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Research Paper

Pitch ranking with different virtual channel configurations in electrical hearing

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ABSTRACT

Monopolar Virtual Channels (MPVCs) use current steering to increase the number of spectral channels provided to cochlear implant users beyond the physical number of electrodes. The current spread created with a current steered channel is similar to the spread found for monopolar stimulation, and this spread may be one of the bottlenecks for improved performance with an increased number of channels. Quadrupolar Virtual Channels (QPVCs) use current focusing in combination with steering in an attempt to increase the number of channels while reducing channel interaction. However, due to the potentially asymmetric current field generated by QPVCs, there may be distortions in the place pitch representation using this mode. A Virtual Tripole (VTP) is introduced as a current focused virtual channel with a relatively symmetrical electric field distribution. In this study, we looked at pitch ranking in cochlear implant users with QPVC, VTP, and MPVC configurations to determine if place pitch shifts similarly across the cochlea or if any of the stimulation modes shift non-monotonically. Results suggest that MPVC and VTP stimulation provide a consistent monotonic shift across cochlear positions while the place shift provided by QPVCs was more variable. The use of VTP stimulation would be recommended instead of QPVC for a speech processing strategy.

1. Introduction

Spectral information is critical for interpreting auditory signals. However, the spectral information provided by a cochlear implant is limited. In most modern commercial implant strategies, each electrode corresponds to a spectral channel, thereby limiting the number of spectral channels to the number of intracochlear electrodes (12–22 depending on the model). Increasing the number of functional channels would presumably provide better spectral information and thus provide better speech in noise understanding and music perception (e.g. Shannon et al., 2004; Srinivasan et al., 2013).

One tool to increase the number of channels provided by an implant is the monopolar virtual channel (MPVC). An MPVC is created when current is provided simultaneously in-phase on two adjacent electrodes, resulting in a peak of stimulation between the two electrodes and a pitch percept in between the pitches provided by either electrode in isolation. Increasing the proportion of the total current provided to the basal electrode, indicated by the coefficient α, shifts the peak of stimulation basally and increases the perceived pitch. As current steered stimulation allows stimulation at locations between physical contacts, the term channel location is used to describe the nominal location provided by a current steered virtual location. For example, channel location 5.6 describes a virtual channel in between electrodes 5 and 6 with $\alpha = 0.6$. Using this technique, an MPVC can be placed anywhere in between the two component electrodes (Firszt et al., 2007; Koch et al., 2007). The spread of excitation with a virtual channel is similar to the spread of excitation from a single physical electrode (Hughes et al., 2013; Busby et al., 2008; Miyoshi et al., 1996). Therefore, because the current fields from MPVCs are similar to current fields from single electrodes but can be placed anywhere between an electrode pair, using an MPVC is functionally similar to providing a new electrode located between the two component electrodes. Advanced Bionics implemented MPVCs in their Fidelity 120 and Optima processing strategies to increase the number of channels presented to 120 using only 16 electrodes. Although patients seem to prefer the newer strategies, it has been difficult to quantify a benefit from the use of virtual channels. Buechner et al. (2008) and Nogueira et al.

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(2009) found no significant differences between virtual channel strategies which were similar to Fidelity 120 and the baseline HiRes strategy with no current steering. In a chronic study between HiRes and the commercially released Fidelity 120, Firszt et al. (2009) found small but significant improvements with Fidelity 120 for 3 out of 7 different speech tests used to evaluate subjects. For the other 4 tests, no differences were detected. Significant improvements were found for pleasantness of music and distinctiveness of instruments with Fidelity 120.

Perhaps the similarity in spread of excitations between MPVC and standard monopolar (MP) stimulation is a limiting factor in the performance benefit from using MPVCs to increase the number of channels. Although presented with up to 22 independent channels of information, most CI users perform as if they only receive between 4 and 8 independent channels (i.e. Friesen et al., 2001). Presumably, the limitation in performance is caused by the broad spread of excitation, which creates large channel interactions. If channel interactions in strategies using MP stimulation are the bottleneck for spectral resolution, then adding more sites of stimulation using MPVCs that have a similar spread of excitation will not alleviate the channel interaction bottleneck. It is therefore not surprising that even with a great improvement in the number of transmitted channels with Fidelity 120, only moderate improvements in performance at best have been observed (e.g. Buechner et al., 2008; Firszt et al., 2009; Nogueira et al., 2009).

