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Effect of signal processing strategy and stimulation type on speech and auditory perception in adult cochlear implant users

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Abstract

Objective: The objective of this study was to investigate the effects of signal processing strategy on speech understanding and auditory function for adult cochlear implant (CI) users with a focus on the effects of sequential versus paired stimulation.

Design: Within-subjects, repeated measures design was utilised to compare performance between processing strategies and stimulation type on various measures of auditory function and subjective sound quality. Testing with subsequent strategies was completed after a total familiarisation time of two weeks.

Study Sample: Ten post-lingually deafened adult CI users were recruited from a clinical population. Participants had a minimum of 13 months CI experience. Ages ranged from 25–78 years. All participants had long-term experience with the optima strategy; eight with sequential stimulation and two with paired stimulation.

Results: We found no statistically significant effect of processing strategy. We observed an effect of stimulation type with sequential stimulation yielding significantly higher performance than paired stimulation for speech understanding in quiet and in noise, and subjective estimates of sound quality. No significant differences were noted across strategy or stimulation for music perception, spectral resolution or temporal resolution.

Conclusions: Many patients utilise paired stimulation – the default stimulation type in the clinical software; however, sequential stimulation yielded significantly higher outcomes on multiple measures.

Keywords

Cochlear implants; signal processing; programming; speech recognition; temporal resolution; spectral resolution; music perception; sound quality

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Disclosure statement

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Introduction

Cochlear implantation (CI) is the standard of care treatment for adults with moderate sloping to profound sensory hearing loss and great difficulty understanding speech. Postoperative speech understating has steadily increased over time, largely due to changes in speech processing strategies such as continuous interleaved sampling (CIS) (Wilson et al. 1991) and n-of-m signal processing (Skinner et al. 1994). Other variables have also likely contributed to advancing patient outcomes including minimally traumatic surgical techniques, commercial availability of atraumatic electrodes, the use of electric-acoustic stimulation for those with residual low-frequency hearing, and expansion of CI criteria (e.g. Gifford et al. 2010; Von Ilberg et al. 2011; Amoodi et al. 2012; Arnolder and Lin 2013).

The electric representation of the acoustic information transmitted through a CI can vary based on processing strategy and can have an effect on temporal and spectral properties of the incoming signal. Most CI processing strategies are envelope based and utilise amplitude modulation of a biphasic current pulse train. That is, the processor extracts the temporal envelope for bandpass filters associated with each individual electrode and then modulates a pulse train with the channel specific, amplitude envelope. Frequency-specific information is transmitted via place of stimulation as stimulation rate is constant across channels. There are newer processing strategies that attempt to manipulate spectral and/or temporal coding through current steering (AB: Fidelity-120 and Optima) or variable stimulation rate (MED-EL: FSP, FS4, and FS4p). Despite the availability of these specialised strategies, it is unclear whether current steering (Brendel et al. 2008; Advanced Bionics, 2008; Buechner et al. 2008; Donaldson, Dawson, and Borden 2011; Drennan et al. 2010; Firszt et al. 2009) or variable stimulation rates (Riss et al. 2014; Mlynski et al. 2016; Zirn et al. 2016) provide significant advantages for speech understanding and/or music perception.

Spectral resolution

Spectral resolution is the ability of the auditory system to resolve the individual frequency components of a complex sound. Studies have shown that only 4–10 independent channels are resolved by adult CI recipients (e.g. Kileny et al. 1992; Fishman, Shannon, and Slattery 1997; Friesen et al. 2001, Shannon, Cruz, and Galvin 2011). The limitation in resolution of spectral channels is thought to be due to both channel interaction (i.e. spread of excitation) and unknown neural survival (Koch et al. 2007; Nelson, Donaldson, and Kreft 2008; Drennan et al. 2010; Donaldson, Dawson, and Borden 2011). To help overcome this limitation, “virtual channels” created via current steering allow for up to 8 individual pitch percepts between the adjacent electrode pairs (e.g. Koch et al. 2007; Firszt et al. 2007). To accomplish this, adjacent electrodes are stimulated simultaneously which will result in a peak in current between the two stimulating electrodes. The peak of the electrical current is “steered” between the electrodes by varying the current amplitude to the electrodes (Townshend et al. 1987; Donaldson, Kreft, and Litvak 2005; Koch et al. 2007; Bonham and Litvak 2008; Saoji, Litvak, and Hughes 2009; Donaldson, Dawson, and Borden 2011). Because current steering potentially allows for more spectral channels than the number of discrete contacts, current steering may result in improved spectral resolution (Drennan et al. 2010) and speech recognition (Firszt et al. 2009).

Fidelity-120 with current steering yielded significant improvements in speech perception of monosyllabic words and sentences in quiet and in noise (presented at +8 dB SNR) as compared to HiRes strategies (Advanced Bionics, 2008). However, as Donaldson, Dawson, and Borden (2011) reported, the stimulation rate was not controlled or tracked across subjects. The stimulation rate of HiRes-P is roughly two times that of Fidelity-120 while this difference does not occur between HiRes-S and Fidelity-120. Thus, the difference in stimulus rate may have impacted outcomes.

