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Effect of stimulation parameters on sequential current-steered stimuli in cochlear implants

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ABSTRACT:
Manipulation of cochlear implant (CI) place pitch was carried out with current steering by stimulating two CI electrodes sequentially. The objective was to investigate whether shifts in activated neural populations could be achieved to produce salient pitch differences and to determine which stimulation parameters would be more effective in steering of current. These were the pulse rate and pulse width of electrical stimuli and the distance between the two current-steering electrodes. Nine CI users participated, and ten ears were tested. The pattern of pitch changes was not consistent across listeners, but the data suggest that individualized selection of stimulation parameters may be used to effect place pitch changes with sequential current steering. Individual analyses showed that pulse width generally had little influence on the effectiveness of current steering with sequential stimuli, while more salient place pitch shifts were often achieved at wider electrode spacing or when the stimulation pulse rate was the same as that indicated on the clinical MAP (the set of stimulation parameters) of the listener. Results imply that current steering may be used in CIs that allow only sequential stimulation to achieve place pitch manipulation.
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I. INTRODUCTION

Cochlear implants (CIs) have been used to restore the hearing of severely to profoundly deaf people. Though effective, CIs do not provide normal hearing (Grifford and Revir, 2010). The spatial resolution of CIs is limited by the number of implanted electrodes as well as current spread. A primary consequence of the limited spatial resolution is the degradation of pitch perception in CI listeners (Gantz *et al.*, 2005). Pitch perception is key for good speech perception and for perception and appreciation of music (Green *et al.*, 2002; Gantz *et al.*, 2005). Melodic contour identification by CI users is generally weak because of limited spatial resolution (Galvin *et al.*, 2007; Spitzer *et al.*, 2021).

A proposed solution for improved spatial resolution is to use current steering to create pitches intermediate to those created by stimulating two adjacent electrodes individually (McDermott and McKay, 1994; Kwon and van den Honert, 2006; Koch *et al.*, 2007; Saoji and Litvak, 2010; Wu and Luo, 2013). The intermediate place pitches reflect increased spatial resolution (Kwon and van den Honert, 2006). Traditionally, current steering is carried out with simultaneous stimulation (e.g., Koch *et al.*, 2007; Saoji and Litvak, 2010; Snel-Bongers *et al.*, 2011; Snel-Bongers *et al.*, 2013; Wu and Luo, 2013). Virtual channels are created by simultaneous stimulation of two adjacent electrodes (Donaldson *et al.*, 2005; Klawitter *et al.*, 2018; Saoji and Litvak, 2010) or by stimulating more electrodes simultaneously to improve control over the current field in the cochlear area targeted (Landsberger and Srinivasan, 2009; Padilla *et al.*, 2017). However, not all commercially available CIs stimulate electrodes simultaneously. While simultaneous stimulation of electrodes allows control over the shape of the current field so as to adjust the position of the peak of stimulation, the intention with sequential stimulation is to limit electrode interaction, so that direct superposition of the electrical currents from electrodes cannot be used to shape the current field. Perhaps for this reason, current steering with CIs that do not allow simultaneous stimulation has received relatively little attention in research studies. Earlier studies, however, have shown that a current-steering effect (or a pitch shift) can be achieved with sequential stimulation (McDermott and McKay, 1994; Kwon and van den Honert, 2006; Swanson, 2008).

McDermott and McKay (1994) showed that the evoked pitch could be altered by adjusting the relative currents on two electrodes using bipolar stimulation. Stimulus pulse width varied across listeners (50, 100, or 200 μs), pulse rate was 250 pulses per second (pps), and the inter-pulse delay between the two current-steering electrodes was 0.4 ms. Intermediate pitches could be evoked on adjacent electrodes in some listeners, but larger electrode separation (up to seven electrodes) was needed in others.

Swanson (2008) stimulated at 1776 pps and used monopolar stimuli on adjacent electrodes to create intermediate pitch percepts. Stimulus pulse width was 25 μs, and the inter-pulse delay was 12.4 μs. He found that all the listeners in the study who achieved a high percentage of

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correct electrode discrimination on adjacent electrodes were also able to pitch rank intermediate pitch percepts.

Kwon and van den Honert (2006) used monopolar stimuli on adjacent electrodes with stimulation rate between 500 and 1800 pps, the same as on the listener's clinical MAP (the set of individualized stimulation parameters). Stimulus pulse width was 25 μs, and the inter-pulse delay was 19 μs. They reported that more than 80% of the listeners who participated in their study could perceive intermediate pitches between stimulating electrodes.

Although these three studies each used different stimulation parameters, current-steered pitch differences were demonstrated in each. These stimulation parameters are not expected to have an equally large influence in adjusting place pitch information.

The objective of the present study was to determine the influence of selected stimulation parameters on the pitch ranking ability of CI listeners when they were presented with sequential current-steered stimuli. The parameters investigated were stimulation pulse rate, pulse width, and electrode separation. The latter is defined to be the distance between the current-steering pair of electrodes. The motivation for selecting these parameters is because of the potential influence of each in determining the activated nerve fibre population, expected to be true for pulse width and electrode separation, or because changing pulse rate is expected to influence the pitch sensation. The selection of parameters is expanded on below.

Pulse rate. Pulse rate is expected to interfere with place pitch and possibly influence the effectiveness of sequential current steering in controlling place pitch, conceivably especially at low stimulation rates where variation in pulse rate would be perceived as a pitch change. Studies have shown a relationship between the pulse rate and perceived rate pitch (McDermott and McKay, 1997), and a number of studies (e.g., McDermott and McKay, 1997; Zeng, 2002) have observed that a fundamental limit to pulse rate discrimination may exist in CIs at around 300–600 pps, or higher in some listeners, with Kong and Carlyon (2010) reporting listeners that could track rate pitch up to 900 pps. As the intention with sequential current-steered stimuli is to adjust place pitch, it is necessary to consider the effect of stimulation rate on perceived pitch. As has been shown in several studies (e.g., McDermott and McKay, 1997; Stohl *et al*., 2008; Landsberger *et al*., 2016), perceived pitch at a selected place of stimulation within the cochlea is dependent not only on the place of stimulation, but also on the stimulation rate, at least at low rates of stimulation. Stohl *et al*. (2008) used two rates of stimulation (199 and 398 pps) and stimulated electrodes across the entire electrode array. Although the higher rate consistently elicited higher pitch in 3/5 listeners at these low rates, rate pitch changes also made the pitch ranking task more difficult for some listeners. Interaction between rate and place depends on parameter choice. McDermott and McKay (1997) showed that place pitch dominated at higher stimulation rates, and Landsberger *et al*. (2016) demonstrated that two different electrodes stimulated at two different rates may have the same pitch but would differ in sound quality. The pitch scaling map in Landsberger *et al*. (2016) shows interaction between rate and place across a range of rates (100–1500 pps) and cochlear places from base to apex. This suggests that rate may have an influence on the extent to which it would be possible to adjust place pitch with sequential current steering. The hypothesis was that rate pitch would interfere more with pitch ranking of sequential stimuli at lower pulse rates, so that pitch ranking ability may be expected to improve at higher pulse rates.

Electrode separation. The distance between the stimulation electrodes during current steering may influence how effective current steering will be in adjusting place pitch in sequential stimulation. Electrodes that are closely spaced could largely excite the same neural population. A number of studies have shown that even for CIs with 22 electrodes, CI users (Friesen *et al*., 2001; Wilson and Dorman, 2008; Croghan *et al*., 2017) or listeners with normal hearing listening to an acoustic model of a CI (Wilson and Dorman, 2008; Strydom and Hanekom, 2011) often utilize only around 4–10 independent information channels in speech recognition tasks. For both listener groups, speech recognition asymptotes at 4–10 electrodes, but significant improvements up to 22 electrodes have been observed in some listeners (Croghan *et al*., 2017).