One way that has been proposed to improve spectral resolution (and increase the number of functional channels) is to reduce the spread of current in the cochlea and therefore reduce the channel interaction from each stimulation site (e.g. Bonham and Litvak, 2008; Jolly et al., 1996). Reshaping the electric field in order to reduce the current spread is known as "current focusing". One of the more studied current focusing stimulation modes is partial Tripolar (pTP) stimulation. In pTP stimulation, current is provided to an active electrode while simultaneously current in the opposite phase is provided to the adjacent flanking electrodes on either side of the active electrode (see Fig. 1). The degree of focusing is controlled by a coefficient σ, which determines the amount of current sent to the flanking electrodes (i.e. active current multiplied by $\sigma/2$ for each of the two flanking electrodes). The remaining current is sent to an extracochlear ground electrode. pTP stimulation provides a reduced spread of excitation at a fixed loudness relative to MP stimulation (e.g. Landsberger et al., 2012; Fielden et al., 2013; Padilla and Landsberger, 2016) as well as improved spectral resolution (Berenstein et al., 2008). Srinivasan et al. (2013) found pTP improves speech understanding in noise with all subjects, while Bierer and Litvak (2016) only found a consistent benefit for poorer performing patients. However, similarly to MP stimulation, the number of channels provided by a cochlear implant with a pTP strategy is limited by the number of electrodes.

Landsberger and Srinivasan (2009) proposed the Quadrupolar Virtual Channel (QPVC) to provide both current steering and focusing simultaneously. A QPVC is created by stimulating two adjacent physical electrodes to steer current similarly to a MPVC. Additionally, two flanking electrodes adjacent to the active electrodes stimulate in opposite phase to reduce the spread of current. The amount of current provided to the flanking electrodes can be adjusted to control the degree of current focusing by a coefficient σ (such that $\sigma/2$ current goes to each flanking electrode) similarly to pTP stimulation. Similarly to MPVCs, QPVCs can provide more sites of stimulation than there are physical electrodes. Similarly to pTP stimulation, QPVCs reduce the spread of excitation (Srinivasan et al., 2010). It has been shown that a patient can discriminate more steps between a given electrode pair using QPVCs than MPVCs in both single-channel (Landsberger and Srinivasan, 2009) and multi-channel contexts (Srinivasan et al., 2012). Hopefully, when implemented in a speech processing strategy, a QPVC would provide both an increased number of channels to the cochlear implant user (via steering) as well as an improved ability to access the information independently (via focusing.)

One attribute of the QPVC is that while the peak of stimulation can be steered by changing the relative amount of current on the two central electrodes (i.e. changing α), the distance between the steered location and the flanking ground electrodes varies as a function of α. When $\alpha = 0.5$, the flanking electrodes are 1.5 contacts away in both the apical and basal directions. However, as α approaches 0 (or 1) then the distance from the steered location to the apical (or basal) flanking electrode reduces and the distance from the basal (or apical) flanking electrode increases. As integer channel locations can be stimulated in QPVC mode using either $\alpha = 0$ or $\alpha = 1$, a nomenclature of QPVC(1,0) and QPVC(0,1) is used to indicate the relative weighting on the two central electrodes composing a QPVC. For example, a QPVC(1,0) at channel location 6 ($\alpha = 0$) provides flanking out-of-phase stimulation on electrodes 5 and 8 while a QPVC (0, 1) at channel location 6 ($\alpha = 1$) provides flanking out-of-phase stimulation on electrodes 4 and 7.

We used the model introduced by Litvak et al. (2007) to visualize the effect of symmetric and asymmetric stimulation configurations. The modeled spread of MPVC and QPVC configurations were plotted in the top panel of Fig. 2. In this plot, it was assumed that there was a moderate (1.5 mm) electrode-to-tissue distance. Current focusing value (σ) was set to 0.75 for the QPVC stimulation mode. The center of gravity (COG) for MPVC stimuli move monotonically from virtual channel positions 5.5 to 6.5 while the COG for QPVCs do not move monotonically. Specifically, the COG increases as the virtual channel location increased from 5 to 6. However, when increasing beyond location 6, the COG shifts to a lower location. As can be seen in the figure, if the COG defines place pitch, QPVC 5.8 and 6.1 would be predicted to have the same pitch while QPVC 5.9 would be higher than either of them. The deviations from monotonicity of COG are illustrated in Fig. 2C.

