

# Comparing Rapid and Traditional Forward-Masked Spatial Tuning Curves in Cochlear-Implant Users

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## Abstract

A rapid forward-masked spatial tuning curve measurement procedure, based on Bekesy tracking, was adapted and evaluated for use with cochlear implants. Twelve postlingually-deafened adult cochlear-implant users participated. Spatial tuning curves using the new procedure and using a traditional forced-choice adaptive procedure resulted in similar estimates of parameters. The Bekesy-tracking method was almost 3 times faster than the forced-choice procedure, but its test–retest reliability was significantly poorer. Although too time-consuming for general clinical use, the new method may have some benefits in individual cases, where identifying electrodes with poor spatial selectivity as candidates for deactivation is deemed necessary.

## Keywords

cochlear implant, spatial tuning, Bekesy tracking, frequency selectivity

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## Introduction

Spatial tuning curves (STCs), also referred to as psychophysical tuning curves (PTCs), have been used in the past to quantify frequency selectivity, or channel interactions, in cochlear-implant (CI) listeners (Bierer & Faulkner, 2010; DeVries & Arenberg, 2018; Nelson, Donaldson, & Kreft, 2008; Nelson, Kreft, Anderson, & Donaldson, 2011; Zhou & Dong, 2017). The procedure to collect this measure is modeled after its acoustic counterpart that uses a forward-masking paradigm to obtain psychophysical frequency tuning curves in normal-hearing or hearing-impaired listeners (Houtgast, 1973; Moore & Alcántara, 2001; Moore, 1978; Nelson, 1991). The premise of this approach is that the fixed low-level, short-duration probe excites spiral ganglion neurons tuned to a narrow region of characteristic frequencies and that any masker that just masks the probe produces the same amount of excitation at the probe location. In this way, PTCs are similar in concept to the neural tuning curves, derived by tones that all produce the same neural response in a given auditory nerve fiber (e.g., Kiang, Sachs, & Peake, 1967). Forward-masked STCs have been used to quantify frequency selectivity (Charaziak, Souza, & Siegel, 2012; Gong, Wang, &

Xian, 2014; Moore, 1978; Zwicker & Schorn, 1978) and to identify irregularities in tonotopy (such as *dead regions*; see Moore & Alcántara, 2001; Moore, Glasberg, & Schlueter, 2000; Moore, Glasberg, & Schlueter, 2009; Summers et al., 2003). Good frequency selectivity is thought to be related to good speech perception in CI users (Drennan, Anderson, Won, & Rubinstein, 2014; Gifford et al., 2018; Henry, Turner, & Behrens, 2005; Saoji, Litvak, Spahr, & Eddins, 2009; Won, Drennan, & Rubinstein, 2007), although STC measures from individual electrodes have not always produced correlations with speech perception (Anderson, Nelson, Kreft, Nelson, & Oxenham, 2011; DeVries & Arenberg, 2018;

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DeVries, Scheperle, & Bierer, 2016). Nevertheless, poor frequency selectivity at a specific site may indicate poor neural survival near that site and/or a large spatial distance between the electrode and the responding neurons. In support of this interpretation, some studies have demonstrated significant improvements in CI users' speech recognition following deactivation of certain electrodes, based on measures of spectral and/or temporal processing, as well as CT imaging (Garadat, Zwolan, & Pfungst, 2012, 2013; Noble, Gifford, Hedley-Williams, Dawant, & Labadie, 2014; Saleh, Saeed, Meerton, Moore, & Vickers, 2013; Zhou, 2016; Zhou & Pfungst, 2012).

Although it may be clinically useful to characterize frequency selectivity at each electrode site, the traditional method of obtaining STCs in CI users is quite labor intensive and time consuming. The ability to rapidly measure STCs may make it more feasible to examine channel interactions across the electrode array in individual CI users in a clinical setting, which may in turn lead to customization of speech processing maps, based on deactivating electrodes with poor or abnormal tuning characteristics.