Brendel et al. (2008) reported improvements in speech perception with a single competing talker using a current steering strategy, Fidelity HiRes-120 versus HiRes. Firszt et al. (2009) reported similar findings indicating a benefit in using Fidelity-120 over HiRes for monosyllabic words and sentence recognition in noise. Donaldson, Dawson, and Borden (2011) reported a significant effect of HiRes over Fidelity 120 for consonant recognition, but no differences on other measures of speech understanding in a unilateral CI listening condition. While Fidelity-120 may not have a consistent impact on speech recognition, increasing the availability of between-electrode pitch percepts could have an impact on music perception as shown through significantly higher music perception ratings using Fidelity-120 versus HiRes (Firszt et al. 2009) as could the manipulation and/or addition of front-end processing such as addition of noise reduction strategies (Koch et al. 2014; Wolfe et al. 2015), microphone directionality (Geißler et al. 2015; Buechner et al. 2014; Goldsworthy et al. 2014), and variation in automatic gain control time constants (Boyle et al. 2009; Boyle and Moore 2015; Khing, Swanson, and Ambikairajah 2013).

Temporal resolution

Temporal resolution is the ability of the auditory system to detect changes in amplitude over time. Research has shown that stimulation rates can influence temporal resolution. One theory is that higher channel stimulation rates should deliver a finer representation of temporal information, elicit stochastic neural activity, and therefore, improve speech perception (e.g. Wilson, Lawson, and M. Zerbi 1995; Wilson et al. 1997; Kiefer et al. 2000; Loizou, Poroy, and Dorman 2000; Rubenstein and Hong 2003). In contrast, other studies have shown that high pulse rates can impair the transmission of temporal information (Middlebrooks 2008; Galvin and Fu 2009). Research has provided mixed results with some studies demonstrating significantly improved speech understanding with higher rates (e.g. Loizou, Poroy, and Dorman 2000; Kiefer et al. 2000; Frijns et al. 2003; Nie, Barco, and Zeng 2006) and others showing little to no difference for rates above ~400–600 pulses per second (pps) (e.g. Holden et al. 2002; Friesen, Shannon, and Cruz 2005; Shannon, Cruz, and Galvin 2011).

Effects of strategy and stimulation

Strategies incorporating paired stimulation can result in a doubling of stimulation rates as compared to sequential strategies; but, concerns regarding channel interaction may mitigate the positive effects of rate (Buechner et al. 2005). Research has yielded mixed results with some studies showing significant improvement in speech understanding for sequential stimulation (sentences in noise and monosyllables: Buechner et al. 2005) and others

documenting no difference in performance across paired and sequential strategies (sentences in quiet: Buechner et al. 2005; sentences in noise: Dunn et al. 2006).

Various aspects of CI stimulation could impact auditory perception; however, results have typically been mixed regarding strategy efficacy. To our knowledge, the impact of these different strategies and stimulation options within each strategy has never been studied systematically in a within-subjects design. Advanced Bionics currently provides three different processing strategies: HiRes, Optima, and Fidelity-120 and the option to choose between simultaneous and paired stimulation for each of these strategies, providing six potential options for clinical use. HiRes is a traditional high-rate, CIS-based strategy. Fidelity-120, as mentioned previously, is also a CIS-based strategy also utilising current steering via simultaneous stimulation between adjacent electrodes. Optima evolved from Fidelity-120 with the exception that it is designed to limit power consumption as two (S) or four (P) electrodes are always stimulated to lower the overall charge requirements for auditory perception.

The purpose of this study was to investigate the effect of processing strategy and stimulation on various measures of auditory function including spectral resolution, temporal resolution, music perception, speech perception and subjective sound quality in order to provide an evidence base for clinical programming recommendations. Our hypotheses were that (1) HiRes strategies would yield better temporal resolution than current steering strategies per Drennan et al. (2010), (2) current steering strategies would provide better spectral resolution than HiRes strategies (Drennan et al. 2010), (3) current steering strategies would yield better music perception than HiRes strategies – with Fidelity120 resulting in better outcomes than Optima, given the potential finer spectral detail with 1 or 2 channels stimulated simultaneously (Fidelity120) as compared to permanent simultaneous stimulation with Optima and (4) sequential stimulation would result in better spectral resolution, speech recognition, and subjective sound quality judgements than paired strategies due to the potential for less channel interaction.

Methods

Participants

Ten experienced adult CI users participated in this study. Each participant had at least 13 months (average of 54.7 months) of listening experience with their CI and were all post-lingually deafened. Participant ages ranged from 25 to 78 years (mean = 53 years) with 7 males and 3 females. Eight participants had been using Optima-S and two were using Optima-P as their everyday strategy upon enrolment. Participant demographic information is displayed in Table 1.