To address the potential issues with QPVC stimulation, a virtual tripole (VTP) is proposed. The virtual tripole is a current focused virtual channel designed to provide symmetrical stimulation across the cochlear duct regardless of choice of α. The specific

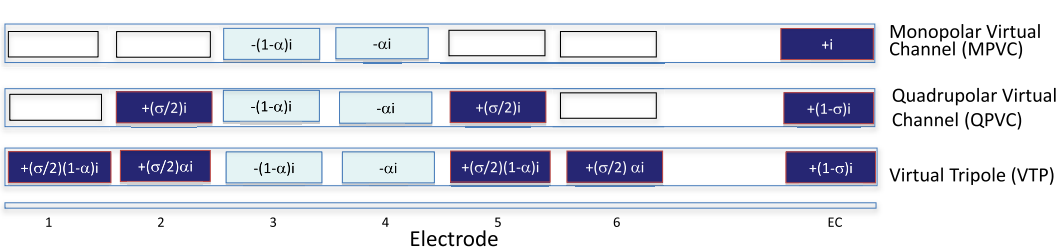

Fig. 1. Schematic of the different stimulation modes used in this study: MPVC, QPVC and VTP. Note that the amplitudes only represent the first phase of a biphasic pulse. The x-axis describes the electrode position such that numbers indicate intra-cochlear electrodes and "EC" indicates an extra-cochlear electrode. The symbols σ, α, and i, refer to the current focusing coefficient, current steering coefficient, and stimulus amplitude (in μa) respectively.

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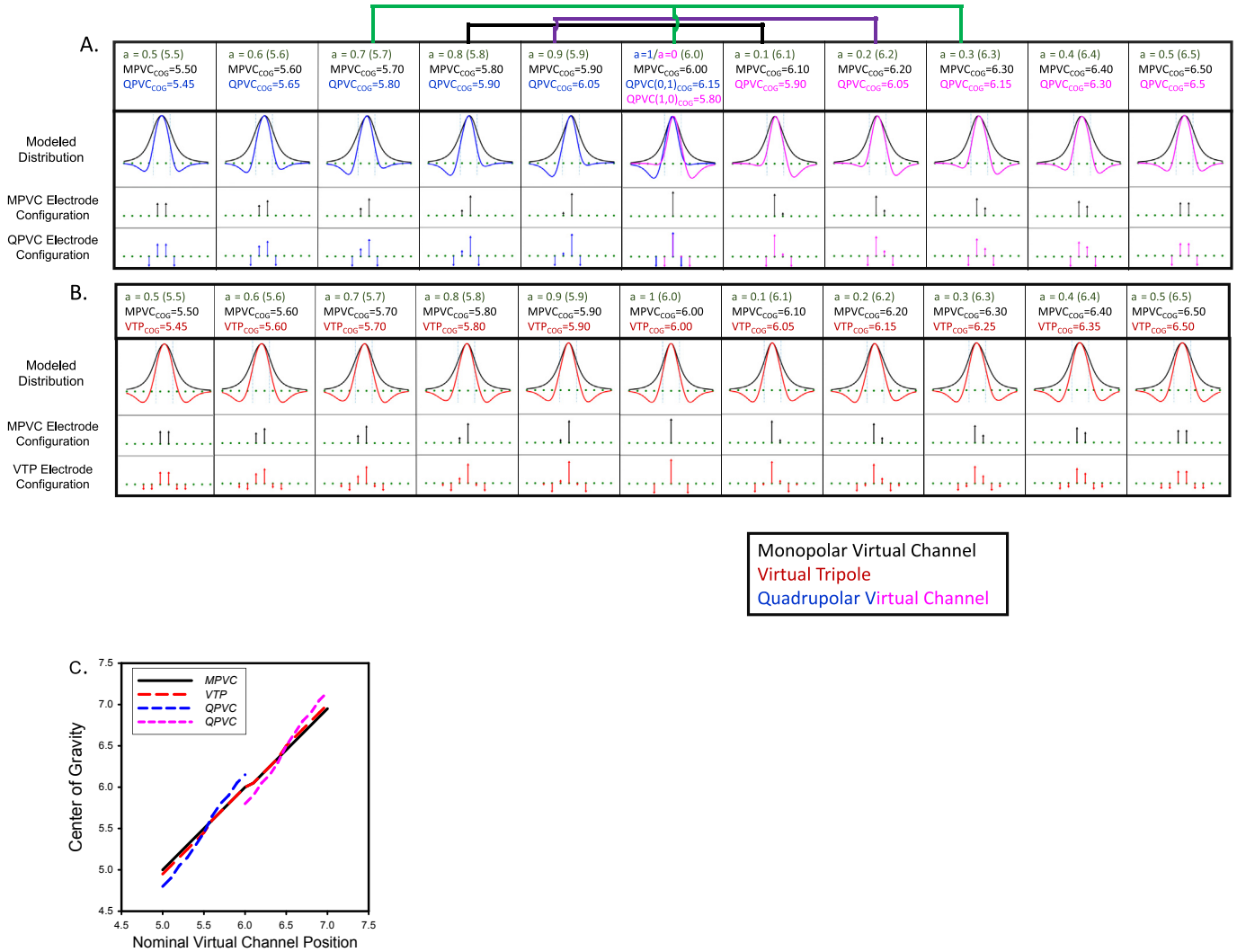