Assuming overlap in the neural populations activated by two electrodes in a current-steering pair, a larger distance between two stimulating electrodes may result in a more easily resolved shift in the neural excitation pattern when current is varied on these two electrodes. However, if the electrodes in the stimulating pair are too far apart, there may be no overlap between the activated neural populations and consequently no effect of current steering on place pitch. Experiments carried out with simultaneous current-steered stimuli showed that there is a gradual deterioration in the just noticeable difference of pitch with increasing electrode separation (Snel-Bongers *et al*., 2011). This study also found that more current adjustment was needed to maintain equal loudness between simultaneous stimuli created using larger electrode separations. The hypothesis in the present study was that larger electrode separations would lead to a more salient pitch shift with sequential stimulus current steering up to a boundary where neural overlap became minimal (estimated to be around 4 mm; McDermott and McKay, 1994).

Pulse width. Studies have shown that using longer pulses results in lower neural thresholds (Shepherd and Javel, 1999) and may lead to a wider area of neural activation (Chatterjee and Shannon, 1998) so that characteristics extracted from the neural excitation pattern (e.g., peak or centroid of the activation area) to identify changes in place pitch may be resolved less easily. As narrower neural activation regions resulting from shorter pulses may lead to less overlap in the neural populations activated by the current-steered electrodes, it was hypothesized that narrower pulse widths would lead to more focused current steering and potentially more salient pitch shifts.

TABLE I. Background information on the nine listeners who participated in the experiments. S3 used her original implant for 17 years before being reimplanted. A new implant had been in use for nine years at the time of the study. S6 had a stimulation pulse width of 25 μs, except on electrodes 10–13, where this was 50 μs.

Listener	Ear	Age at study (years)	Duration of CI use at study (years)	Implant	Number of active electrodes	Stimulation rate per channel (pps)	Stimulation pulse width (μs)	Stimulation mode
S3	Right	67	12	CI24R–Contour Advance	22	500	25	MP1 + 2
	Left (original)	67	17	CI22M–Straight	18	240	25	BP + 1
	Left (new)	67	9	CI24RE–Contour Advance	15	500	75	MP1 + 2
S25	Left	36	3	CI24RE–Contour Advance	22	900	25	MP1 + 2
S13	Left	66	11	CI24R–Contour Advance	20	900	25	MP1 + 2
S24	Right	26	10	CI24RE–Contour Advance	22	1200	25	MP1 + 2
S19	Right	48	10	CI24RE–Contour Advance	22	900	25	MP1 + 2
S28	Right	63	10	CI24RE–Contour Advance	22	1200	25	MP1 + 2
S6	Right	60	6	CI512–Contour Advance	22	900	25 (10-13 = 50)	MP1 + 2
S20	Left	31	12	CI24R–Contour Advance	21	900	25	MP1 + 2
S5	Left	49	3	CI24RE–Contour Advance	22	250	25	MP1 + 2

II. METHODS

A. Listeners

Nine experienced, post-lingually deaf CI users of the Nucleus device with the Contour Advance electrode array participated in the experiments (Table I). The study included ten ears as listener S3 completed the experiments with both ears. Collection of data for this study was approved by the relevant research ethics committees of the University of Pretoria before testing commenced. Listeners provided written informed consent.

B. Stimuli

Experiments were carried out using the L34 research processor (provided by Cochlear Europe Ltd.) programmed by means of the Nucleus MATLAB toolbox (Swanson, 2008). Table II shows the stimulation parameters that were varied during 15 experimental conditions. All other stimulation parameters were chosen to be as close as possible to the default parameters in the clinical MAPs of each listener and to ensure that stimulus conditions were met where neural populations activated by the current-steering electrode pair were expected to overlap, as expanded on below. The interphase gap between anodic and cathodic pulses was always 8 μs, and monopolar stimulation was used throughout.

1. Design of stimuli to ensure overlapping activated neural populations

Sequential stimulation on two adjacent or nearby electrodes could result in two distinct neural activation sites or two overlapping sites depending on stimulus parameters as shown in modeling work by Frijns *et al.* (2009). To achieve a current-steering effect, it was necessary to select stimulation parameters that were expected to result in temporal integration of the neural activity and in spatial overlap between the nerve fibre populations excited by the two electrodes. These stimulation parameters were the distance between the two electrodes of a current-steering pair, the delay between the pulses on these, and the stimulus level.

Electrodes of the current-steered pair that was furthest apart (2.1 mm center to center) were selected to be well within the range within which McDermott and McKay (1994) and Snel-Bongers *et al.* (2011) found it possible to create intermediate pitches. These were 4 mm with sequentially stimulated electrodes using bipolar stimulation mode (McDermott and McKay, 1994) and 4.4 mm for simultaneous stimulation in monopolar stimulation mode (Snel-Bongers *et al.*, 2011).

TABLE II. The three stimulation parameters varied in the 15 experiments. Stimulation pulse rate was varied in experiments 1–9 while keeping the pulse width constant, and this was repeated for three electrode separations. These were 0.7, 1.4, and 2.1 mm, measured between electrode centers. Experiments 10–15 varied pulse width across the rest of the selected range while keeping the pulse rate constant, and this was repeated for the three electrode separations. The final column shows the resulting delay between pulses on the two electrodes (the delay between the commencement of the pulses on the first and second electrodes). Pulse delay was implicitly related to the pulse width used.

Experiment number	First parameter: Pulse rate (pps)	Second parameter: Pulse width (μs)	Third parameter: Electrode separation (number of electrodes)	Pulse delay between stimulus on first and second electrode (μs)
1	1776	25	1	70.4
2	1776	25	2	70.4
3	1776	25	3	70.4
4	888	25	1	70.4
5	888	25	2	70.4
6	888	25	3	70.4
7	200	25	1	70.4
8	200	25	2	70.4
9	200	25	3	70.4
10	1776	79	1	187.7
11	1776	79	2	187.7
12	1776	79	3	187.7
13	1776	132	1	281.5
14	1776	132	2	281.5
15	1776	132	3	281.5

The pulsatile electrical stimuli for the two current-steered electrodes were interleaved, with the second electrode stimulated directly after the first so that the phase delays between pulses on the two electrodes were minimized, called burst mode in Venter and Hanekom (2014). Burst mode was used to ensure that the two stimuli would fall within a window in which pulses from two sequentially stimulated electrodes were expected to interact, that is, in which the neural responses would be integrated. Interaction, measured as a threshold shift of a second electrode stimulated subsequent to the first, decays with longer time delays between the pulses on the two electrodes (Middlebrooks, 2004). An interaction decay time constant of around 350 μs was measured by Middlebrooks in an animal model with electrodes that were 1.4 mm apart at their centers. The longest time delay between pulses on adjacent electrodes in the present experiments was 281.5 μs, well within the delay in which interaction is expected.

Finally, stimulus levels were selected to ensure that the neural populations activated by the two electrodes would overlap. Frijns *et al.* (2009) showed in their model that neural populations would probably not overlap at lower stimulus levels for the electrode separation that they used (HiFocus 1J electrode array with contacts spaced 1.1 mm apart) but that activated neural populations would fuse for stimulus levels of around -3 dB re maximum comfortable level (MCL) and higher. Relatively high stimulus levels were used in the present study with all stimuli presented between 75% of the dynamic range (DR) and MCL. DR was measured as the range between threshold and MCL. For the DRs for all experimental conditions and all listeners in the study, this translated into stimulus levels between –2.1 dB re MCL and MCL.

2. Design of experimental variables

Each parameter tested had three variations. As rate pitch probably cannot be extracted from stimuli presented at high stimulation rates, interaction between rate and place pitch was expected to be low at high rates. High-rate stimulation well above the proposed limit of temporal pitch perception may help to avoid a potential confounding influence of temporal pitch perception. For example, Schatzer *et al.* (2014) selected a rate of 1500 pps, and Baumann *et al.* (2011) selected 800 pps. A high stimulation rate of 1776 pps was selected as the first variation in the present study, following Swanson (2008).

Literature shows that a limit to pulse rate discrimination in CIs may exist at around 300 pps (McDermott and McKay, 1997), although this may be markedly higher, up to above 900 pps, dependent on the specific listener (Kong and Carlyon, 2010; Goldsworthy and Shannon, 2014), age of the listener (Johnson *et al.*, 2021), and stimulation parameters (Venter and Hanekom, 2014). Therefore, 200 pps, a stimulation rate below this proposed limit, was tested as the other extreme when varying pulse rate. With a similar argument, Stohl *et al.* (2008), considering the interaction between rate and place of stimulation, selected pulse rates of 199 and 398 pps. These were intended to be below the rate at which rate pitch typically asymptotes, their rationale being that the influence of pulse rate on place pitch should primarily be limited to the range in which differences in rate pitch can be distinguished by CI listeners. An intermediate pulse rate of 888 pps between 200 and 1776 pps was also tested.