Each participant completed two study visits. The first visit involved a baseline assessment of speech understanding, music perception and basic auditory function using the participant's own everyday strategy and stimulation type. After baseline assessment, the subjects' sound processors were reprogrammed with the remaining five combinations of strategy and stimulation. New maps were based on the subjects' original clinical programme. Only processing strategy, stimulation and global adjustments to M levels were adjusted to achieve

equivalent loudness across programmes – per listener report – in order to emulate changes that might be made in a clinical setting and to limit the potential confounds of across-electrode changes or other programming variables. Pulse duration was calculated automatically using the automatic pulse width algorithm, APWII, which is designed to provide the narrowest pulse duration, and thus fastest rate, while ensuring that upper stimulation levels do not exceed voltage compliance limitations based on electrode impedances and charge required for upper stimulation levels. This is the default pulse duration setting and was chosen to most closely match clinical practice. As a result, the channel stimulation rate did vary across the strategies with paired stimulation resulting in higher stimulation rates most pronounced for the HiRes strategies. The mean channel stimulation rates, in pulses per second (pps), for sequential and paired strategies for each participant are shown in Table 1.

Participants were instructed to use each of the five new programmes equally over a two-week period by switching programmes approximately every two hours, every day. We recognise that this familiarisation strategy is not necessarily consistent with typical CI usage patterns nor with typical research-based familiarisation in the literature (e.g. Firszt et al. 2009; Donaldson, Dawson, and Borden 2011). However, we consulted with 3 audiologists in our clinic who are all CI recipients to determine a familiarisation method for which participants would be compliant that would also minimise disruption of everyday listening activities should one or more programmes yield less than desirable sound quality and/or speech understanding.

The second visit consisted of repeat testing on all assessments completed at the first visit using each of the five new programmes. Participant compliance for programme use was verified via data logging. Table 2 displays individual and mean programme or slot usage, in % total time, derived from the data log reports. Though the percentages were not equivalent, each participant used each of the 5 programmes. Because the programme assignment for each participant was counterbalanced, the strategy and stimulation type in each of the five programme slots was different for each participant. Despite this, each participant seemed to converge on Fidelity120-S as that represented the highest percentage of use followed by Fidelity120-P, HiRes-S, HiRes-P, and Optima-P (or Optima-S for the two subjects who had been using Optima-P). For our first two enrolled participants, we lost the datalogs and visit history reports following research and clinical database merging.

Experimental tasks

Baseline testing and subsequent testing order was determined by a randomised Latin square and included spectral modulation detection (1 cyc/oct), amplitude modulation detection (4 and 200 Hz), musical chord discrimination (spectral), musical beat alignment task (BAT) (temporal), speech understanding in quiet and noise, and qualitative sound quality judgements. Participants completed each test using all six possible strategy and stimulation combinations. The 7 unilaterally implanted participants with hearing in the non-CI ear wore an earplug during testing. Audiometric thresholds in the non-CI ear were sufficiently high (i.e. poor) such that plugging the ear resulted in no acoustic perception of the presented stimuli see (Table 1) for pure tone average (PTA), in dB HL, in the non-CI ear. The 3

bilaterally implanted participants simply removed the other processor as none of the participants had hearing preservation in the implanted ear(s). Details regarding each of the tasks are provided below.

Spectral modulation detection

Spectral modulation detection was assessed via the acoustic quick spectral modulation detection (acoustic QSMD, Holder, Levin, and Gifford 2018) task at a calibrated level of 60 dB SPL presented in the soundfield. Participants were presented with a 3-interval forced choice task in which two presentation intervals contained flat spectrum noise and the third was spectrally modulated. Spectral modulation was accomplished through applying logarithmically spaced, sinusoidal modulations to a broadband carrier stimulus (125–5600 Hz). For the acoustic QSMD task, six trials are presented for each of ten modulation depths ranging from 4–22 dB, in 2-dB steps with a fixed spectral modulation rate of 1.0 cycle/oct for a total of 60 trials per condition. No feedback was provided.

Temporal modulation detection

Temporal modulation detection was evaluated using sinusoidal amplitude modulation (SAM) at 4 and 200 Hz. The carrier stimulus was a broadband noise with high- and low-pass cut-offs of 100 Hz and 6000 Hz, respectively. A two-interval forced choice paradigm was used in which listeners selected which of the two intervals contained SAM using a response box. Visual feedback was given after each response. Stimulus duration was 500 ms (10 ms rise/fall times). Each run started at a modulation depth of –12 dB corresponding to a modulation index (m) of 0.25. An adaptive tracking procedure utilising a 2-down, 1-up stepping rule was used converging on 70.7% correct (Levitt 1971). There was a maximum of 60 trials per run with a run terminating after 8 turnarounds. The tracking used 4-dB steps for the first two turnarounds and 2-dB steps for the last six turnarounds. Stimuli were presented through Sennheiser HD 265 linear circumaural headphones at a level of 60 dB SPL, calibrated using a Larson Davis AEC201-A Ear Simulator. These large circumaural headphones were placed over the CI sound processors. Two runs were completed at each modulation rate. If SAM thresholds differed by more than 3 dB across the two runs, a third run was completed and the threshold was calculated as the mean across the three runs. In the event that a threshold could not be obtained (i.e. the participant could not reliably track threshold even with 100% modulation), the SAM threshold was recorded as 0 dB ($m = 1.0$) for analysis and presentation.

