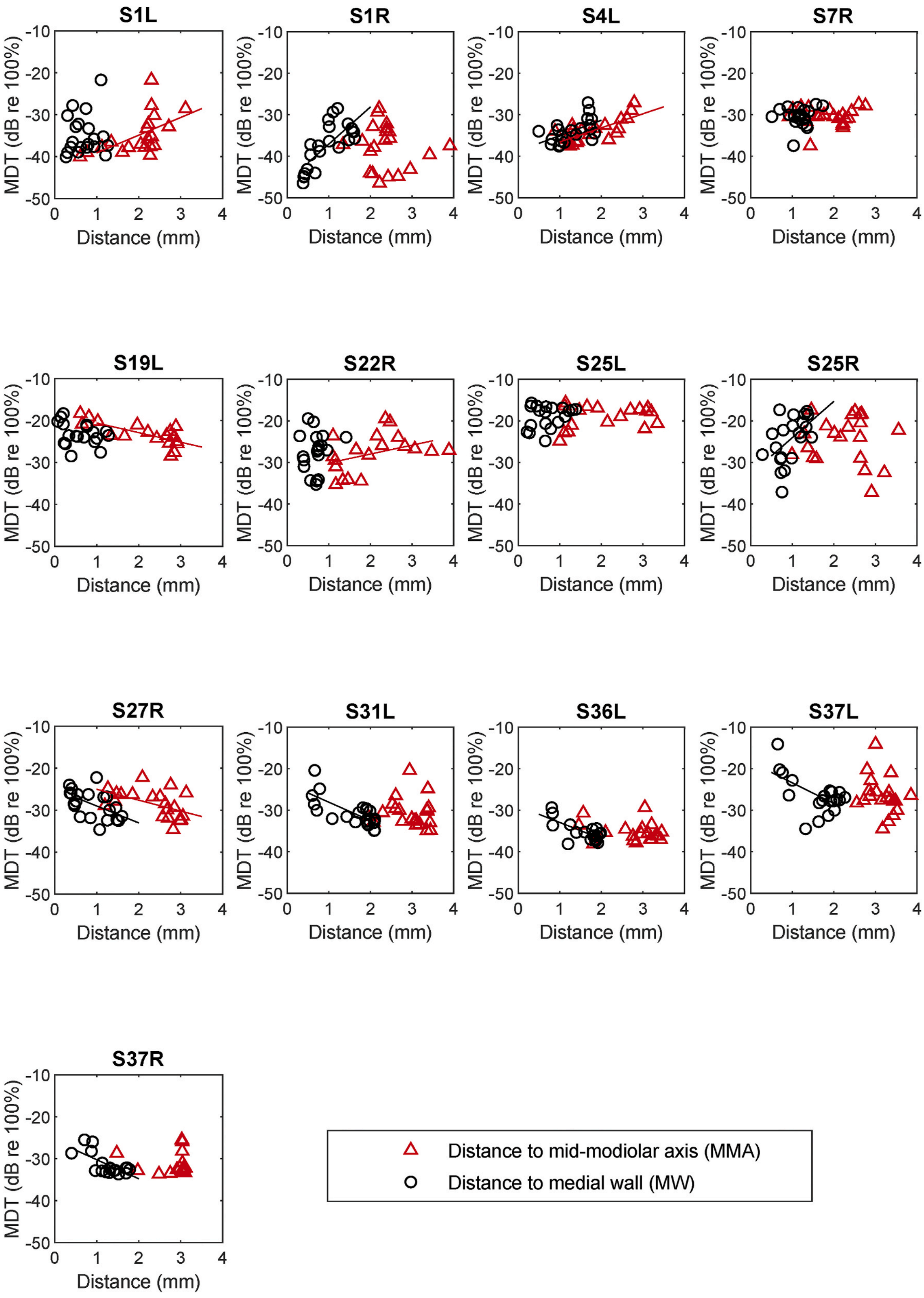

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Fig. 4. Scatter plots of modulation detection thresholds (MDTs) as a function of the distance of electrodes from the medial wall (MW, black circles) and mid-modiolar axis (MMA, red triangles). Panel labels are displayed as titles above each panel. The regression lines indicate the linear trends between MDTs and corresponding distance measures in case of a significant correlation (two tailed, $p < 0.05$). Correlation coefficients and p-values for each panel (ear) can be found in Table 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

relationship with either distance. The number of electrodes translocated to SV did not seem to impact the direction of the correlations. Among the two ears that had all 22 electrodes in SV, S19L showed a negative correlation with MDTs, whereas S25L showed a positive correlation. Participants implanted with the straight arrays (S31L, S36L, and S37L) all showed a negative correlation between MDT and the distance measures.