Fig. 2. A) The curves in panel A represent modeled activation patterns for MPVC (black curves) and QPVC (blue and magenta curves) as a function of virtual channel position in 0.1 α steps from positions 5.5 to 6.5. Blue curves indicate QPVCs created using flanking electrodes 4 and 7 while magenta curves indicate QPVCs created using flanking electrodes 5 and 8. Below the distribution curves are illustrations of the electrode configurations used to generate the corresponding distributions. Green dots indicate electrode positions while the arrows indicate amplitude and phase of stimulation from the electrode. Black arrows indicate the configuration for MPVC stimulation while blue and magenta arrows indicate the configurations for the QPVCs with flanking electrodes. Above the distributions in green are the values of α used to generate the distribution with the nominal virtual channel location in parenthesis. Below that are the virtual channel locations which represent the center of gravity (COG) for MPVC (in black) and QPVC (in blue or magenta) for each of the modeled distributions. At the top of the panel are a set of lines used to connect panels of different α values. They are used to indicate QPVC configurations which produce similar centers of gravity (and possibly similar place pitches.) For example, the QPVC COG for position 5.8 is similar to the QPVC COG position for 6.1. B) The curves in panel B represent the distributions for MPVC (black) and VTP (red) stimulation modes as a function of virtual channel position in 0.1 α steps from positions 5.5 to 6.5. Similarly to panel A, the electrode configurations used to create the spreads of excitation are illustrated below in black (MPVC) and red (VTP). Above, the nominal virtual channel position is indicated in green, and the COG for MPVC and VTP stimulation are presented in black and red respectively. C) The modeled COG for MPVC (solid black), VTP (dashed red), and QPVC (dashed blue and dashed magenta) stimulation modes as a function of the nominal virtual channel location (green values in panels A and B). Note that the dashed blue line represents the COG for QPVC stimuli generated with flankers at electrodes 4 and 7 while the dashed magenta line represents the COG for QPVC stimuli generated with flankers at electrodes 5 and 8. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

implementation of VTPs are presented in Fig. 1. The VTP differs from the QPVC in that each of the flanking electrodes in the QPVC are replaced by two flanking electrodes such that each flanking electrode pair creates a flanking virtual electrode also steered by α. The result is a stimulation mode such that the flanking virtual electrodes are always 2 contacts away from the peak of stimulation regardless of α. As illustrated in the bottom panel of Fig. 2, the Litvak model with the same parameters (1.5 mm electrode-to-tissue distance and $\sigma = 0.75$) predicts that VTP stimulation mode provides a monotonic change in COG for virtual channel positions 5.5 and 6.5. Furthermore, for a given virtual channel position, the COG for MPVC and VTP are similar (Fig. 2C).

In the present manuscript, an experiment was conducted to determine if pitch changes monotonically for MPVC, QPVC, and VTP stimulation when steered across a physical electrode location. For each stimulation mode (MPVC, QPVC, and VTP), the pitch of stimulation at virtual channel locations between 4.5 and 7.5 were ranked relative to stimulation at location 6 in the same stimulation mode. As MPVC and VTP stimulation modes are symmetrical, we hypothesized that a sigmoidal function of channel location would well describe the proportion of times a given virtual location is reported to be higher than the reference stimulation on electrode 6. However, we further hypothesize that the distribution of responses around a QPVC stimulus at location 6 will be distorted because of the non-monotonic COGs as illustrated in Fig. 2A. For example, relative to a QPVC at location 6 using ground electrodes 5 and 8 (i.e.

a QPVC(1,0)), basalward shifts will sound higher in pitch. However, small shifts in the apical direction (approximately between 6 and 5.7) will not consistently be perceived as lower in pitch. As a result, sigmoidal function of channel location for QPVC stimuli would produce a shift in the location of the 50% intercept (representing a pitch match) as well as a shallower slope at the corresponding point relative to what would be observed with the symmetrical (MPVC and VTP) stimulation modes. Note that while the present manuscript (and above example) focus on place pitch asymmetries around electrode 6, the asymmetries expected around electrode 6 would also be expected at all electrode locations.