Chord discrimination

Musical based spectral resolution was completed using chord discrimination. Participants were presented with a two-alternative forced choice task in which they indicated if two chords they heard were “same” or “different” using a response pad. Chords were presented as dyads, triads and tetrads as major or minor chords. Fundamental frequency of each chord ranged from 220.0 to 1046.5 Hz. All 105 trials were randomised and presented for each condition with 50% of stimuli being the same and 50% of stimuli being different. The chord stimuli were delivered via direct connect at a level deemed to be most comfortable for each listener. Participants were instructed to indicate whether they would like the level of the stimulus increased or decreased and the presentation level was set accordingly.

Beat alignment task (BAT)

Temporal judgement of the beat in combination with a spectro-temporally complex stimulus was measured using the Beat Alignment Task (BAT) (Iverson and Patel 2008). Subjects listened to musical excerpts from various genres (average duration of 15.9 s) with an evenly timed train of beeps superimposed over the music (1-kHz tone, 100-ms duration). The timing of the beeps with respect to the musical excerpt was varied in tempo and phase. Tempo-error stimuli were altered to have an inter-tap interval (ITI), the time between the beats, of 10% shorter or longer than the on-beat version. Phase-error stimuli used the on-beat ITI but varied the phase by +25% and -25% of the ITI. Participants were instructed to indicate whether the beeps superimposed over the music were “on the beat” or “off the beat” of the musical excerpt using a response pad. Stimuli were delivered through direct connect at a level deemed the most comfortable level for each listener. Participants were familiarised with the stimuli prior to each trial and were instructed not to tap or move their body rhythmically with the music.

Speech perception

Speech perception was assessed using consonant-nucleus-consonant (CNC) words (Peterson and Lehiste 1962) in quiet and AzBio sentences (Spahr et al. 2012) at +5 dB signal to noise ratio (SNR) – measures currently included in the adult Minimum Speech Test Battery (MSTB 2011). One CNC list (50 words) was presented in quiet for each condition. One AzBio list (20 sentences) was presented at +5 dB SNR using 20-talker babble, for each condition. Recorded stimuli were presented at a calibrated level of 60 dB SPL (A weighted) at 0 degrees azimuth in the soundfield. During speech testing in noise, noise and speech were collocated at 0 degrees azimuth. CNC and AzBio list numbers were recorded to avoid repetition for a given subject.

Sound quality judgement

After speech perception testing, listeners were asked to rate subjective sound quality, irrespective of performance, using a numerical visual analogue scale with 1 being extremely poor sound quality and 10 being the best sound quality. Rating of initial processing strategy was completed at the first visit and subsequent ratings for remaining programmes were gathered after speech testing was completed at the second visit.

Analysis

All statistical analyses were completed using IBM SPSS Statistics version 25 (Armonk, NY). For all analyses, we used a linear mixed model with strategy (HiRes, Optima, and Fidelity-120) and stimulation (paired versus sequential) as the primary variables impacting performance for speech recognition, sound quality, and auditory function. *Post hoc*, all-pairwise multiple comparisons were completed using the Holm-Sidak statistic. Two subjects (1, 2) did not complete the BAT, qualitative judgements, or initial amplitude modulation testing at 200 Hz.

Results

Effect of stimulation on M levels

Table 3 displays mean M levels averaged across all electrodes for each of the strategies (HiRes, Optima, and Fidelity-120) and stimulation types (paired and sequential). There was no statistically significant effect of strategy [$F_{(2,54)}=0.06$, $p = 0.94$, $\eta_p^2=0.002$], a significant effect of stimulation [$F_{(1,54)}=12.85$, $p = 0.0001$, $\eta_p^2=0.20$], and no interaction [$F_{(2,54)}=0.01$, $p = 0.98$, $\eta_p^2=0.0004$]. Thus, M levels were higher for sequential as compared to paired stimulation, as expected. Mean M levels, collapsed across strategy, were 242.2 and 188.2 clinical units for sequential and paired stimulation, respectively.

SAM detection

For SAM detection, we investigated main and interaction effects for strategy (HiRes, Optima, and Fidelity-120), stimulation (paired versus sequential), and modulation rate (4 and 200 Hz). We found no effect of strategy [$F_{(2,106)}=1.6$, $p = 0.21$, $\eta_p^2=0.03$], no effect of stimulation [$F_{(1,106)}=3.7$, $p = 0.057$, $\eta_p^2=0.031$], a significant effect of modulation rate [$F_{(1,106)}=544.07$, $p < 0.0001$, $\eta_p^2=0.99$], and no three-way interaction [$F_{(7,106)}=0.66$, $p = 0.71$, $\eta_p^2=0.04$]. Collapsed across strategy and stimulation, mean SAM detection thresholds were -15.5 and -2.3 dB for 4 and 200 Hz, respectively. Figure 1(A,B) displays individual and mean SAM detection thresholds for 4 Hz and 200 Hz, respectively.