Sek, Alcántara, Moore, Kluk, and Wicher (2005) and Sek and Moore (2011) reported on the use of a fast procedure to collect psychophysical tuning curves in both normal-hearing and hearing-impaired listeners. Their procedure was based on Bekesy tracking, which was accomplished by having the listener detect a pure tone that was pulsed on and off in the presence of a continuous narrowband noise masker whose center frequency slowly increased or decreased. They found that the morphology of the tuning curves was similar between the fast sweep procedure and the traditional forced-choice adaptive procedure, and that the sweep procedure took about 4 min to complete, which, if reliable, may be sufficiently fast to implement in a clinical setting. Although a similar procedure has not yet been tested in CI users for STCs, Bierer, Bierer, Kreft, and Oxenham (2015) implemented a Bekesy-like sweep procedure, using current steering between adjacent electrodes, in CI users for measuring absolute thresholds and compared the results with those gathered from a more traditional forced-choice adaptive threshold procedure measured on discrete electrodes. The authors concluded that behavioral thresholds obtained from the two procedures were similar, but that the sweep method was nearly 4 times faster. This study investigated the use of a similar sweep method to measure STCs to establish whether it is possible to provide a rapid and clinically feasible measure of spectral resolution in CI listeners at the level of individual electrodes. Forward-masked STCs obtained with this new method were compared with those obtained using a traditional forced-choice adaptive procedure. The test–retest reliability of the

two procedures was assessed, along with the respective test times.

## Methods

### Subjects

Twelve postlingually deafened adults participated. All were implanted with an Advanced Bionics (Valencia, CA) CI (see Table 1). Six of the subjects were tested at the University of Washington in Seattle (subject identifiers with an “S”), while the remaining six subjects were tested at the University of Minnesota in Minneapolis (subject identifiers with a “D”). The University of Washington Human Subjects Division (IRB #3332) and the University of Minnesota Institutional Review Board (Protocol 8804M00507) approved all procedures, and all subjects provided written informed consent prior to participating.

### Stimuli

For the probe, monopolar (MP) stimulation mode was used throughout. In MP mode, the active current is sent to one electrode within the cochlea and the return current is routed to an extracochlear electrode on the case of the internal cochlear stimulator (ICS). The probe electrodes used in the experiment spanned apical, middle, and basal regions of the electrode array; specific probe electrodes for each subject are shown in Table 1. For the masker, steered quadrupolar (sQP) stimulation mode was used. In sQP mode, the active current is steered between two adjacent electrodes, with the proportion sent to each electrode determined by the steering coefficient ( $\alpha$ , ranging from 0 to 1), and a fraction of the return current is split between the two electrodes flanking the two active electrodes, with the remainder of the return going to the extracochlear electrode on the ICS. The focusing coefficient ( $\sigma$ ) defines the fraction of current returning via the flanking electrodes; the closer  $\sigma$  is to 1, the more focused the electrical field will be. For MP,  $\sigma$  was set to 0 (all return current sent to extra-cochlear electrode) and for sQP,  $\sigma$  was set to 0.5. The masker was swept between electrodes 2 and 15 for each STC, regardless of the probe electrode.

Biphasic, charge-balanced, cathodic-phase-first pulse trains were used. Phase durations were 97  $\mu$ s/phase and the pulse rate was 997.9 pulses per second for both the masker and probe. Each masker pulse train was 200.4 ms and each probe pulse train was 20 ms in duration. The masker-probe gap (offset to onset) was 20 ms in duration. All stimuli were presented and controlled using research hardware and software (“BEDCS”) provided by the Advanced Bionics Corporation (version 1.18). Programs were written within Matlab