A stimulation pulse width of 25 μs was the MAP pulse width for most of the listeners, explaining why this pulse width was tested. At the other extreme, a 132 μs pulse width was chosen because it was the longest pulse duration that could be applied at a stimulation rate of 1776 pps. The 79 μs pulse width was midway between 25 and 132 μs.

Current was varied on selected electrodes to achieve a pitch shift. Each experiment was carried out with three different combinations of current-steering electrodes, these being electrodes 11 and 12, 11 and 13, and 11 and 14 (electrode 22 was most apical). Current steering is often carried out with adjacent electrodes. The reason for including wider electrode separations in the present study as well was twofold. First, not all CI electrode arrays have electrodes that are spaced as closely to each other as those used in the present study (about 0.7 mm center to center for the Contour Advance array). For example, the Standard Med-El electrode array (from their Classic series) has electrode contacts that are spaced about 2.4 mm apart, while electrodes are about 1.1 mm apart in the Advanced Bionics HiFocus 1J electrode array. Second, if it could be shown that current-steering effects can be obtained at larger electrode separations, current steering could be used to activate nerve fibres that would have been targeted by a defective electrode in an array with closely spaced electrodes. This method, called spanning, has been proposed previously by Snel-Bongers *et al.* (2011) for simultaneous stimulation. They showed that intermediate pitches could be created between two non-adjacent current-steering electrodes up to 4.4 mm apart. It is therefore important to know whether spanning can be achieved with sequential stimulation.

3. Current-steering stimuli and expected pitch ranking order

In the main tests, each experiment consisted of four stimuli (Table III), which had to be pitch-ranked. The current levels indicated in the table are explained below. Current levels are always specified in current units (CU), related to current in mA through an equation given in McKay *et al.* (2003). The intention was to steer current by varying the current levels on electrodes X and Y, the two electrodes of a current-steered pair. Table III shows schematically (last two columns) what the intention was with the stimuli. Stimuli A and D were single-electrode stimuli, as either electrode X or Y was activated at zero current levels. These stimuli should result in current distributions that would activate neural populations that are most distinct. Stimuli B and C activated electrodes X and Y differentially, and the hypothesis was that this would shift the activated neural population between the two extremes if a sequential stimulation current-steering effect was achieved. The

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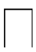
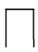
TABLE III. Amplitudes of stimuli A–D used in each of the 15 experiments with stimulation currents always given in CU. These are the amplitudes before roving was applied. MCL always refers to the current levels of the equal-current dual-electrode stimuli used to determine DR. The second and third columns illustrate the intention with the stimuli. Columns 4 and 5 indicate the current levels after stimulus A was loudness-balanced to stimulus D, but before the dual-electrode stimuli were loudness-balanced to stimulus D. I_A and I_D are the current levels used for the single-electrode stimuli A and D. Δ_B and Δ_C are the current adjustments needed to the stimulus currents of stimuli B and C, respectively, to achieve loudness balancing to stimulus D. Δ_B and Δ_C could be positive or negative.

	Simple illustration of stimulation amplitude of stimuli		Before loudness balancing dual-electrode stimuli B and C to reference D		After loudness balancing dual-electrode stimuli B and C to reference D	
Stimulus	Electrode X	Electrode Y	Stimulation current on electrode X (electrode 11)	Stimulation current on electrode Y (electrode 12, 13, or 14)	Stimulation current on electrode X (electrode 11)	Stimulation current on electrode Y (electrode 12, 13, or 14)
A			0	I_A; this is MCL of electrode pair X, Y, adjusted by loudness balancing to reference stimulus D	0	I_A
B			$I_D - 15$ CU	I_A	$(I_D - 15\text{ CU}) + \Delta_B$	$I_A + \Delta_B$
C			I_D	$I_A - 15$ CU	$I_D + \Delta_C$	$(I_A - 15\text{ CU}) + \Delta_C$
D			Reference stimulus current level I_D, presented at MCL of electrode pair X, Y	0	I_D	0

expectation was, therefore, that listeners should be able to rank the pitches of these four stimuli with pitch increasing from stimulus A to stimulus D. This is referred to the expected pitch order when it is assumed that sequential current steering was successful in adjusting place pitch.

Stimuli A–D were all equally loud (achieved through a loudness balancing procedure explained below), and in stimuli B and C, one electrode was stimulated at 15 CU less than the other.

C. Procedure

All 15 experiments of Table II, presented in the same order to listeners, were completed with each of the ten ears. Each experiment could be divided into three tasks: determining DR, loudness balancing the stimuli, and pitch ranking the stimuli. Determining DR and loudness balancing was completed for all variations in parameters and for all the ears. Stimuli A–D had to be loudness-balanced to ensure that loudness cues would not influence pitch ranking, and to achieve this it was necessary to first determine at which levels to stimulate electrodes X and Y of each of these four stimuli. Once the safe stimulus ranges were known for all variations in parameters, loudness balancing followed.

1. Determining DR

The DRs of the stimuli that were expected to be loudest, namely the dual-electrode stimuli (B and C), were determined first. Dynamic range was determined in CU as the difference between the threshold and MCL. Dynamic ranges were determined for each of the experimental conditions (Table II) for the interleaved stimulation pattern of electrodes X and Y. Stimuli were 500 ms in duration with equal stimulation currents on the two electrodes, while pulse width, pulse rate, and electrode separation varied with the experimental condition.

The listener had to move the slider on a graphical user interface on a personal computer, altering the stimulation current in steps of one CU equally on both electrodes until the stimulus was just audible. This amplitude was stored as the threshold. Next, the listener had to move the slider to a loudness that was perceived as the loudest comfortable sound, which was stored as the MCL. This was repeated three times for each experimental variation, and the mean of the three attempts was stored as the threshold or MCL, respectively. The difference between these was then taken as the DR. This procedure determined MCLs in the condition where the loudest stimuli were expected and consequently determined a safe stimulation range for dual-electrode stimuli. In the main experiments, one of the two electrodes in a dual-electrode stimulus always either received no stimulus or was stimulated at 15 CU less than the other. The intention was to use clearly audible but comfortable sounds in the main experiments by selecting stimulus levels that were close to MCL. Although the individual MCLs for electrodes X and Y were expected to be higher than for dual-electrode stimuli, the MCLs determined for the latter were used as an approximation to the MCLs for individual stimulation of electrodes X and Y.

2. Loudness balancing the stimuli

The stimuli (A–D) used in the pitch ranking experiments were loudness-balanced to ensure equal loudness across stimuli. Loudness balancing followed the procedure of an earlier study (van Wieringen *et al.*, 2005). Three stimuli were presented consecutively without any delay for 500 ms each: a test stimulus, bracketed by two identical reference stimuli (always stimulus D) that were used as loudness balancing references. The second stimulus (A, B, or C) was the test stimulus that had to be loudness-balanced against the reference. Only the test stimulus amplitude could be varied.

The listener had to adjust a slider until the test stimulus was perceived to be as loud as the two reference stimuli. Single-electrode stimulus A was the first to be balanced against D. Designating electrical current (in CU) by the symbol I, the current level of stimulus D (single-electrode stimulus on electrode X) was $I_{D.}$ This was the current at the MCL determined before. The loudness-balanced current level of electrode Y obtained thus was $I_{Y\_LB.}$ The loudness-balanced current relationship between electrodes X and Y was then used to determine the levels at which X and Y had to be presented in stimuli B and C. Electrodes X and Y were stimulated at current levels that were different from their loudness-balanced values by 15 CU in stimuli B and C. This means that, using stimulus B as an example, if the loudness-balanced level of electrode Y was 1 CU more than that of electrode X after loudness balancing stimuli A and D, the initial current levels (before loudness balancing stimulus B to the reference) of X and Y would be $I_Y = I_{Y\_LB} = I_D + 1$ CU and $I_X = I_D - 15$ CU, respectively. When loudness balancing stimuli B and C against the reference, the difference in current level between stimulating electrodes X and Y was maintained by adjusting the current levels on these electrodes by the same amount, Δ_B and Δ_C, respectively. Table IV shows an example of the current levels before and after loudness balancing for one of the listeners.