Next, we investigated whether the direction of the MDT-distance correlations could be explained by participants' speech recognition performance. The correlation coefficients between MDTs and the distance measures reported above were correlated with both SRT and AzBio test scores, and the relationships can be seen in Fig. 5. Correlation coefficients relating MDTs to MW distance showed a significant negative correlation with SRTs (Pearson's R, $r = -0.55$, one tailed $p = 0.027$) and a significant positive correlation with the AzBio scores (Pearson's R, $r = 0.64$, one tailed $p = 0.0092$). Similar significant trends can be observed for the MDT-MMA correlation coefficients and the two speech measures (Pearson's R; with SRT: $r = -0.81$, one tailed $p = 0.0004$; with AzBio: $r = 0.51$, $p = 0.039$). The above correlation analysis suggested that close electrodes were more likely to be beneficial for modulation sensitivity in ears measured with good speech recognition outcomes. On the other hand, for the participants who performed poorly on the speech tests, close electrodes were detrimental for modulation sensitivity. The correlation between MDT-MW coefficients and SRT ($p = 0.027$) and the correlation between MDT-MMA coefficients and AzBio ($p = 0.039$) were no longer significant after Bonferroni correction (0.05/2 tests = 0.025).

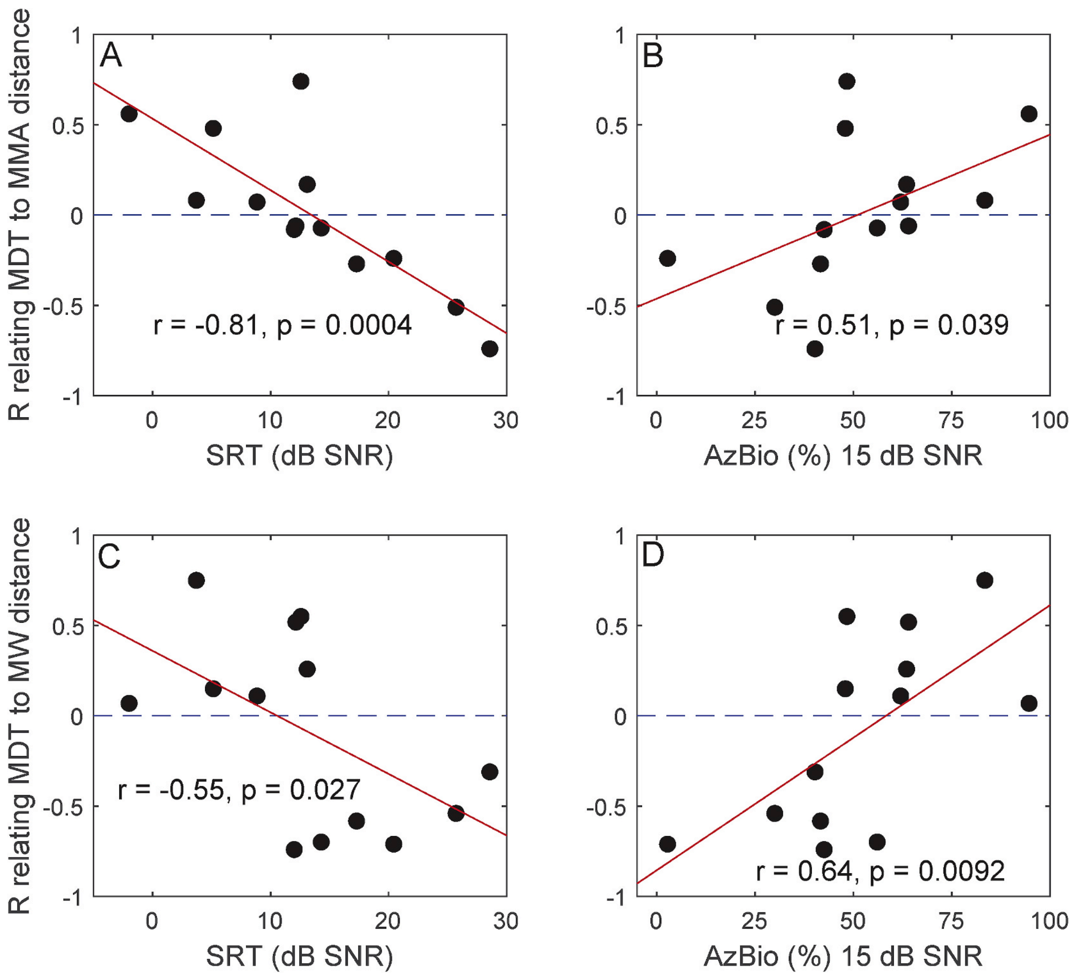

Fig. 5. Correlation coefficients relating MDTs to the MMA distance measure as a function of SRTs (Panel A) and AzBio (Panel B). Correlation coefficients relating MDTs to the MW distance measure are shown as a function of SRTs (Panel C) and AzBio (Panel D). For each relationship, the corresponding correlation coefficients and p-values are included.

4. Discussion

In the present study, we examined the relationship between temporal modulation sensitivity and electrode position and related these correlations to the participants' speech recognition performance. The major finding of this study was that close electrodes did not always predict good modulation sensitivity. Among the thirteen ears that were tested, close electrodes were beneficial for five ears, detrimental for six ears, and showed no effect for the remaining two ears. Further, the ears that benefited from proximal placement of electrodes in terms of modulation sensitivity also performed better on speech tests.

4.1. Electrode position patterns