**Table 1.** Subject Demographics.

Subject code	Gender	Age (years)	CI use (years)	Etiology	Duration HL prior to implant (years)	Electrode	ICS	Probe electrodes
D02	F	66.8	15.0	Unknown	1	HFII	C-II	4,8,14
D19	F	57.1	12.3	Unknown	11	HF	HR90K	4,10,14
D27	F	64.9	7.4	Otosclerosis	13	HFIJ	HR90K	4,8,10
D28	F	71.2	13.7	Familial progressive SNHL	7	HFP	C-II	4,8,12
D33	M	76.7	3.3	Noise exposure; trauma	< 1	HFIJ	HR90K	4,10
D39	M	69.3	7.7	Unknown	7	HFIJ	HR90K	4,6,8,10,12,14
S22	F	77.0	10.0	Familial progressive SNHL	22	HF Helix	HR90K	8
S29	M	86.0	9.0	Unknown	30	HFIJ	HR90K	4,8,12
S42	M	66.0	15.0	Unknown	16	HFIJ positioner	HR90K	4,8,12
S43	M	71.0	3.0	Unknown	22	HF Mid-Scala	HR90K	4,8,12
S46	M	68.0	4.0	Unknown	54	HFIJ	HR90K	4,8,12
S47	F	39.0	2.0	Unknown	28	HF Mid-Scala	HR90K	4,8,12

Note. "D" denotes University of Minnesota subjects and "S" denotes University of Washington subjects. CI = cochlear implant; ICS = internal cochlear stimulator; SNHL = sensorineural hearing loss; HL = hearing loss.

(The Mathworks, Natick, MA), which controlled the low-level BEDCS routines. Identical software and hardware were used at both testing sites.

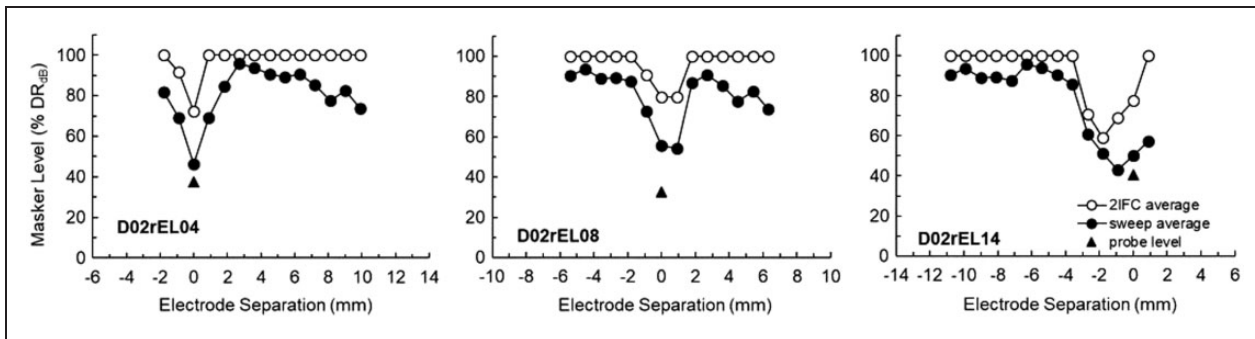
### Procedure

**Absolute thresholds and MCLs.** To obtain STCs, both absolute thresholds and most comfortable listening levels (MCLs) were first measured for each electrode tested, for both the masker and probe stimuli. For each subject, MCLs were measured using a method of adjustment. To determine MCL, the current was manually adjusted (initially in 2-dB steps and then in either 0.5- or 1.0-dB steps as the loudness increased) until the subject reported a loudness rating of "6/most comfortable" on the Advanced Bionics clinical loudness scale. All MCLs measured were below device compliance. Absolute thresholds were measured across the array of electrodes for the masker and probe stimuli using a single forward and backward sweep in a Bekesy-like tracking procedure, as described by Bierer et al. (2015; see also DeVries & Arenberg, 2018). Listeners were instructed to hold down the space bar while they heard the probe sound and release the space bar whenever the probe became inaudible. The pulse train starting level was below MCL, the current level changed in steps of 1 dB, and the  $\alpha$  value changed in steps of .1 between each pair of electrodes. The final threshold estimates for each electrode for each masker and probe were obtained by a weighted averaging of consecutive current levels along the forward and backward sweeps. The dynamic range in dB ( $DR_{dB}$ ) for each electrode was calculated by taking the MCL current level (in dB), relative to the absolute threshold current level, and defining that level

as 100%  $DR_{dB}$  with absolute threshold (also in dB) as 0%  $DR_{dB}$ . In the sweep procedure, the pulse trains were presented every 500 ms. Measurement of the absolute thresholds and MCLs for both the probe and masker stimuli provided all listeners with the opportunity to hear the stimuli repeatedly in isolation before they were presented together in the STC portion of the experiment.