TABLE IV. An example of loudness-balanced stimuli (all currents in CU) before any roving was applied. These data are for listener S13 for experiments 7, 8, and 9 and stimuli A–D (see Table III). Stimulation current levels in column 3 are after loudness balancing stimulus A to reference stimulus D, but before loudness balancing stimuli B and C to the reference. Column 4 gives the final loudness-balanced levels after stimuli B and C have been loudness-balanced to D. Currents on the two electrodes of stimuli B and C were adjusted by the same amounts in these two loudness balancing tasks, Δ_B and Δ_C, respectively. The amounts by which currents had to be adjusted to achieve balanced loudness across stimuli A–D are typical of the present group of listeners.

Experiment	Stimulus	Before loudness balancing B and C to D: Current on electrodes X, Y (CU)	After loudness balancing B and C to D: Current on electrodes X, Y (CU)
7	A	0, 189	0, 189
7	B	170, 189	165, 184
7	C	185, 174	180, 169
7	D (reference)	185, 0	185, 0
8	A	0, 184	0, 184
8	B	170, 184	172, 186
8	C	185, 169	187, 171
8	D (reference)	185, 0	185, 0
9	A	0, 187	0, 187
9	B	171, 187	168, 184
9	C	186, 172	186, 172
9	D (reference)	186, 0	186, 0

3. Roving of stimulus level

As a further precaution to prevent the listeners from using loudness as a cue in the pitch ranking task, roving of the stimulus level was added to each stimulus presented during the pitch ranking experiments. Similar to other studies, a roving range of ±10% of the DR of the listener was chosen (Laneau and Wouters, 2004; Snel-Bongers *et al.*, 2012). The increase or decrease in current applied during roving was equal for both electrodes in stimuli B and C, so that the ratio of current of the two stimulating electrodes remained the same. For stimuli A and D, roving was applied only to the stimulating electrode and not to the zero-stimulus electrode.

4. Pitch ranking of stimuli

In the main experiment, listeners had to pitch rank each of the four stimuli against one another in the 15 conditions shown in Table II. A two-alternative forced choice (2AFC) procedure was used for pitch ranking. A stimulus randomly selected from stimuli A, B, C, or D was presented for 500 ms, followed by 500 ms of silence, followed by another random stimulus presentation of 500 ms. The listener had to indicate which one of the two sounds was judged to be higher in pitch. No feedback was given, but listeners could repeat the two stimuli once before indicating a decision, similar to the approach in some other studies (e.g., Galvin *et al.*, 2007). The second presentation of a stimulus differed from the first, as random roving was applied at every stimulus presentation. Listeners, however, seldom repeated stimuli. Each combination of two stimuli (e.g., B and D) was presented ten times in each order (B, D and D, B in this example).

III. RESULTS

A. Multidimensional scaling (MDS) analysis

The results were tabulated in a stimulus-response matrix, which showed how many times the stimuli of each column were rated higher in pitch than the stimuli of each row. The pitch rank of the different stimuli was determined using MDS methods. It would have been possible to simply calculate perceptual distances (d') between pitch-ranked stimuli,[1] but MDS analysis provided a more powerful analysis tool, as expanded on below.

First, although listeners had to perform a pitch ranking task, other cues may have contributed to their judgment of pitch, and the existence of a second dimension (along with the pitch dimension) had to be ruled out. Specifically, this would also confirm that the loudness controls described earlier were effective in suppressing loudness as a potential cue. Many researchers prefer to use cumulative d' values to express the perceptual distance between stimuli (McDermott and McKay, 1994; Kwon and van den Honert, 2006; Swanson, 2008), but this is under the assumption that the perceptual dimension of pitch is unidimensional (Kwon and van den Honert, 2006). It has, however, been shown that perceptual data of non-simultaneous dual-electrode stimuli

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can be described by a two-dimensional space (McKay *et al.*, 1996). That study was conducted using bipolar stimulation, and the dimensions could be correlated with the positions of the two electrode pairs. While the number of dimensions necessary to describe perceptual data when sequential dual-electrode, monopolar stimulation is applied may not be the same as that of bipolar stimulation, no available literature appears to confirm that pitch perception should be restricted to be unidimensional in this case. This had to be tested through MDS analysis.

Second, while d' values consider the perceptual distance between two stimuli, MDS considers all four stimuli simultaneously to find both the pitch rank order and the perceptual distance between stimuli that best represents the perceptual distances between all four stimuli in a single dimension. In this way, MDS analysis reflects the perceptual distances captured in the pitch rank stimulus-response matrices more accurately than expressing perceptual distances through d' values obtained through pairwise comparisons. In addition, while the pitch rank order has to be assumed when cumulative d' values are used to express perceptual distances between stimuli, no such assumption is made in MDS analysis. MDS determines the pitch rank order from all the data available in the stimulus-response matrix.

MDS was carried out using built-in MATLAB functions. Notably, the MDS stress factor and scree plot of all the data (Kruskal, 1964; Wickelmaier, 2003), for all the listeners, indicated consistently that a single dimension could sufficiently represent the perceptual distance between the stimuli. This was interpreted as meaning that listeners used a single perceptual dimension when judging pitch direction and that the four stimuli could be ranked in this dimension. This dimension is interpreted to be a place pitch dimension, given that stimuli were carefully loudness-balanced. This corresponds to findings by Klawitter *et al.* (2018) for simultaneous stimulation. They confirmed through an MDS analysis that sensation changed along a single perceptual dimension for physical and virtual electrodes in their current-steering experiments and that this dimension was most likely place pitch.

The outcome of the MDS provides an unbiased pitch rank order of the different stimuli and the perceptual distance between the different stimuli. The MDS results were used to draw cumulative MDS graphs, similar to cumulative d' graphs often seen in literature (McDermott and McKay, 1994; Kwon and van den Honert, 2006; Swanson, 2008). These are shown in Figs. 1 and 2. Since the cumulative MDS was derived from the MDS that was calculated in a one-dimensional space, $S_{AC} = S_{AB} + S_{BC}$ and $S_{AD} = S_{AB} + S_{BC} + S_{CD}$, where S_{AC} is the perceptual distance (in arbitrary pitch units) between the position of stimulus A and the position of stimulus C along the y axis of the cumulative MDS graphs, which represents pitch distance.

Cumulative MDS graphs in Figs. 1 and 2 express perceived pitch in arbitrary perceptual pitch units on a linear scale. The reference pitch (0 on the ordinate) for each of the 15 experiments was always stimulus A. Each tick on the ordinate corresponds to this reference pitch for one of the 15 experiments. Stimuli B, C, and D could be ranked higher in pitch than stimulus A and would then be plotted above the reference pitch value of a particular experiment along the ordinate or ranked lower and then be plotted below the reference pitch value on the ordinate. Two stimuli in a particular experiment that were more different in pitch (a larger perceptual distance) would be spaced further apart on the ordinate. The largest observed pitch difference between stimulus A (reference pitch of 0) and any of the other stimuli (B, C, and D) was used to normalise data, so that the pitch rank could range between -1 and 1 on these cumulative MDS graphs.

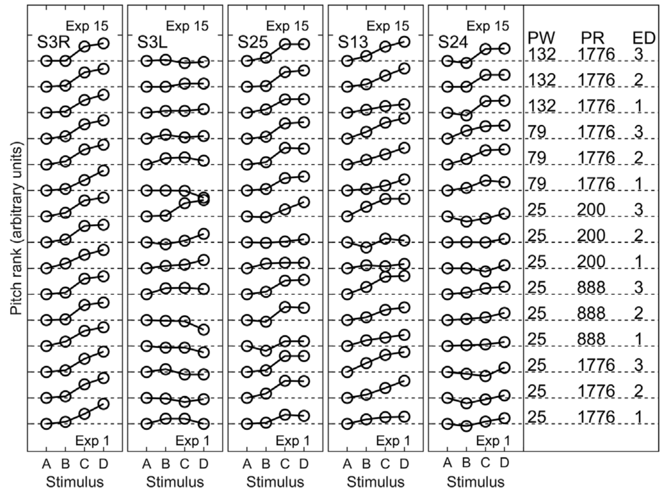

FIG. 1. Cumulative MDS graphs for the first five listeners in Table I. Each panel consists of 15 cumulative MDS graphs, one for each experiment (Exp), numbered from bottom to top. Each cumulative MDS graph was plotted from -1 to 1 (normalized arbitrary perceptual units along a pitch dimension). There are 15 ticks on the y axis. Each of these represents the 0 mark of the cumulative MDS graph of the corresponding experiment. This means, for example, that the second tick on the y axis represents the $+1$ mark of experiment 1, the 0 mark of experiment 2, and the -1 mark of experiment 3. Pulse rate (PR), pulse width (PW), and electrode distance (ED) of each experiment are indicated on the right.