Speech perception: CNC and AzBio at +5 dB

Figure 2 shows individual and mean CNC word recognition and AzBio sentence recognition at +5 dB SNR, both in percent correct, as a function of processing strategy. For CNC word recognition (Figure 2, left panel), we found no effect of strategy [$F_{(2,54)}=0.25$, $p = 0.78$, $\eta_p^2=0.009$], a significant effect of stimulation [$F_{(1,54)}=7.4$, $p = 0.009$, $\eta_p^2=0.12$], and no interaction [$F_{(2,54)}=0.05$, $p = 0.95$, $\eta_p^2=0.002$]. Sequential stimulation yielded significantly higher CNC scores as compared to paired stimulation with mean CNC scores, collapsed across strategy, of 72.8% and 60.5% for sequential and paired stimulation, respectively. Individual CNC word recognition scores ranged from 22 to 94% correct.

For AzBio sentence recognition at +5 dB SNR (Figure 2, right panel), we found no effect of strategy [$F_{(2,54)}=0.32$, $p = 0.73$, $\eta_p^2=0.01$], a significant effect of stimulation [$F_{(1,54)}=6.4$, $p = 0.01$, $\eta_p^2=0.11$], and no interaction [$F_{(2,54)}=0.15$, $p = 0.86$, $\eta_p^2=0.006$]. Sequential stimulation yielded significantly higher AzBio sentence recognition in noise scores as compared to paired stimulation with mean AzBio sentence recognition at +5 dB – collapsed across strategy – of 28.0% and 15.6% for sequential and paired stimulation, respectively. Individual AzBio sentence recognition in noise scores ranged from 0 to 89% correct.

Sound quality judgement for speech stimuli

Figure 3 shows individual and mean sound quality judgements with respect to processing strategy and stimulation. Statistical analysis revealed no effect of strategy [$F_{(2,42)}=2.8$, $p = 0.07$, $\eta_p^2=0.12$], a significant effect of stimulation [$F_{(1,42)}=9.7$, $p = 0.003$, $\eta_p^2=0.19$], and no interaction [$F_{(2,42)}=0.12$, $p = 0.89$, $\eta_p^2=0.004$]. Sequential stimulation yielded significantly higher sound quality estimates as compared to paired stimulation with mean sound quality

estimates, collapsed across strategy, of 7.1 and 5.6 for sequential and paired stimulation, respectively. Individual sound quality ratings ranged from 2 to 10.

Prior listening experience

Because two of the participants had long-term experience with paired stimulation and eight participants had long-term experience with sequential stimulation, we completed an additional analysis of stimulation type and experienced stimulation type on measures of speech recognition and sound quality. Because we found no effect of strategy for speech recognition or for sound quality, we averaged scores across strategy for these analyses. Linear mixed model analyses were completed investigating main effects for prior stimulation experience (sequential vs. paired) and interaction effects for stimulation type (sequential vs. paired) and prior stimulation experience. We did not re-run the main effects for stimulation type given the main effects previously reported. For CNC word recognition, statistical analysis revealed no effect of prior experience [$F_{(1,16)}=0.04$, $p = 0.85$, $\eta_p^2=0.002$] and no interaction between stimulation type and prior experience [$F_{(2,16)}=2.96$, $p = 0.08$, $\eta_p^2=0.27$]. Similarly, for AzBio sentence recognition at +5 dB, there was no effect of prior experience [$F_{(1,16)}=0.33$, $p = 0.58$, $\eta_p^2=0.02$] and no interaction between stimulation type and experience [$F_{(2,16)}=3.06$, $p = 0.075$, $\eta_p^2=0.28$]. Finally for sound quality estimates, there was no effect of prior experience [$F_{(1,12)}=3.84$, $p = 0.07$, $\eta_p^2=0.24$] and no interaction between stimulation type and experience [$F_{(2,12)}=0.66$, $p = 0.53$, $\eta_p^2=0.10$]. These analyses revealed that stimulation type for which the listener had most experience did not significantly affect speech recognition or estimates of sound quality.

Quick spectral modulation detection (QSMD) task

Figure 4 displays individual and mean QSMD scores, in overall percent correct. For the QSMD task, we investigated main and interaction effects for strategy (HiRes, Optima, and Fidelity-120), stimulation (paired vs. sequential), and modulation depth (22, 20, 18, 16, 14, 12, 10, 8, 6, and 4 dB). Statistical analysis revealed no effect of strategy [$F_{(2,540)}=2.2$, $p = 0.11$, $\eta_p^2=0.008$], no effect of stimulation [$F_{(1,540)}=2.1$, $p = 0.15$, $\eta_p^2=0.004$], a significant effect of modulation depth [$F_{(9,540)} = 16.8$, $p < 0.001$, $\eta_p^2=0.22$], and no three-way interaction [$F_{(47,540)}=0.52$, $p = 0.99$, $\eta_p^2=0.04$]. *Post hoc* analyses were not completed for modulation depth as this is an expected effect and not related to the current research questions. Individual performance, averaged across modulation depth, ranged from 22% (below chance) to 88% correct.