**Spatial tuning curves.** For each subject, STCs were collected using both the traditional adaptive forced-choice procedure and the new sweep procedure. The masker threshold and MCLs for each electrode were used as the lower and upper limit of stimulation, respectively, in both STC procedures. Probe levels were presented at an average of 39%  $DR_{dB}$  (range: 24.4–54.8%  $DR_{dB}$ ) across all electrodes tested. The probe level was initially set to approximately 30%  $DR_{dB}$ ; however, this level was adjusted if the salience of the probe was poor, thus making it difficult to complete the sweep STC. Masker levels were also set in terms of  $DR_{dB}$  to facilitate comparison across electrodes (2–15) for both methods. Previous research by Nelson et al. (2008, 2011) found no effect of probe level on slopes or bandwidths over a similar range of probe and masker test levels.

The sweep procedure was very similar to that used to determine absolute thresholds (see previous section), but with the probe remaining at a fixed level and electrode location, and only the masker sweeping across the array and varying in level. As in the threshold measurements, the sweep was performed in both the forward (increasing frequency) and backward (decreasing frequency) directions, with one run being defined as the average of both [see Figure 1(a) in DeVries & Arenberg (2018) for a



**Figure 1.** STCs for subject D02. Each panel shows tuning curve obtained for the traditional adaptive procedure (open circles) and sweep procedure (filled circles) for probe electrodes 4, 8, and 12 (left to right). The filled triangles indicate the position and level of the probe.  $DR_{dB}$  = dynamic range in dB.

depiction of sweeps]. Again, the masker and probe combination was presented every 500 ms, with the masker level and location varying in the same way as in the measurements of absolute threshold. The final STC for each subject and probe electrode location was defined as the average of two such runs.

In the traditional adaptive procedure, STCs were measured using a two-interval two-alternative forced-choice (2AFC) task with a two-up, one-down adaptive procedure that tracks the 70.7% correct point of the psychometric function (Levitt, 1971). Each run began with the masker level at least 3 dB below MCL, and the level was initially increased or decreased by 1 dB depending on the listener's responses. After the first two reversals, the step size was decreased to 0.5 dB, where it remained for the final four reversals. The average stimulus level at the last four of the six total reversals was defined as threshold for that run. Two such thresholds were measured and averaged to define the masker threshold for each electrode (2–15).

**STC parameters.** The STCs were characterized using the following parameters: apical slope, basal slope, tip width, and tip shift. Both the apical and basal slopes were calculated in terms of  $\%DR_{dB}$  per mm by fitting only the steepest portions of the tuning curves using visual inspection. The slope fits typically included at least three points; however, in 22% (32 of the total 144 slopes fit), only two points were used in the fitting process (Nelson et al., 2008). These extremely steep slopes were limited by the subject reaching MCL on maskers very close to the probe electrode. The tip width was quantified using a  $BW_{10\%DR}$  measure. The  $BW_{10\%DR}$  calculates the width (in mm) at 10 percent of  $DR_{dB}$  above the tip of the tuning curve (Nelson et al., 2008), where the tip of the STC was specified at the midpoint of the bandwidth. The tip shift was calculated in terms of distance (in mm) of the STC tip from the probe electrode location. Different electrode arrays have differing distances