In human CI recipients, electrode positions vary greatly within and across participants. The variations entail translocation of the electrodes from ST, insertion depth of the electrode array in the cochlea, and the distance of the electrode to the target neurons in the modiolus [22,30–32]; Finley et al., 2008; [33]. Placing electrodes closer to the neural elements is thought to be advantageous, as it is expected to produce neural excitation patterns that mimic the tonotopic organization of a normal-hearing cochlea. In the present study, two electrode-modiolus distances were measured: (1) distance from a given electrode to the medial wall of the cochlea, i.e., MW distance and (2) distance from the electrode to the central axis of the modiolus, i.e., MMA distance. It is difficult to determine which distance more closely describes the site of action potentials initiation due to the differences in the location of the spiral ganglion cells in the modiolus, presence of peripheral processes, and whether action potentials were generated at the peripheral processes. More detailed discussion is provided below. Due to this uncertainty, both distances were included in the analyses.

The general trends in the patterns of two distance measures against insertion angles are consistent with the previous studies on Cochlear Nucleus participants (e.g., Fig. 3 of [26] and Fig. 2 of [24]. The MMA distance was always greater than the MW distance, but this difference reduced with insertion angle, as the diameter of the cochlear spiral reduces, so does the distance between mid-modiolar axis and lateral wall of the cochlea. Since an electrode array is a single continuous structure that is inserted into a cochlear spiral, a pattern of distance measures against insertion angles is expected to trace a relatively smooth function [24]. A trend that was commonly observed here and in Ref. [24] was a far-close-far-close pattern, where the distances were the greatest at the base and the middle of the array around electrode 10, and smaller in the remaining two areas. For participants with deeper insertion depth (S4L, S7R), the difference between the two distance measures was smaller than for participants with shallower insertion depth, as expected. Translocation of electrodes from the ST regions occurred 50% of the time (see Table 2), which is in line with previously reported statistics on electrode position for similar electrode types (e.g., Ref. [34].