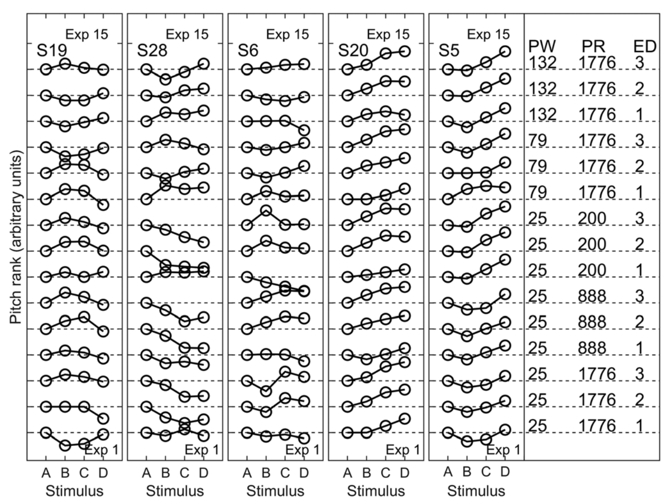

FIG. 2. Cumulative MDS graphs for the last five listeners in Table I. These graphs should be interpreted in the same way as those in Fig. 1. Exp, experiment.

Considering the perceptual distances in pitch in Figs. 1 and 2, no consistent trend appeared across the experiments for all the listeners, but the results of some listeners were similar for certain stimulation parameters. Listener S3, with ear S3R, was the only listener who was able to pitch rank the four stimuli of all 15 experiments in the expected order. The latter was the expected pitch ranking order if sequential current steering was indeed successful in adjusting place pitch. Most listeners were able to distinguish between stimulus A and stimulus D and, as expected, ranked stimulus D higher than stimulus A. However, two listeners, S19 and S28, often ranked stimulus A higher than stimulus D. For a few listeners (e.g., S5 and S28), larger perceptual distances were observed between stimuli for the experiments where wider stimulation pulse widths were used.

There appeared to be a noticeable change in the perceptual distance between stimuli for the experiments where a pulse rate of 200 pps was used. Some listeners, e.g., S3L and S5, seemed to have better pitch ranking ability in these experiments, while others, e.g., S13 and S25, performed well in all the experiments except those carried out at 200 pps. It is of interest to note that the MAP stimulation rates were low for listeners who performed well in pitch ranking at a pulse rate of 200 pps. The MAP stimulation rate of listener S5 was 250 pps, and although the MAP stimulation rate of S3L was 500 pps, the original implant of S3L stimulated at 240 pps. Conceivably, these two listeners were adapted to these lower rates and therefore performed better at these rates. This was explored in the statistical analysis below.

It is of interest to consider the effect of age on the perceptual distances in pitch (Figs. 1 and 2) through some examples. At age 67, S3 was the oldest listener in the study and with ear S3R also the best performer, having ranked the pitch of the four stimuli in the expected order in 15/15 experiments. Her other ear (S3L), however, was a poor performer (pitch ranked in expected order in 4/15 experiments), suggesting that variables other than age had an influence. S13 (aged 66) could pitch rank the four stimuli in the expected order in almost all (13/15) experiments, while S24 (at 26 the youngest listener) could achieve this in 8/15 experiments. In summary, while age-related decline in the auditory processing of spectral information has been reported (Chauvette *et al.*, 2022), there was no clear age-related effect evident in the present data. This was not tested statistically because of the small sample set.

B. Statistical analysis

The MDS results show the perceptual distance between stimuli, as well as the pitch rank order for the four stimuli for each experiment and each ear tested. A multilevel statistical model [linear mixed model (LMM)] was used to assess the effect of the three independent stimulation parameters (PR, PW, and ED) as well as the effect of the variable "listener" (which captured individual differences between the ears tested) on the pitch ranking results.

The underlying hypothesis was that if a current-steering effect could be achieved in the listeners during the pitch ranking experiments, they would always be able to rank the stimuli in an expected order. As a summary measure, the percentage of repetitions to which the response of the listener was as expected (assuming an effective current-steering effect) was calculated. Every stimulus pair in the pitch ranking experiment could lead to either a correct or incorrect result (pitch rank order was according to expectation or not). Results follow a binomial distribution, so that chance level approaches 50% for a large number of trials. The expected order from low to high pitch was assumed to be stimuli A, B, C, and D. The percentages correct (according to expectation) were used as input data for the multilevel analysis.

Data were analyzed with a multilevel LMM. As there were repeated measures within subjects (the same listeners participated in all 15 experiments, and there were five trials per listener per experimental condition), the model was developed as a multilevel LMM with repeated measures in SAS software. The dependent variable was percentage correct. Independent variables were those that were manipulated in the experiments: PW, ED, and PR. The interaction of the MAP pulse rate (PR_{MAP}) with the manipulated pulse rate was included in the final model. This is explained below.

Level 1 in the multilevel model represents the within-listener repeated measures, while level 2 represents the listeners (between-subject factors). The most general model considered containing all the interactions was

$$\begin{aligned} &\mathit{Percentage\ correct} \\ &\quad = b_0 + b_{1j}PR_{ij} + b_{2j}PW_{ij} + b_{3j}ED_{ij} \\ &\qquad + b_{4j}PR * PR_{MAP} + b_{5j}PW_{ij} * PR_{ij} \\ &\qquad + b_{6j}PR_{ij} * ED_{ij} + b_{7j}PR_{ij} * ED_{ij} \\ &\qquad + u_{0j} + \varepsilon_{ij}, \end{aligned} \tag{1}$$

with i the level 1 indexing variable (repeated measures within listeners), j the level 2 indexing variable (listeners), b_0 a fixed intercept estimated from the data, b_{1j} to b_{7j} listener-specific slopes, u_{0j} the intercept variance that modeled the random intercepts across listeners, and ε_{ij} the residual.

The final model was determined through a manual stepwise step-up procedure, commencing from a null model ($\mathit{Percentage\ correct} = b_0 + u_{0j} + \varepsilon_{ij}$) and considering whether the addition of individual fixed effects and random effects would result in a significant change in the log-likelihood.

As outcome of this procedure, the best fitting model included the fixed effects (ED, PR, and PW), interaction between PR and the listener's MAP pulse rate ($PR*PR_{MAP}$), and random slopes across listeners for ED. While the slope for ED varied significantly between listeners (estimated variance = 20.02, Wald $Z = 2.02$, $p = 0.043$), slopes did not vary markedly across listeners for PR and PW (slope

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TABLE V. Estimates of fixed effects in final model.

Parameter	Estimate	Standard error	df[a]	t	Significance p-value	95% confidence interval Lower bound	Upper bound	Effect size: Cohen's f^2
Intercept	64.85	4.52	9.26	14.34	<0.001	54.66	75.03	
PW	0.04	0.01	473.98	4.21	<0.001	0.021	0.059	0.035
ED	2.61	1.47	9.00	1.78	0.108	−0.703	5.93	0.0001
PR	−0.01	0.001	424.23	−8.16	<0.001	−0.014	−0.009	0.116
PR * Map_PR	1.592×10^{-5}	1.610×10^{-6}	404.21	9.89	<0.001	1.275×10^{-5}	1.908×10^{-5}	0.173

[a]Degrees of freedom (df).

variances of 0.00002 and 0.01, respectively; Wald $Z = 1.76$, $p = 0.079$ for PR, and Wald $Z = 2.01$, $p = 0.045$ for PW), so that random slopes for PR and PW were not included in the final model. A weak positive correlation between PW and PR was observed (correlation coefficient of 0.26). Interactions between the independent variables (PR*PW, PR*ED, and ED*PW) were neither significant nor improved the goodness of fit and were therefore not included in the final model.