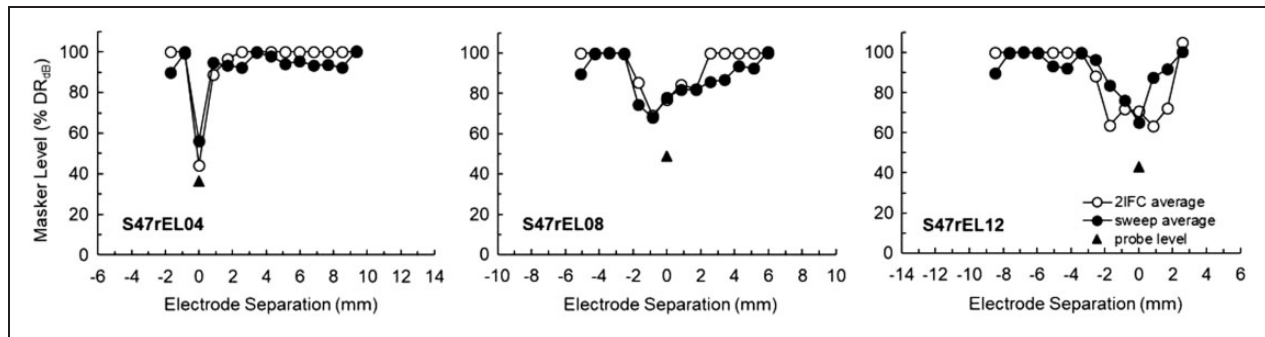
between electrode contacts, and this was taken into consideration when determining the amount of tip shift.

## Results

### Comparison of STC Measures

The STCs obtained with the traditional two-interval forced-choice (open circles) and the sweep procedures (filled circles) are shown for one sample subject (D02) across probe electrode locations in Figure 1. The filled triangle in each panel shows the location and level of the probe electrode. In this example, the pattern of the two STC procedures match quite closely for all three probe locations, with the masked thresholds for the forced-choice procedure being consistently higher than those for the sweep procedure. This pattern of masked thresholds with the forced-choice procedure thresholds being similar in pattern but higher than those with the sweep procedure was observed for most of the other subjects (24 out of 36 probe electrodes tested). Figure 2 shows the STCs for another sample subject (S47). This subject's STCs depict the kinds of patterns observed in the other third of the probe electrodes tested, where some differences were present between the two measures.

The parametric measures from each STC were calculated separately from the measures obtained in the first and second runs for each procedure. This allowed us to assess the test–retest reliability of each of the two measures (2IFC or sweep). The scatter plots in Figure 3 show the estimates of the apical and basal slopes, the tip width and the tip shift measures from runs 1 and 2 of the forced-choice procedure (left column) and the sweep procedure (right column). For each comparison, the Pearson's correlation coefficient,  $r$ , was significantly greater than zero ( $p < .002$  in all cases). In fact, none of the  $r$  values was less than .5, suggesting reasonably good test–retest reliability. However, the test–retest reliability of the 2IFC procedure was generally higher. For all four



**Figure 2.** STCs for subject S47. Each panel shows tuning curve obtained for the traditional adaptive procedure (open circles) and sweep procedure (filled circles) for probe electrodes 4, 8, and 12 (left to right). The filled triangles indicate the position and level of the probe.  $DR_{dB}$  = dynamic range in dB.

measures, using the Fisher  $r$ -to- $z$  transformation, the  $r$  values for the 2IFC procedure were significantly greater than the  $r$  values for the sweep procedure ( $p < .02$  in all cases).

To examine the similarity of the derived STC parameters between measurement methods, Figure 4 shows scatter plots for the apical slopes, basal slopes,  $BW_{10\%DR}$ , and tip shifts for all probe electrodes tested, estimated using the average of the two runs for each procedure. The Pearson's correlation coefficients, indicated on each graph panel, were significant in all cases, with coefficients ranging between .49 and .66, which is reasonable given the test-retest reliability for each measure. However, the fact that the solid trend line was generally shallower than the dotted unity line suggests that the sweep method tended to underestimate the range of STC parameter values relative to the 2IFC method. In the case of the apical slopes, where the trend was greatest, it was driven primarily by three points, all from the same subject (S46), whose estimated slopes were much shallower for the sweep method than for the 2IFC method.