4.2. Relationship between spatial tuning and electrode position

Previous work from our laboratory showed that temporal modulation sensitivity depended on sharpness of forward-masked spatial tuning curves. The first aim of the present study was to examine how much variation in the sharpness of tuning was accounted for by electrode position. To measure a spatial tuning curve using forward masking, the levels of forward maskers (varying in location) that were required to just mask a low-level probe signal were measured. If the masker and probe excite overlapping neural populations, then the forward masker will drive the excited neurons into a refractory period, reducing the probability of these neurons responding to the subsequent probe signal. Thus, masker level required for masking to occur is expected to increase as the spatial separation between the masker and probe increases, and the shape or steepness of the spatial tuning curves reveals the width of excitation produced by the low-level probe signal. Previous studies showed that spatial tuning varies across the tonotopic axis, suggesting that it is dependent on the local irregularities at each electrode (e.g., Ref. [35]. Spatial tuning curves were measured at selected electrodes in the present study. After removing the across-participant variability in the electrode position and tuning variables, our data showed that electrode position explained a marginally significant amount of variance, i.e., 24%, in the steepness of the tuning curves across electrodes. This means that a majority of the variance in tuning was not explained by electrode position, and the finding is consistent with a recent study by Ref. [21], where they reported that electrode position only predicted spatial tuning curves in half of the ears tested.

One factor that could contribute to the weak correlation is that the inherently difficult procedure has introduced some noise in the tuning measure. In a forward masking paradigm, the probe signal is typically separated from the masker with a short time delay. The short time delay can make it difficult for participants to distinguish the probe from the forward masker if their temporal resolution is poor [36]. This potential dubiety is further increased when masker and probe are presented at the same electrode and are perceived to have the same pitch. These factors can cause a potential confusion between masker and probe, leading to underestimated masker level at the probe site, which in turn leads to overestimated tuning.

The more likely factor contributing to the weak correspondence between electrode position and spatial tuning curves is the local neural condition. If the probe electrode is placed close to the modiolus, but is in a region with poor neural survival, detection of the probe signal would require a higher current level to recruit neurons more distant to the stimulation site. Thus, the width of excitation by the probe would be broader than what is expected from the electrode's distance from the modiolus. Human histological studies have reported that pathology in deafened ears varies along the tonotopic axis and that the pattern of variation is unique for each cochlea [9–11]. Neural health entails the quantity and responsiveness of the surviving neurons. Responsiveness of the surviving neurons can reduce if there is neuron shrinkage, demyelination, reduced response rate, greater fatigue, and reduced dynamic range [37,38]. In summary, if good modulation sensitivity depends on narrow neural excitation, then it should depend on a perimodiolar electrode placement stimulating a healthy cochlea.

4.3. Correlations between electrode position and MDTs

Based on the reasoning given above, that is, good modulation sensitivity depends on close electrodes stimulating a healthy cochlea, one would expect the relationship between MDT and electrode position to be ear specific. For ears that have generally good neural health, close electrodes should produce a spatially refined excitation pattern that facilitates modulation detection, whereas for ears with generally poor neural health, close electrodes may not be beneficial. Our data support this hypothesis. In the current participant sample, close electrodes were beneficial for five ears, demonstrating a positive correlation between the distance measures and MDT. Close electrodes were detrimental for six ears, and for the remaining two ears, electrode position had no effect. In order to explain the data based on individual participants' neural status, we measured speech recognition based on the assumption that participants with good neural status would do better on the speech tests. Earlier human histological studies failed to find a relationship between the spiral ganglion cells and speech recognition measured when the CI users were alive (e.g., Refs. [39–41]. However, several confounding factors, such as cause of death and the varying time gap between death and when speech measures were made, can mask the relationship. A more recent study by Ref. [42], which removed these confounding factors by comparing outcomes between the two ears of bilaterally implanted participants, found a significant correlation between spiral ganglion cells and CNC word recognition scores.