2. Methods

2.1. Subjects

Eight post-lingually deafened users of the Advanced Bionics CII or HiRes 90 K cochlear implant system participated in the study. Data was collected from 6 subjects (C3, C103, C104, C105, C106 and C107) at New York University (NYU) and from 2 subjects (C7 and C14) at the University of Southern California (USC). One bilaterally implanted subject (C105) was tested separately for each of her ears. All subjects gave informed consent to the project as approved by either the NYU or USC Institutional Review Board.

2.2. Stimuli

All stimuli consisted of single channel electrical stimulation presented MPVC, VTP or QPVC modes at multiple cochlear locations. All current focused stimuli (VTP and QPVC) were presented with a current focusing coefficient of $\sigma = 0.75$. All stimuli consisted of fixed-amplitude cathodic-first biphasic pulse trains presented at 1000 pps with a phase duration of 226.27 μs, no interphase gap, and a duration of 300 ms. The long phase duration was selected for this experiment (as well as Landsberger and Srinivasan (2009) and Srinivasan et al. (2010)) to ensure adequate loudness could be obtained for all current focused stimuli for all subjects. Stimulation was presented using the BEDCS software package provided by Advanced Bionics.

2.3. Procedure

In the present experiment, stimulation at locations between 4.5 and 7.5 were pitch ranked relative to stimulation at location 6 using MPVC, VTP, QPVC(1,0), and QPVC(0,1) stimulation. Before running the experiment, all stimuli were loudness balanced to reduce level effects. The dynamic ranges for all stimuli were estimated before loudness balancing to determine the acceptable range of amplitudes that can be used in the determination of a loudness balance.

2.3.1. Dynamic range estimation

The dynamic range for stimuli representing the physical electrodes 4, 5, 6, 7 and 8 was estimated for MPVC, VTP, QPVC(1,0) and QPVC(0,1) stimulation modes. Stimuli were initially presented at an amplitude below threshold and gradually increased in 5 μa steps until the amplitude reached a level corresponding to "Maximal Comfort". As the stimulation amplitude increased, subjects reported the loudness using an 11 point loudness scale provided by Advanced Bionics (from 0 - No Sound to 10 - Very Uncomfortable). The amplitudes corresponding to "(1) Barely Audible", "(3) Soft", "(6) Most Comfortable", and "(8) Maximal Comfort" were recorded (maximum amplitude presented to subjects is level 8). Because pitch ranking would only be conducted for locations between 4.5 and 7.5, dynamic ranges for QPVC(1,0) at location 8 and QPVC(0,1) at location 4 were not measured.

2.3.2. Loudness balancing

All stimuli for which the dynamic range were estimated (locations 4, 5, 6, 7, and 8 in MPVC, VTP, QPVC(0,1) and QPVC(1,0) modes) were loudness balanced to a reference stimulus. The reference stimulus consisted of MP stimulation on electrode 6 at the amplitude corresponding to "Most Comfortable" loudness. During the loudness balancing procedure, the presentation of the reference and target (the stimulus being balanced) stimuli were continuously interleaved. Each stimulus was presented for 300 ms and separated by a 500 ms inter-stimulus interval. The subject was asked to adjust the loudness of the target stimulus such that the loudness of the two stimuli was the same. Subjects controlled the amplitude of the target stimulus using a knob (Powermate from Griffith Technologies). Subjects rotated the knob left and right to increase or decrease the target current amplitude in 1 μA steps, until similar loudness was reached for the target stimulus and pressed the knob to select the chosen current level and finish the trial. The average of three loudness balance estimates for each location and stimulation mode was used as the amplitude corresponding to equal loudness as the reference stimulation.