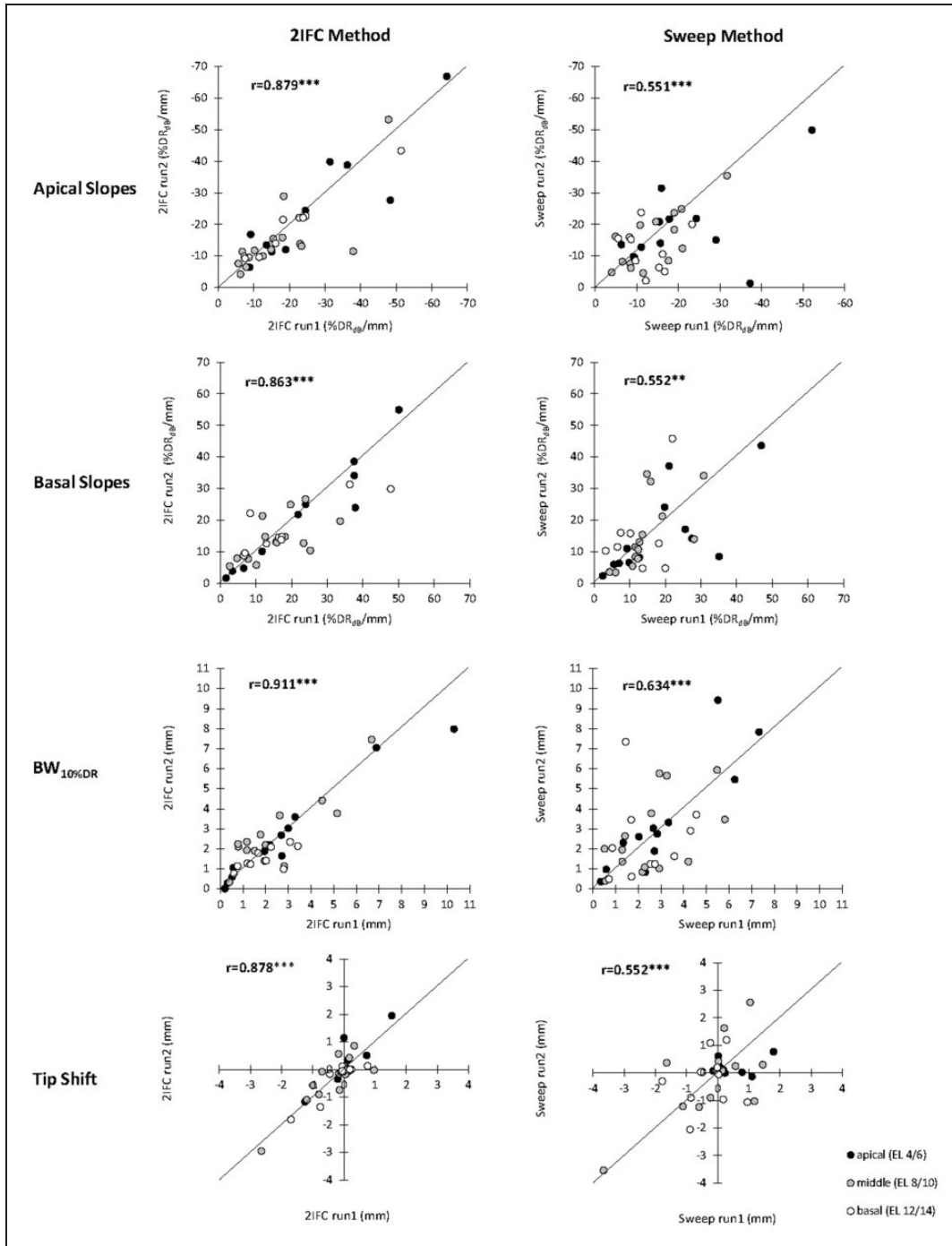
### Test Duration

A primary goal of this study was to test whether the sweep STC procedure can be performed within a timeframe that makes it clinically feasible. The duration of testing time was substantially shorter for the sweep procedure than for the adaptive forced-choice procedure. The average time, as estimated at the University of Minnesota site, to complete two STC runs per probe electrode for the forced-choice procedure was 62 min, while the time to complete two STC runs (two upward and two downward sweeps) for the sweep procedure was 23 min. This shows an improvement in testing time; the sweeps taking about one third of the time to complete. However, even 23 min per electrode makes the test unlikely to be useful under current clinical constraints.