The final multilevel model was, therefore,

$$Percentage\ correct = b_0 + b_1 PR_{ij} + b_2 PW_{ij} + b_{3j} ED_{ij} + b_4 PR * PR_{MAP} + u_{0j} + \varepsilon_{ij}. \quad (2)$$

Results of the statistical analysis are shown in Table V (estimates of fixed effects) and Table VI (estimates of covariance parameters). The last column in Table V shows effect sizes expressed as Cohen's f^2 (Cohen, 1988), calculated with the method in Selya *et al.* (2012).

R^2 was used as measure of the goodness of fit of the final model. $R^2 = 0.20$, indicating that 20% of the variance in the outcome is explained by the independent variables (PW, ED, and PR). The effect size for the overall model ($f^2 = 0.25$) is moderate to large, indicating that PW, ED, and PR explain 25% of the variance in pitch rank judgments relative to the unexplained variance.

Considering the random effects in the final model, the estimates of the covariance parameters (Table VI) show that there were significant variances in the slopes between listeners for ED; Wald's $Z = 2.02$, $p = 0.044$. The intraclass correlation coefficient (ICC) calculated from Table VI, ICC = 0.74, suggests that the 74% of the variance accounted for in the outcome results from variation between the listeners. This becomes self-explanatory when it is realized that there are many more parameters (including ones that cannot be controlled) that have an impact on the performance ability of each CI user.

As much of the variance accounted for in the outcome was because of individual differences between listeners, an individual-level analysis was carried out. The multilevel model in Eq. (2) was adapted by removing the indexing variable j (listener) so that the random effect, random slopes for ED across listeners (b_{3j}), was replaced with a fixed slope (b_3). This resulted in a fixed effects model that considered the fixed effects of PW, ED, and PR for each listener. The results of this statistical analysis are summarized in Table VII, and Fig. 3 shows the individual outcomes for the ten ears for PW, PR, and ED. The data points are always the average of five trials. To avoid clutter, regression lines are shown only for large effect sizes (Table VII).

The variation across listeners is clear for all three independent variables. Table VII shows that the manipulated variables influenced the ability to pitch rank the stimuli differently across listeners. While variation in PW and PR across listeners is evident in Fig. 3, these slopes are flat relative to that of ED, with slope variance noted above, indicating that large changes in PW and PR do not influence the outcome to the same extent as small changes in ED. As explained earlier, this is why random slopes for PR and PW were not included in the final model.

Without inclusion of the interaction term PR*PR_{MAP} during the step-up procedure, PR did not have a statistically significant effect on the percentage of correct responses, $F(1, 539.5) = 1.94$, $p = 0.164$. However, the individual analyses (Table VII) show that changes in PR did have a significant influence in 7/10 listeners, with moderate to large effect sizes in these listeners.

TABLE VI. Estimates of covariance parameters of the final model.

Parameter		Estimate	Standard error	Wald Z	Significance p-value	95% confidence interval Lower bound	Upper bound
Repeated measures	AR1 diagonal	68.98	3.82	18.05	<0.001	61.88	76.89
	AR1 rho	0.22	0.04	5.88	<0.001	0.15	0.29
Intercept variance across listeners	UN (1,1)	193.95	94.99	2.04	0.041	74.27	506.49
Covariance between intercept and ED	UN (2,1)	−12.22	22.35	−0.55	0.584	−56.03	31.58
Variance of ED across listeners	UN (2,2)	20.45	10.13	2.02	0.044	7.74	54.00

TABLE VII. Individual analyses, indicated effect sizes, and significance of fixed effects. Cohen's f^2 is reported as the measure for effect size.

Listener	Cohen's f^2 for PW	Cohen's f^2 for ED	Cohen's f^2 for PR	p-value for PW	p-value for ED	p-value for PR
S13	0.00	1.71	0.32	0.779	<0.001	<0.001
S25	0.02	0.49	0.54	0.263	<0.001	<0.001
S3L	0.00	0.04	0.18	0.742	0.031	0.004
S3R	0.06	0.01	0.11	0.029	0.460	0.003
S24	0.35	0.01	0.05	<0.001	0.459	0.055
S19	0.00	0.00	0.00	0.923	0.642	0.627
S28	0.99	0.34	0.01	<0.001	<0.001	0.452
S6	0.13	0.66	0.20	0.063	<0.001	0.015
S20	0.07	0.76	0.12	0.026	<0.001	0.004
S5	1.01	0.03	1.27	<0.001	0.174	<0.001

Interestingly, individual estimates of fixed effects showed that for some listeners decreasing the pulse rate resulted in a significantly lower percentage of correct scores, while for other listeners decreasing the pulse rate had the opposite effect or no effect, explaining why the overall analysis did not show an effect of pulse rate. Specifically, listeners S3R, S6, S13, S20, S24, and S25 performed significantly better at the highest stimulation rates, while S19 and S28 showed no significant change in performance at any stimulation rate. S5 and S3L performed significantly better at the lowest rates of stimulation.

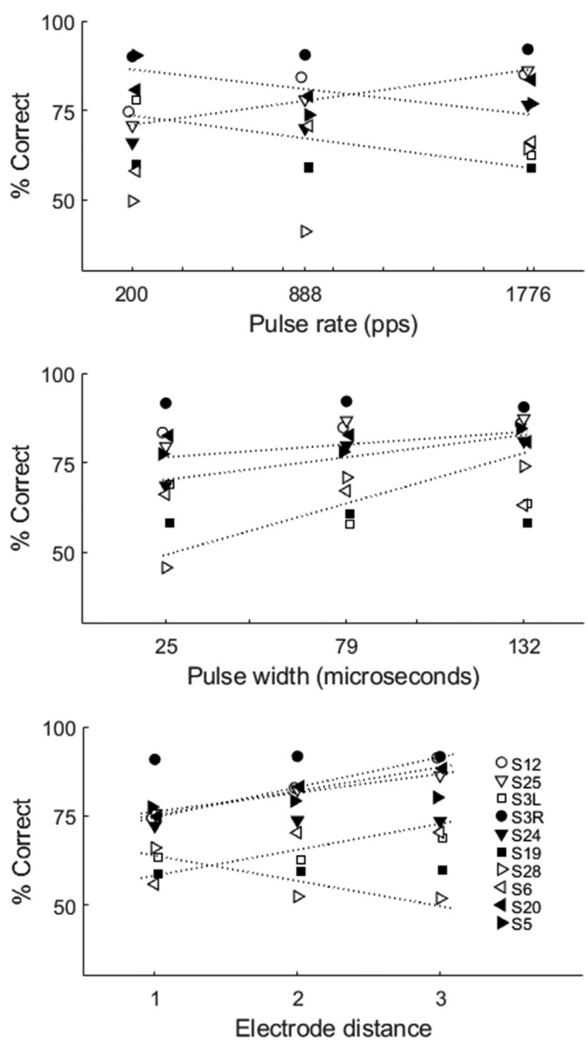

FIG. 3. Percentage of correct responses for the ten ears shown individually as a function of PR, PW, and ED. Each data point represents the average of five trials. To make reading of the graphs easier, data for the listeners are slightly spread apart artificially on the abscissa, and regression lines are shown only where the effect size was large (Table VII). The legend indicates which symbols correspond to which listener.

It is especially interesting to note how the two ears of S3 differed. Table I shows that the stimulation rate in the MAP of S3L (original implant) and of S5 was low (240 and 250 pps, respectively). Of the six ears that performed better at high stimulation rates, five used stimulation rates of 900 or 1200 pps in their MAPs, and S3R used 500 pps. From this it appears as if the clinical stimulation rate may have had an influence on place pitch perception with the tested stimulation rates. This observation motivated the inclusion of the interaction between the tested stimulation rate and the MAP stimulation rate in the model. This resulted in the final model [Eq. (2)] that improved the fit to the data significantly, and in this model PR and the interaction term ($PR*PR_{MAP}$) are both significant (Table V). This supports the notion that a familiar MAP stimulation rate may have influenced the performance of the CI users in the current-steering experiments at different tested rates.