For current steered locations, the amplitudes required to maintain equal loudness were interpolated from the equally loud amplitudes previously measured at the physical locations. Commercial strategies using current steering with MPVCs (i.e. Fidelity 120 and Optima) use this approach to estimate appropriate amplitudes for current steered stimuli as it has been demonstrated to be appropriate by Snel-Bongers et al. (2011, 2013). Previous work with QPVCs (e.g. Landsberger and Srinivasan, 2009; Srinivasan et al., 2010) involved loudness balancing each virtual channel step for the QPVC (and MPVC) stimuli. However, when the loudness balancing data for MPVC and QPVC virtual channel steps from Landsberger and Srinivasan (2009) were reanalyzed, no differences were observed between the accuracy of interpolated values for the QPVC and MPVC stimuli. Specifically, using a paired *t*-test, no differences were found between the r^2 values for each of the loudness balanced levels for MPVC and QPVC stimuli for the same electrode pairs ($t(31) = -0.189$, $p = 0.851$). Therefore, it was assumed that linear interpolation would be similarly appropriate for focused and unfocused virtual channels.

2.3.3. Pitch ranking

Pitch ranking was conducted using a two-interval forced choice task (2IFC). One interval always provided stimulation at location 6 in MPVC, VTP, QPVC(1,0), or QPVC(0,1) modes while the other interval provided stimulation in the same stimulation mode but at a location somewhere between 4.5 and 7.5 It is worth noting that the QPVC references were never compared to their physical identities. Instead, when the reference at position 6 was generated with a QPVC(1,0), representation of the other interval at position 6 was generated with a QPVC(0,1). Conversely, when the reference at position 6 was generated with a QPVC(0,1), representation of the other interval at position 6 was generated with a QPVC(1,0). Each stimulus was presented for 300 ms with a 500 ms inter-stimulus interval at an amplitude corresponding to equal loudness with an amplitude jitter ±0.3 dB relative to the equal loudness amplitude. Jitter was added to minimize the effect of any loudness differences that might remain even after loudness balancing. Locations were tested in 10% electrode steps (i.e. $\alpha = 0.1$ steps) for locations between 5.5 and 6.5 and in 25% electrode steps (i.e. $\alpha = 0.25$ steps) for locations between 4.5 and 5.5 as well as between 6.5 and 7.5.

After hearing the two sounds, subjects were asked to pick which interval contained the sound that was higher in pitch. Subjects responded using either a response box (Ergodex DX-1) which had two buttons labeled "1" and "2" to select the interval with the higher pitch or a regular keyboard by pressing either "1" or "2". In a

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block of pitch matching trials, all locations were compared once to location 6 in a fixed stimulation mode in random order (totaling 18 comparisons per block). Fifteen blocks were run for each stimulation mode in a randomized order. A total of 1080 comparisons were made (18 sites of stimulation x 15 repetitions x 4 stimulation modes). The estimated pitch for each subject at each stimulation mode were found by fitting a sigmoidal function to the raw data.

2.3.4. Data fitting

A sigmoidal psychometric function as shown in Equation (1) was used to fit the results obtained from the pitch ranking task performed by the subjects. In the equation, *x0* is the estimated point where 50% of the responses are higher than the reference electrode and 1/β is the slope of the curve.

$$f(x) = \frac{1}{1 + e^{-(x-x0)/\beta}} \quad (1)$$

The point where 50% of the responses were considered higher in pitch than the reference electrode position (6) was used as an estimate of the electrode position with the same pitch as the reference electrode for each mode. This position should be perceived by subjects at electrode position 6 if the stimulation is symmetrical. The slope for the fitting at the point of equality is also obtained from the sigmoidal function.

3. Results

Before examining the entire data set, a simple comparison between pitch rankings of QPVC(1,0) and QPVC(0,1) at channel location 6 was made. The proportion of times that QPVC(0,1) was ranked higher than QPVC(1,0) was calculated for each of the 9 tested ears. As predicted by Fig. 2a, QPVC(0,1) was more frequently described as higher pitch than QPVC(1,0) for all subjects. Fig. 3 presents a boxplot of how frequently each subject ranked QPVC(0,1) as higher than QPVC(1,0). The ranking of pitch for QPVCs was found to be significantly different than chance (0.5) using a one-sample *t*-test ($t(8) = 7.54$, $p < 0.0001$).