Music perception (chord discrimination and BAT)

Figure 5 displays individual and mean chord discrimination and BAT performance, both in percent correct. For chord discrimination (Figure 5, left panel), there was no effect of strategy [$F_{(2,54)}=0.04$, $p = 0.96$, $\eta_p^2=0.001$], no effect of stimulation [$F_{(1,54)}=0.13$, $p = 0.72$, $\eta_p^2=0.002$], and no interaction [$F_{(2,54)}=0.007$, $p = 0.99$, $\eta_p^2=0.0002$]. Mean performance, collapsed across strategy and stimulation, was 64.6% with individual scores ranging from 63.3% to 65.2%. Given that chance performance was 50% for this measure, all participants demonstrated poor chord discrimination. For overall performance on the BAT (Figure 5, right panel), there was no effect of strategy [$F_{(2,42)}=0.07$, $p = 0.93$, $\eta_p^2=0.003$], no effect of stimulation [$F_{(1,42)}=0.15$, $p = 0.70$, $\eta_p^2=0.004$], and no interaction [$F_{(2,42)}=1.47$, $p = 0.24$,

$\eta_p^2=0.024$]. Mean BAT performance, collapsed across strategy and stimulation, was 66.0% with individual scores ranging from 60.0% to 71.3% correct.

Discussion

The primary aim of this study was to investigate the effects of processing strategy and stimulation on various measures of speech recognition and auditory function in order to provide an evidence base for clinical programming recommendations. Our hypotheses were that (1) HiRes strategies would yield better temporal resolution than current steering strategies (per Drennan et al. 2010), (2) current steering strategies would provide better spectral resolution than HiRes strategies (Drennan et al. 2010), (3) current steering strategies would yield better music perception than HiRes strategies, and (4) sequential stimulation would result in better spectral resolution, speech recognition, and subjective sound quality judgements than paired strategies due to the potential for less channel interaction.

Research design

Upon reprogramming each participant's sound processor with five new strategies, participants were instructed to use each of the five strategies equally over a two-week period by switching between programmes approximately every two hours. This was based on discussions with CI users regarding a familiarisation method that would promote compliance while minimising disruption to everyday listening. While all participants utilised each programme, programmes were not always utilised an equal amount (Table 2). Thus, we recognise that the familiarisation time may not have been sufficient for all participants. If more time was allotted for familiarisation with each new combination of strategy and stimulation type, it is possible that results may be affected.

Temporal resolution (SAM detection and BAT)

We had hypothesised that HiRes strategies would yield better temporal resolution as compared to current steering strategies (Optima and Fidelity-120). This hypothesis was based on results presented by Drennan et al. (2010) who had shown significantly better discrimination of Schroeder phase complexes for HiRes as compared to current steering strategies. They theorised this effect to be due to the introduction of fluctuations in the temporal envelope resulting from current steering strategies that were uncorrelated with the incoming signal. However, we did not observe an effect of strategy for SAM detection nor for the temporal-based perception of music using the BAT. The differences in the current study and those reported by Drennan et al. (2010), may be due to the choice of stimuli and tasks investigating temporal resolution. In the current study, we employed SAM detection tasks using a broadband carrier as well as a more spectro-temporally complex signal with the music-based BAT.

Though we did not observe a significant effect of strategy for temporal resolution, we did see a trend for better performance with HiRes over current steering strategies (Optima and Fidelity-120), most notably at 200 Hz. For SAM detection, mean thresholds collapsed across stimulation type for 4 Hz were -15.9 , -15.6 , and -15.0 dB for HiRes, Optima, and Fidelity-120, respectively. For 200 Hz, mean thresholds collapsed across stimulation were

–3.2, –1.7, and –1.8 dB for HiRes, Optima, and Fidelity-120, respectively. Although this did not reach statistical significance, the trend for lower (i.e. better) SAM thresholds at 200 Hz for HiRes over current steering strategies is consistent with Drennan et al. (2010) as well as Green, Faulkner, and Rosen (2004), the latter of which showed that temporal modulation detection was better in the absence of dynamic spectral changes, or when stimulation was limited to a fixed location.

Spectral resolution (QSMD and chord discrimination)

We had hypothesised that current steering strategies would provide better spectral resolution than HiRes strategies. However, we found no effect of strategy on QSMD with a rate of 1 cyc/oct nor for spectral-based perception of music using a task of chord discrimination. For QSMD, we anticipate that lack of an effect may be related to large between-subject variability with performance ranging from below chance up to 88% correct (collapsed across modulation depth), considerable channel interaction with all strategies and stimulation types, and information transmission using envelope-based strategies. This finding is in opposition to Drennan et al. (2010) who found that Fidelity-120 strategies yielded better spectral ripple discrimination than HiRes strategies. It is important to note that spectral ripple discrimination incorporated an adaptive psychoacoustic task resulting in ripple discrimination thresholds ranging from just below 2 to over 6 ripples/oct. The QSMD task as used in this study, however, was based on a method of constant stimuli using a single modulation rate (1 cyc/oct) to serve as a quick measure relevant for clinical use. Thus, it is possible that neither the QSMD task nor the chord discrimination task was sensitive enough to reveal differences in spectral resolution across strategies.