Thus, if we were to use speech recognition to infer neural status in the tested ears, our data would support the idea that whether close electrodes provide benefit for modulation detection hinges on the nerve condition of the ear. Note we used a speech-in-noise measure, while the study used CNC words [42]. However, speech-in-noise tests are typically more sensitive measures than speech-in-quiet tests. The negative correlation between the distance measures and MDT was puzzling. It is possible that in these ears with general poor neural health, the close electrodes produced excitation patterns even broader than the distant electrodes, thus poorer MDTs were associated with smaller distances, but it is unlikely. A more plausible explanation is that, via elevated current level, the close electrodes may have recruited sufficient neurons from neighboring regions to achieve the required loudness (50% DR), but they may still not be sufficient to code modulation. As a result, in these ears distant stimulation was proven more advantageous. The two ears exhibiting no effect of distance on modulation sensitivity might perfectly represent a scenario of intermittent patterns of neural survival and patchy regions reported in histological studies [43,44]. For mixed nerve conditions, close electrodes can be beneficial in regions with good neural survival and detrimental near dead regions. The fixed effect of electrode position on MDT is consistent with previous reports that showed that while switching from monopolar to bipolar configuration, the effect on modulation sensitivity can be in either direction [18,45]. Of course, alternatively, it may be that the differential effects of electrode position bear no relationship to the neural status of the ear, and participants who were able to detect modulation better with closer electrodes tended to have better speech recognition. The mechanisms, if unrelated to neural health, are unclear. Nonetheless our data showed that they are also unrelated to whether the electrodes have translocated to SV. The mechanisms also seemed to be unrelated to the electrode type. One might expect distant electrodes to produce poorer MDTs in participants implanted with the straight array, since for these participants the overall distance of the array from the modiolus was already large. However, for all three participants with the straight arrays, increase in electrode distance further helped with modulation detection.

One interesting observation was that for most ears, only one distance measure showed a significant relationship with modulation sensitivity. This can be attributed to the fact that the two distance measures do not perfectly correlate with each other, as explained above. More importantly, the distance measure (MW or MMA) that best characterizes the stimulation path may be different across ears. The exact location of spiral ganglion cells, as well as whether the action potential is generated at locations more central to the peripheral processes, varies across ears. Further, translocation to SV may not necessarily increase the distance of electrodes from the MW of the cochlea, but it might increase the impedance of the current path, as the medial wall of SV is denser than that of ST. In apical regions, the geometry of SV is such that the MW of the cochlea may not accurately estimate the location of excitation that occurs in the modiolus. Thus, depending on the anatomy of the ear, the physiological conditions of the nerve, and the canal the electrode resides in, one distance measure may characterize the location of excitation better than the other.

4.4. Implications for array type selection

The present study provides additional evidence that in human participants with CIs, electrode position plays an important role for CI function. The unique finding from the present study is that for modulation sensitivity, the effect of electrode position was ear dependent. When data were collapsed across participants, distant electrodes were associated with higher ECAP thresholds and steeper growth of the ECAP functions, but unrelated to other measures that were correlated with the count of spiral ganglion cells in animal models [26]. However, if the relationship was also ear dependent, as reported here, the information would have been lost by adopting a single linear model for data collapsed across participants.

Regardless of the mechanisms underlying the ear-dependent relationship between electrode position and modulation sensitivity, our data suggested that perimodiolar electrode arrays might not be universally advantageous for all CI users, at least for improving temporal modulation sensitivity. If neural survival is the factor driving the ear-dependent relationship, then it would be important to establish reliable measures to evaluate neural status in implant candidates. For ears that were implanted with a perimodiolar array but showed detrimental effects of close electrodes, implants that are not contour shaped might have been more suitable and perhaps would have led to better speech recognition outcomes.

4.5. Limitations and future directions

The variables that were being correlated in the study, e.g., MDTs, distances, were measured in the same ear, which might violate the assumption of independence. However, the distances were physical measurements of the ear while MDT was a behavioral measure, thus they should be considered independent of each other. Previous studies have used both measures to implement site-selection strategies where the stimulation sites that show better performance on the measure were used and the poorly-performing sites were removed. The electrode-modiolus distance was used to predict the spatial neural excitation patterns and close distance was expected to provide better spectral resolution. MDTs were used to predict how well the temporal modulations were coded by the ear. Both strategies have led to improved speech recognition results, but these were reported in different studies using different participant samples (e.g., Ref. [6]. For our subjects who showed negative correlations between these two variables, it would be interesting to remove electrodes with either far distance or poor MDTs to determine which measure is more important for speech recognition.

5. Conclusions

In conclusion, we found that electrode position moderately correlated with the sharpness of tuning curves. Electrode position also correlated with MDTs, but the direction of the correlations was ear specific. Closer electrodes improved MDTs only for subjects with good speech recognition performance. Closer electrodes produced poorer MDTs in subjects with poorer speech recognition performance. We attribute the pattern of the data to individual differences in neural survival.

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