Figure 3 suggests that performance usually improved in the same direction or did not improve when PW was increased. Individual tests of fixed effects showed that PW had a statistically significant effect on the percentage of correct responses of five of the ears tested. Effect sizes were small for two of these five cases (Table VII) and large for S28 and S5.

Electrode separation had a significant effect in 6/10 ears tested, with large effect sizes in five of these listeners. While the ability to pitch rank the stimuli improved as ED increased in these listeners, the opposite was true of S28.

None of the manipulated parameters had any significant influence on the percentage of correct responses of S19, as also seen in Fig. 3. Also, S3R could always rank pitch according to expectation irrespective of variation in the independent variables. This ceiling effect resulted in small effect sizes.

IV. DISCUSSION

The results confirmed that current steering with sequential stimulation may be used to produce pitch shifts in some

CI users, as also concluded by Landsberger and Galvin (2011). In most instances, pitch did change when current was steered from stimulus A to stimulus D (Figs. 1 and 2). Of ten ears tested, nine could rank pitch correctly (using 75% correct as the threshold) in one or more conditions. These figures show that pitch ranking ability depended on parameter choice and that this varied across listeners, suggesting that an individualized approach may be followed to select parameters that could potentially achieve effective manipulation of place pitch with sequential current-steered stimuli. It appears, however, that not all CI users would benefit equally from attempts to manipulate pitch with sequential current-steered stimuli. The study considered to which extent particular stimulation parameters would facilitate the manipulation of place pitch.

A. Electrode separation

Most of the listeners in the present study (9/10 ears) could pitch rank sequential current-steered stimuli correctly in one or more experimental conditions (using 75% correct as threshold) when separation between stimulating electrodes was ED = 3. Each of the three electrode distances were included in five experiments (Table II), so that five comparisons between pitch ranking ability at ED = 1 and ED = 3 could be made for each listener. Pitch ranking ability was better at ED = 3 than at ED = 1 in 37/50 experimental conditions across the ten ears tested.

In summary, pitch ranking ability was often better at larger electrode spacing, which could be ascribed to a more distinctive shift in population of activated nerve fibres than when electrodes are more closely spaced. The amount of shift in the activated neural population will depend on current spread. When electrodes are further apart, these shifts in the excitation pattern are expected to become more salient. The distance between electrodes that would allow place pitch manipulation will depend on the extent to which two electrodes stimulate overlapping neural populations, which is in turn determined by spread of current away from an electrode. Monopolar stimulation leads to relatively large current spread, so that current manipulation on closely spaced electrodes may lead to shifts in the neural excitation pattern that are too small to be salient. Current spread is determined not only by device parameters (the design of the specific electrode array's contacts and the mode used, i.e., a monopolar or bipolar mode), but also by user-specific parameters (electrode placement within a particular CI user's cochlea and the anatomy of the CI user's cochlea, which will determine current pathways). Smaller spread of current should increase the resolution with which pitch manipulations can be done with current steering. Fortunately, it may be possible to adjust spread of excitation in current-steered stimuli through current focusing with multi-electrode stimuli, as shown by Landsberger and Srinivasan (2009) and Padilla *et al.* (2017).

B. Pulse rate

Seen across listeners, the influence of pulse rate was inconsistent, so that pulse rate alone did not have a statistically significant influence on pitch ranking of current-steered stimuli. Pitch ranking ability of 8/10 ears improved significantly in experiments where the stimulation pulse rate was the same as the stimulation rate indicated in the MAP of the CI user. This is reflected in the statistical model, where the inclusion of the $PR{*}PR_{MAP}$ interaction term resulted in a final model where pulse rate is shown to significantly influence the percentage of correct responses. Temporal and place pitch information typically covary in normal hearing, but they are decoupled in CIs. Oxenham *et al.* (2004) showed that stimuli that convey the temporal information of low frequency sinusoids to higher frequency places lead to poor pitch perception of tones in listeners with normal hearing. The authors speculated that this was indicative of the importance of achieving a correct match between place of stimulation and rate of stimulation in CIs. The latter has been the topic of several pitch matching studies where pitch matching between an electrically elicited pitch sensation and an acoustic pure tone was attempted. For example, Schatzer *et al.* (2014) found that for reliable pitch matches between the two ears of CI users with single-sided deafness, there had to be a reasonable match between place of stimulation and rate of stimulation. It should be noted that interaural place pitch matches in CI users are strongly influenced by the conditions tested so that place pitch matches can be unreliable (Goupell *et al.*, 2019). Systematically varying rate and place of stimulation, Landsberger *et al.* (2016) showed that two electrodes stimulated at different rates may have similar pitch but that the sound qualities of the electrodes were typically different, using the descriptors "clean," "noisy," "high," and "annoying" for the pitch sensation. Among others, listeners reported that low rates sounded cleaner on more apical electrodes and less clean on more basal electrodes and that low rates of stimulation sounded noisy on more basal electrodes. Shannon *et al.* (2011) investigated the effect of stimulation rate on speech recognition but also asked listeners to rate the sound quality of the speech presented at the different rates. They found that listeners consistently preferred their everyday speech processors above the experimental processors.

Taken together, these studies show that rate of stimulation influences sound quality, that listeners may have specific preferences for rate of stimulation, and that listeners prefer experimental speech processors that stimulate at the rate set in their MAP. The present data show an advantage for particular stimulation rates when manipulating place pitch. This may be because of the interplay between rate and place of stimulation and the resulting effect on sound quality, so that, for example, the pitch shift in a noisy sound may be more difficult to hear than in a clean sound. Alternatively, this may be because a rate preference has been developed in a particular listener. While not enough data are available to attach significance to this, the present data suggest that stimulation rates that are unfamiliar to the particular CI user may interfere with the cues needed to extract the place pitch created by current-steered stimuli.

C. Pulse width

While the neural activation area would probably covary with pulse width (Zhou *et al.*, 2020), neither the centroid nor the peak position of the neural activation area is predicted to change markedly when pulse width is changed. The present data appear to be consistent with this as stimulation pulse width did not markedly influence pitch ranking ability with sequential current-steered stimuli (while the influence of PW is significant, the effect size is small; Table V), suggesting that the place pitch cues contained in the neural excitation pattern are stable through changes in pulse width. The implication is that varying pulse width to change the neural excitation pattern would not advance the effectiveness of pitch manipulation with sequential current-steered stimuli.

D. Pulse delay

There may be a trade-off between pulse delay and electrode separation that would determine when a single pitch sensation is formed. McKay *et al.* (2001) investigated this interplay in the context of loudness of electrical stimuli. They considered loudness summation of stimuli consisting of pulses on two electrodes, tested at various electrode separations and various delays between the pulses on the two electrodes. The authors argued that, when electrodes are widely spaced, electrical pulses would stimulate distinct neural populations, and they would contribute independently to loudness. Interestingly, even when two electrodes stimulated an overlapping neural population, they found that the distance between the electrodes had little effect on loudness so that the loudness contribution of pulses could be approximated to be independent irrespective of distance between electrodes. This was ascribed to two counteracting effects that may occur when two electrodes activate the same neural population. Within this shared population, fibres are activated by electrical pulse trains from two electrodes so that they are stimulated at twice the rate of the single-electrode pulse rate. However, because of refractory effects, fibres may not fire on each stimulation pulse, so that the net effect in their study was that loudness remained relatively constant as electrode spacing is varied.

One interpretation of the seemingly independent contributions to loudness from pulses on different electrodes may be that electrodes usually stimulate non-overlapping neural populations. There is, however, a large body of evidence that shows that spread of excitation is broad (e.g., Friesen *et al.*, 2001; Zhu *et al.*, 2012), so that apparent independent summation of loudness is not a valid test for the amount of overlap between neural populations stimulated by two electrodes. Rather, an MDS analysis would show whether distinct neural populations were activated (in which case one would expect the MDS to indicate that the pitch sensation had more than one dimension) or whether there was significant overlap in the activated neural populations (in which case the pitch sensation is expected to vary along a single dimension as current was steered). The present data showed that the current-steered pitch sensation varied along a single dimension, implying that the sequential pulses on different electrodes were integrated into a single pitch sensation. It is conceivable that sequential stimulation applied on two electrodes within the refractory period of the nerve fibres or within a temporal integration window may be perceived as a single pitch sensation even when electrodes stimulate non-overlapping neural populations. This has not been tested in the context of place pitch manipulation with sequential current-steered stimuli and requires further investigation.