### Discussion

The main conclusion of this study is that the STC parameters derived from the sweep method are correlated with those derived from the traditional forced-choice method. This aspect of the data is consistent with the results of Bierer et al. (2015), who compared forced-choice and sweep methods in CI users to estimate absolute thresholds, as well as with Sek et al. (2005), who compared PTCs under simultaneous masking in normal-hearing and hearing-impaired listeners using the two methods. However, in contrast to the findings with absolute thresholds, the test-retest reliability of the STC parameters was significantly poorer with the sweep procedure than with the forced-choice procedure. Indeed, bootstrap simulations (not shown here) indicated that about 4 times the number of repetitions would be required in the sweep procedure to produce test-retest reliability ratings that approached those found with the forced-choice procedure. The increased number of repetitions would negate the benefit of the factor of three reduction in testing time per run. It should be noted that the parameters (i.e., timing between stimulus presentations,  $\alpha$  sweep speed,  $\alpha$  step size, level step size) of the sweep procedure were optimized for the absolute threshold measures and were just applied to the STC measure in this experiment. It might be that these parameters can be adjusted to improve the test-retest reliability of the sweep STC.

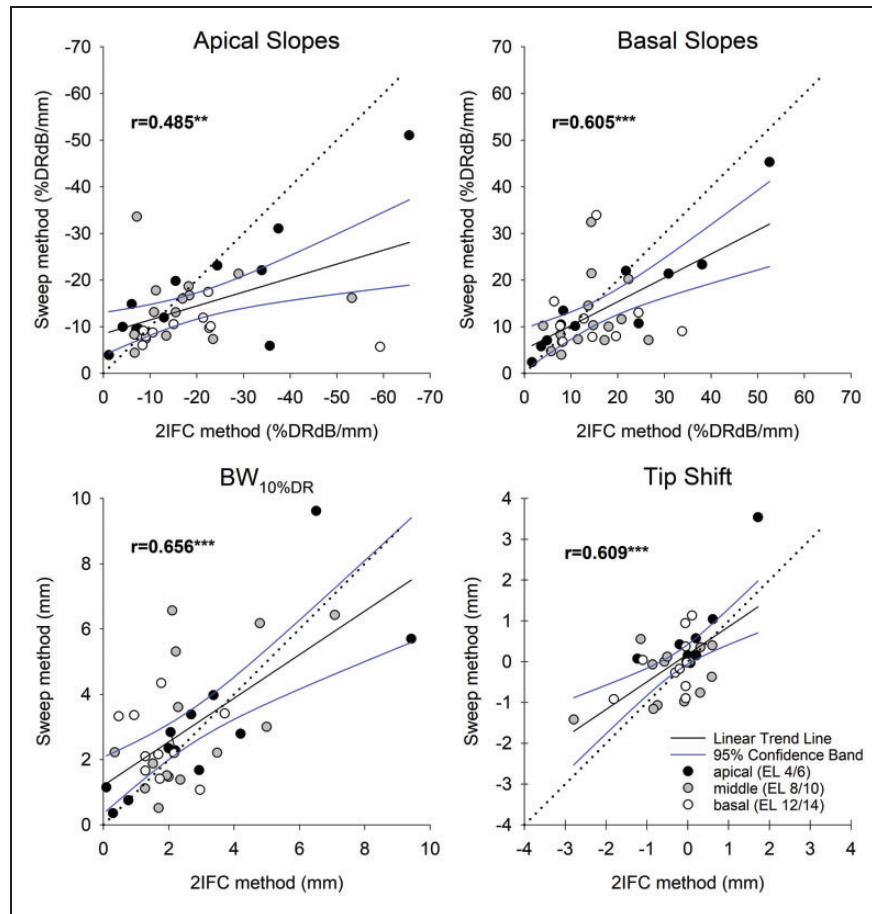
In addition to some systematic differences in STC parameter estimates between the two methods, one difference between the outcomes reported here with CI users and the outcomes from the study with normal-hearing and hearing-impaired listeners (Sek et al., 2005) is that we found that masker threshold levels were higher for the forced-choice method than for the sweep method in about 66% of cases. In contrast, Sek et al. (2005) reported the opposite trend, with higher thresholds for the sweep method than for the