Music perception

In theory, current steering programmes, specifically Fidelity-120, hold potential for greater music-based spectral resolution; however, as described above, we did not observe an effect of strategy for musical chord discrimination. The range of scores for this task was 63.3%–65.2%, which was only slightly higher than chance (50%). Though listeners with normal hearing can discriminate <1 semitone, it takes between 3.0 and 7.5 semitones, on average, for adult CI users to detect a difference in pitch (e.g. Fujita and Ito 1999; Kang et al. 2009; Drennan et al. 2015). Chords presented in this study only differed by one semitone, which was likely not a perceptual difference for many subjects. Thus, the lack of effect of strategy – specifically current steering versus HiRes – may be attributed to the limitation of the chord discrimination measure. These results are consistent with findings of Drennan et al. (2010) who found no difference in performance on the Clinical Assessment of Music Perception (CAMP) test of pitch discrimination (Kang et al. 2009) across Fidelity-120 and HiRes. Even though there were no significant differences across strategy for the current study, it is important to note that participant 3 opted to keep Fidelity-120-S for use as a music programme after the experiment was finished as he reported better music perception and appreciation with this strategy. This was not the programme that resulted in the highest performance for chord discrimination, but the listener reported a preference for music-based sound quality. It is possible that the familiarisation time was not long enough for this participant. Given more time to acclimate to the new programme, the subjective benefit may have resulted in higher performance.

Results from the BAT also showed no significant differences in rhythmic perception across processing strategies. Rhythm perception for CI users approaches that of normal-hearing listeners (e.g. Gfeller and Lansing 1991, 1992; Gfeller et al. 1997; Hsiao and Gfeller 2012). Since the BAT is based on rhythm, we would assume that CI users would perform close to that of normal-hearing listeners. Results from trials with normal-hearing listeners showed that participants identified on-beat clicks with 90% accuracy (Iverson and Patel 2008). The CI users in the current study demonstrated poorer performance with a mean of 66.0% and individual scores ranging from 60.0% to 71.3%. Reasons for poorer temporal beat accuracy and the lack of effect of strategy could both be due to the spectro-temporally complex nature of the stimuli and the fact the task was not designed nor validated for use with CI users.

Speech understanding: sequential vs. paired stimulation

The overarching goal of this study was to provide an evidence base for clinical practice regarding differences in the performance of CI users when using paired vs. sequential strategies. We hypothesised that sequential stimulation would yield better performance than paired stimulation on every measure based on the negative effects of channel interaction (e.g. Stickney et al. 2006). While the spread of excitation cannot be eliminated with intracochlear electrical stimulation, it is reasonable to assume that having twice as many electrodes stimulated at a time in paired compared to sequential programmes could yield greater channel interaction and potentially signal degradation. Researchers have shown that switching from sequential to paired programmes results in lower M levels as there is a summation of the electrical fields for the simultaneously stimulated channels (e.g. Buechner et al. 2005). The current results confirmed this finding such that M levels were significantly higher for sequential as compared to paired stimulation. Furthermore, the results confirmed our hypothesis that sequential stimulation yielded significantly higher outcomes for speech recognition and sound quality.

Limitations

Though we found a statistically significant benefit for sequential over paired stimulation for both speech recognition and estimates of sound quality, a potential limitation is that these data could have been influenced by the listeners' prior stimulation experience and/or relatively short familiarisation time with each new combination of strategy and stimulation type. Recall that statistical analysis of stimulation experience (sequential vs. paired) revealed no main effect of experience nor an interaction between stimulation type and prior experience. This could have been due to small sample size and/or recruiting only two listeners who had long-term experience with paired stimulation. We made multiple attempts to recruit additional individuals with long-term experience using paired stimulation but, were unsuccessful likely due to the fact that Vanderbilt's programming philosophy includes a sequential stimulation as default for all CI recipients. Despite the uneven balance of participants with sequential experience, listeners who had long-term experience with paired stimulation (participants 4 and 10) did not achieve higher performance with paired stimulation nor did they rate paired strategies higher than sequential strategies for subjective sound quality (Figures 2 and 3). This suggests that speech recognition performance and resultant sound quality with paired stimulation may not be optimal and that individuals with longterm experience using paired stimulation should be able to transition to sequential

stimulation and achieve similar or even higher levels of speech recognition and subjective sound quality.

For the two participants with long-term Optima-P experience, both retained a sequential programme, namely Optima-S, following study completion. While the stimulation-based differences for CNC word recognition and AzBio sentence recognition noise for these two individuals were not significantly different on an individual level per 95% confidence intervals for the tests completed (CNC: Thornton and Raffin 1978; AzBio: Spahr et al. 2012), the difference in performance, sound quality, and potentially listening effort was perceptually different enough for these listeners to voluntarily retain a sequential programme. In contrast, none of the eight listeners who had long-term experience with sequential stimulation elected to keep a paired programme at the completion of the study. In conclusion, though we had attempted to control for listener experience by providing experience with each programme – rather than acute testing – an additional investigation is warranted using a balanced set of individuals with long-term use of both paired and sequential strategies.

Summary and conclusion

Processing strategy and stimulation type can have an impact on performance across many measures of auditory perceptual function. Though we did not find an effect of strategy (HiRes, Optima, Fidelity-120), sequential stimulation yielded significantly better performance on measures of speech understanding in quiet and in noise as well as subjective estimates of sound quality. Additionally, there were no measures for which the use of sequential stimulation caused a decrement in performance. This finding holds clinical relevance for the use of sequential stimulation over the current default paired stimulation.