The objective with stimulation in burst mode when stimulating sequentially was to ensure that interaction would take place at the neural level. This means that nerve fibres in the neural population activated by the second electrode of a current-steering pair may have been in their refractory period, which may have resulted in suppressed excitation to the second pulse. Nerve fibres toward the edges of the activated populations of each electrode would presumably not be subject to refractory effects to the same extent. Therefore, while the objective with the stimulus design was to bring about temporal interaction between electrodes, the resulting refractory effects may have affected the spatial neural excitation pattern as well. Changes in the spatial excitation profile are expected to influence place pitch, but whether this would have enhanced or suppressed pitch differences among stimuli A–D needs further investigation.

E. Loudness of sequential dual-electrode stimuli

While the present study concludes that pitch shifts can be effected in some listeners by sequential current steering, it is clear from previous studies (Frijns *et al.*, 2009; Landsberger and Galvin, 2011) that loudness varies dissimilarly for simultaneous and sequential dual-electrode stimulation, so that control over loudness would require careful consideration when attempting to manipulate pitch with sequential stimulation.

Frijns *et al.* (2009) used computer modeling to predict the neural excitation patterns of dual-electrode current steering for simultaneous and sequential stimuli and compared model predictions of loudness with loudness balancing data in users of the Advanced Bionics HiRes90K CI with the Hifocus 1J electrode array. This device allowed comparison of simultaneous and sequential stimulation in the same listeners. Similarly, Landsberger and Galvin (2011) compared simultaneous and sequential stimulation in the same listeners. Frijns *et al.* defined a steering parameter, α, that characterized the fraction of the total current that was delivered on the more basal electrode. Both of these studies concluded that sequential stimulation required current compensation to maintain equal loudness across current-steered stimuli, so that at $\alpha = 0.5$ (equal current on both electrodes) the summed current for dual-electrode stimuli reached almost double that of the single-electrode currents ($\alpha = 0$ or $\alpha = 1$). In other words, each electrode in a sequential dual-electrode stimulus had to receive approximately the same amount of current as the single-electrode stimulus to maintain equally loud stimuli at $\alpha = 0.5$. In contrast, both studies found that for simultaneous stimulation, equally loud single-electrode and dual-electrode stimuli required that the total current (shared between the two electrodes) remained the same.

To compare present data with those of Frijns *et al.* (2009) and Landsberger and Galvin (2011), the dual-electrode currents of Table III were converted into corresponding α-values using the definition in Frijns *et al*. These calculated α-values varied in a range between 0.47 and 0.53 across the 15 experiments. Therefore, from the conclusions relating to sequential stimulation in Frijns *et al.* and Landsberger and Galvin, the total current for the dual-electrode stimuli of the present experiments was expected to be around twice that of the single-electrode currents to maintain equal loudness. This was indeed the case as can be seen in the example of current adjustments required to achieve equal loudness in Table IV. The values in this table are typical of the outcomes across all loudness balancing tasks, experimental conditions, and listeners. It was consistently found that, to maintain equal loudness in the present experiments ($\alpha \approx 0.5$), relatively small adjustments from single-electrode stimulus levels were required to obtain the current of each electrode in a dual-electrode stimulus. Specifically, of the total number of loudness balancing tasks (10 ears, 15 experiments), current adjustment required to achieve loudness balancing was almost always (in 147 of the 150 loudness balancing tasks) smaller than 10% of the DR of the listener in the specific experimental condition, while the average adjustment was 0.12 CU. This means that, at $\alpha \approx 0.5$, the total current required for sequential dual-electrode stimuli to loudness match single-electrode stimuli varied in a narrow range that was around twice that of the single-electrode currents, corresponding to the findings of Frijns *et al*. and Landsberger and Galvin.

As noted before, this current adjustment was not required for the simultaneous stimuli of Frijns *et al*. (2009) or Landsberger and Galvin (2011). Considering this from a different viewpoint, as α was varied in simultaneous stimulation, the current on each electrode of a dual-electrode stimulus had to be decreased relative to that of the single-electrode stimuli ($\alpha = 0$ and $\alpha = 1$) so that total current remained constant to ensure that loudness was maintained. The current on each electrode needed to be halved at $\alpha = 0.5$. On the other hand, to achieve equal loudness between sequential dual-electrode and single-electrode stimuli at $\alpha \approx 0.5$ requires little adjustment to the current levels of the former relative to the current levels of the latter, typically smaller than 10%.

F. Implications

First, while the pattern of pitch changes for sequential current steering was not consistent across all listeners in the present study, the data indicate that place pitch could indeed be manipulated by sequential current steering and that an individualized selection of stimulation parameters may be needed to effect pitch changes. This suggests that it should be possible to improve place pitch resolution with sequential stimulation in some CI users implanted with electrode arrays that have wider electrode spacing. Examples of these are the Standard Med-El electrode array from their Classic series or the Med-El Flexsoft array, both with electrode spacing of 2.4 mm. This is similar to the maximum distance between electrodes tested in the present study (2.1 mm), suggesting that current steering with sequential stimuli may be effective in creating intermediate pitches between those associated with two adjacent electrodes in these arrays.

In addition, similar to simultaneous current steering (Snel-Bongers *et al*., 2011), sequential current steering may be useful in bridging single-electrode failures in arrays where electrodes are spaced closely enough, potentially restoring the normal pitch resolution of the particular electrode array design. Examples of these are the Contour Advance or Straight electrode arrays of the Nucleus CI, where electrode bands are 0.7 and 0.75 mm apart, respectively. Current steering would probably not be effective in replacing a failed electrode in an array where electrodes are much further apart.

Second, loudness will vary as α is varied in dual-electrode sequential stimulation (Frijns *et al*., 2009), so that speech processor algorithms that attempt to effect intermediate pitches with sequential current steering will require more sophistication in determining the correct current levels for dual-electrode stimuli than in the case of simultaneous current steering. The latter requires no or small adjustments of current to maintain equal loudness with varying α (Donaldson *et al*., 2005; Frijns *et al*., 2009). If, however, $\alpha = 0.5$ is selected as the current-steering condition in dual-electrode sequential stimulation, the present data as well as those of Frijns *et al.* (2009) and Landsberger and Galvin (2011) suggest that loudness changes may be imperceptible or small when the single-electrode current levels are retained in the dual-electrode stimuli.

Third, pitch shifts will probably only be effected if specific stimulus conditions are met. High stimulation levels [close to MCL as used in the present experiments and in Frijns *et al*. (2009)] may be required to ensure that activated neural populations overlap, and electrode spacing should be small enough to ensure neural overlap (McDermott and McKay, 1994). It will probably be necessary to ensure temporal integration of sequential stimuli by stimulating different electrodes within a time delay expected to result in interaction between neural responses. With these stimulus conditions met, intermediate place pitches could be effected with sequential stimulation in some CI users. While meeting these stimulus conditions mentioned will not guarantee that pitch shifts can be effected in all listeners, an important implication is that unintended occurrence of pitch shifts should be expected in some CI users under normal listening conditions when listening with their everyday MAP. This is so because adjacent electrodes are stimulated in quick succession in typical sequential stimulation speech processing strategies, and if two adjacent or nearby electrodes activate overlapping neural populations at relatively high levels of stimulation, the present data suggest that pitch shifts will occur for some CI users. These may be time-varying pitch shifts at multiple places along the cochlea. It is not clear to what extent this will affect speech perception. It is known that frequency mismatches between the target frequency and the perceived pitch influence speech understanding (Di Nardo *et al.*, 2010), but also that large frequency mismatches are generally expected in CIs (Landsberger *et al.*, 2015), so that any additional pitch shifts from unintentional current steering may be inconsequential for speech perception. If, however, these pitch shifts were found to interfere with speech perception, the effect may be mitigated by staggering the order of electrode stimulation (Todd and Landsberger, 2018). This will require further investigation.

[1]To explain the terminology preferred in this article: Although the perceptual distance considered was pitch difference between stimuli, the more general reference to perceptual distance was generally preferred. As the actual pitch difference between two stimuli was not determined through pitch matching experiments, referring to "perceptual distance between two pitches" is technically a more correct description than referring to "pitch difference."

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