**Figure 3.** Correlations of the STC parameters for the first run versus the second run for each measurement method (2IFC-left column, sweep-right column). The black-filled symbols represent the values from electrodes in the apical region of the array (ELs 4 and 6;  $n = 12$ ). The gray-filled symbols represent the values from the electrodes in the middle region of the array (ELs 8 and 10;  $n = 14$ ). The white-filled symbols represent the values from the electrodes in the basal region of the array (ELs 12 and 14;  $n = 10$ ). Top to bottom rows: apical slopes, basal slopes,  $BW_{10\%DR}$ , and tip shift. Correlation values are indicated on each panel as well as the level of significance ( $^{***}p < .001$ ;  $^{**}p < .01$ ).

forced-choice method in most cases. This difference is presumably due to a difference in the detection criteria used by listeners in the sweep method, because the forced-choice method should yield criterion-free

threshold estimates (Green & Swets, 1966). This apparent discrepancy may reflect some important differences in the stimuli between the two studies. First, Sek et al. (2005) measured PTCs under simultaneous masking,



**Figure 4.** Correlations of the STC parameters for the adaptive versus the sweep method. Top row: apical slopes (left) and basal slopes (right). Bottom row: BW<sub>10%DR</sub> (left) and tip shift (right). Correlation values are indicated on each panel as well as the level of significance ( $^{***}p < .001$ ;  $^{**}p < .01$ ;  $^{*}p < .05$ ). The dotted line is the unity line, the solid black line is the linear trend line, and the area within the blue curves represents the 95% confidence band. The black symbols represent the values from electrodes in the apical region of the array (ELs 4 and 6;  $n = 12$ ). The gray symbols represent the values from the electrodes in the middle region of the array (ELs 8 and 10;  $n = 14$ ). The white symbols represent the values from the electrodes in the basal region of the array (ELs 12 and 14;  $n = 10$ ).

with relatively long (500 ms) probe tones that were periodically pulsed on and off within a continuous and relatively wide masker noise band. In contrast, in this study, we measured forward-masked thresholds of a very brief probe (20 ms) presented shortly (20 ms) after a gated masker. As suggested by Sek et al. (2005), the continuous nature of the acoustic masker, the long probe duration, its periodic presentation, and the qualitative difference between the probe tone and the noise masker may have all led to a relatively liberal detection criterion on the part of the subjects during the sweep procedure, which in turn would lead to higher masker levels at threshold. In contrast, for the CI users, the probe and masker were both pulse trains with equal pulse rates, making them less perceptually dissimilar. This may have led to listeners adopting a more conservative criterion when judging whether the probe was actually present at the end of each masker, especially if probe and masker are on the same electrode, leading to lower masker levels at

threshold. However, the important point is that the detection criteria used by subjects seem to have been relatively uniform across the electrode array, leading to similar shaped STCs regardless of the method used. In terms of estimating the effects of spectral resolution, vertical shifts in the STC (as are produced by uniform shifts in the detection criterion) do not impact the estimated shape of the tuning curve.

The fact that the new sweep method takes about a third of the time to collect comparable data, relative to the traditional forced-choice procedure is encouraging; however, this benefit is offset by the poorer test-retest reliability. In addition, its use may remain limited in clinical settings, as the time to measure the thresholds and MCLs, in addition to an STC for one electrode, will certainly exceed 30 min, which is already half the normal time allotted for a reprogramming session at many implant centers. It may be that a method using simultaneous masking, such as that tested under acoustic

hearing by Sek et al. (2005) and Kluk and Moore (2009), would result in more reliable, and hence more efficient, STC measures. In either case, the procedure could prove useful in individual cases, such as when specific electrodes are suspected of not providing good speech information (e.g., DeVries & Arenberg, 2018).

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