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Figure 1.
Individual and mean temporal modulation detection thresholds, in dB (20 log m), at 4 Hz (A) and 200 Hz (B). Error bars represent ± 1 standard error.

Figure 2. Individual and mean CNC word recognition and individual and mean AzBio sentence recognition in noise at +5 dB SNR, in percent correct. Error bars represent ± 1 standard error.

Figure 3. Individual and mean subjective sound quality ratings for speech in quiet and in noise. Error bars represent ± 1 standard error.

Figure 4.

Individual and mean spectral resolution estimates for the quick spectral modulation detection (QSDM) task with a spectral modulation rate of 1 cyc/oct. QSDM scores are expressed in percent correct averaged across all modulation depths from 4 to 22 dB, in 2-dB steps. The horizontal dashed line represents chance performance (33.3% correct). Error bars represent ± 1 standard error.

Figure 5. Individual and mean chord discrimination and individual and mean scores on the BAT, in percent correct. The horizontal dashed line represents chance performance (50% correct). Error bars represent ± 1 standard error.

Table 1.

Individual participant demographics including age, gender, internal device and processor, channel stimulation rates (in pps) averaged across the sequential and paired strategies, ear tested, months of CI use prior to enrolment, pure tone average (PTA) in the non-CI ear, and initial strategy used prior to enrolment.

Subject	Age	Gender	Internal device & processor	Mean stim rates for sequential & paired (pps)	Ear	Months of CI Use	PTA in non-CI ear (dB HL)	Initial strategy
1	34	Male	HiRes 90K, Naida Q90	2294, 3553	Left	161	N/A bilateral CI	Optima-S
2	25	Female	HiRes 90K Advantage, Naida Q70	1828, 1810	Left	31	80.0	Optima-S
3	70	Male	HiRes 90K Advantage, Naida Q70	3248, 4021	Left	29	93.3	Optima-S
4	68	Male	HiRes 90K Advantage, Naida Q70	2879, 3815	Right	46	76.7	Optima-P
5	32	Female	HiRes 90K Advantage, Naida Q70	1635, 1943	Right	35	75.3	Optima-S
6	78	Male	HiRes 90K, Naida Q70	2241, 2715	Right	112	60.0	Optima-S
7	61	Female	HiRes 90K Advantage, Naida Q90	1882, 2799	Left	13	N/A bilateral CI	Optima-S
8	51	Male	HiRes 90K Advantage, Naida Q70	2807, 3860	Left	48	118.3	Optima-S
9	63	Male	HiRes 90K Advantage, Naida Q90	3042, 4020	Left	22	68.3	Optima-S
10	59	Male	HiRes 90K Advantage, Naida Q70	1695, 3161	Right	52	N/A bilateral CI	Optima-P

Table 2.

Individual and mean programme/slot usage, in % total time, derived from the data log reports.

Subject	120-S	120-P	HiRes-S	HiRes-P	Optima-S	Optima-P
1			Missing data			
2			Missing data			
3	63%	16%	11%	5%		5%
4	14%	29%	19%	20%	18%	
5	48%	16%	19%	14%		3%
6	19%	20%	17%	24%		20%
7	39%	17%	30%	7%		7%
8	45%	8%	15%	15%		17%
9	31%	19%	24%	11%		15%
10	26%	8%	24%	20%	22%	
Mean	35.6%	16.6%	19.9%	14.5%	13.4%	

Table 3.

Individual and mean M levels, in clinical units (CU), averaged across all electrodes for each of the strategies (HiRes, Optima, and Fidelity-120) and stimulation types (paired and sequential).

Strategy	Electrode															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
HiRes-S	250.2	260.1	267.3	265.6	265.7	265.5	261.9	259.8	237.7	246.3	237.4	228.4	223.1	222.9	206.0	175.6
F120-S	242.0	251.9	257.9	257.4	257.5	257.3	252.8	251.4	228.6	237.2	229.1	220.2	214.9	213.2	198.7	170.8
Optima-S	245.6	255.5	262.6	261.0	261.1	260.9	256.8	254.6	232.6	241.2	233.3	223.8	218.5	217.8	202.6	169.0
HiRes-P	187.3	198.4	206.0	209.5	209.6	209.4	204.6	202.7	185.6	189.0	180.3	172.3	167.0	168.8	154.0	130.8
F120-P	183.0	194.1	200.9	205.2	205.3	205.1	199.3	198.6	180.8	183.8	176.2	168.0	162.7	165.0	151.3	127.0
Optima-P	188.3	199.4	207.0	210.5	210.6	210.4	204.8	204.4	186.7	189.2	182.1	173.3	168.0	169.0	154.3	131.2
MEAN Simultaneous	245.9	255.8	262.6	261.3	261.4	261.2	257.1	255.3	232.9	241.6	233.3	224.1	218.8	218.0	202.4	171.8
MEAN Paired	186.2	197.3	204.6	208.4	208.5	208.3	202.9	201.9	184.3	187.3	179.6	171.2	165.9	167.6	153.2	129.7