Results for the 2IFC ranking task were plotted and fitted as shown in Fig. 4. The figure shows the proportion of times that subjects reported that the target stimulus was higher in pitch than the reference stimulus as a function of the virtual channel position of the target stimulus. Each panel in the top 3 rows shows an individual subject's data and the corresponding fittings using Equation (1). Each value for each subject at a given channel location was added and then divided by the number of subjects tested. The panel in the bottom right corner shows the data and fits averaged across subjects. For some subjects (e.g. C7 and C103), the fits and slopes are similar for all four stimulation configurations. However, for subjects for whom the different configurations do not provide similar fits, the QPVC fits (e.g. C105, C106, and C107) tend to have shallower slopes and shifted 50% intercepts relative to the MPVC fits. A notable deviation in response patterns can be observed for the MPVC pitch ranking for C107. When stimulation is more than 0.5 electrode contacts away from 6 (either apically or basally), the pitch is described as higher than what is provided by electrode 6. However, when electrode 6 is compared to itself the pitch is described as lower. No obvious explanation for this pattern is apparent. The patterns for other stimulation modes for C107 are more conventional. The curve fitting for the QPVC modes have very low r^2 (0.3 and 0.5), showing that this subject had a hard time performing this task, while the fitting for VTP mode has a larger r^2 (0.8), showing that his pitch ranking is more reliable with this focused stimulation mode. The slopes for subject C7 are the steepest of all of the subjects and provide similar estimated pitch identities. Subject C105 was tested with both ears. Performance with her left ear was more variable than with her right ear. Nevertheless, the slopes for MPVC and VTP crossings are higher than QPVC slopes for both of her ears. For subject C106, performance with MPVC and VTP stimulation modes follow a similar pattern as C105. For most subjects (C3, C14, C103, C105, C106, C107) the estimated pitch match position for QPVC(1,0) (light green fitting curve and symbols) is more apical than the estimated pitch match position for QPVC(0,1) (yellow fitting curve and diamond symbols). In general, curve fittings for all subjects have very large r^2 values (greater than 0.9), so although it is possible that better fits could be found for some of the subjects who have a hard time performing the task, as shown by Zychaluk and Foster (2009), we kept the psychometric function fitting for all the subjects.

Fig. 5 shows the fittings for each of the stimulation modes tested in different panels including all the subjects at the same time. In this figure, the similar behavior between MPVC and VTP pitch ranking can be more clearly seen (except for subject C107 who cannot pitch rank in MPVC mode). It appears that VTP pitch ranking slopes are slightly steeper. For the two QPVC mode compared, the figure shows that the results are more mixed and the slopes seem to be flatter.

Boxplots of the estimated pitch match positions calculated from the psychometric function are presented in Fig. 6A. The estimated equal pitch match location is typically near the reference electrode position 6. However, the variability for the equal pitch match location for QPVC stimulation is greater than for MPVC or VTP stimulation modes.

A one-way repeated measures ANOVA detects a statistically significant difference between the estimated equal pitch match for each subject across the different stimulation modes tested ($F(3,31) = 4.67$, $p = 0.008$). Post hoc results using the Holm-Sidak method detected significance when pitch ranking with the two different QPVC modes ($t(14) = 3.418$, $p = 0.01$) and between pitch ranking in the MPVC and QPVC(1,0) mode ($t(14) = 2.922$, $p = 0.03$). No other significant differences were found between the different stimulation modes. Fig. 6B further illustrates the pattern of place pitch shift as the deviation from the estimated pitch with MPVC stimulation with each of the stimulation modes.

Slopes for the sigmoidal functions around the 50% performance

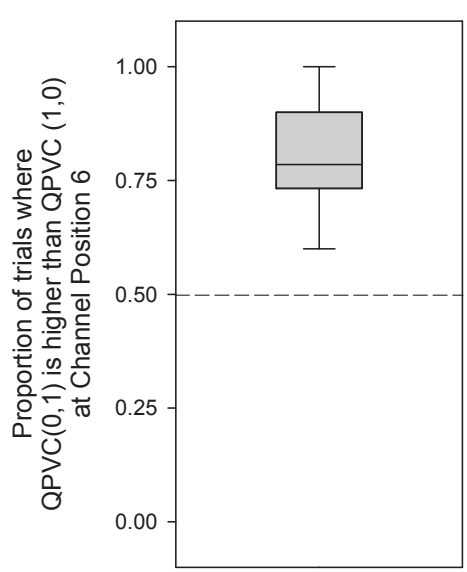

Fig. 3. Boxplot of the proportion of trials for each subject where QPVC(0,1) is higher than QPVC(1,0). The dashed line at 0.5 indicates chance performance. Note that the results are consistent with Fig. 2A.

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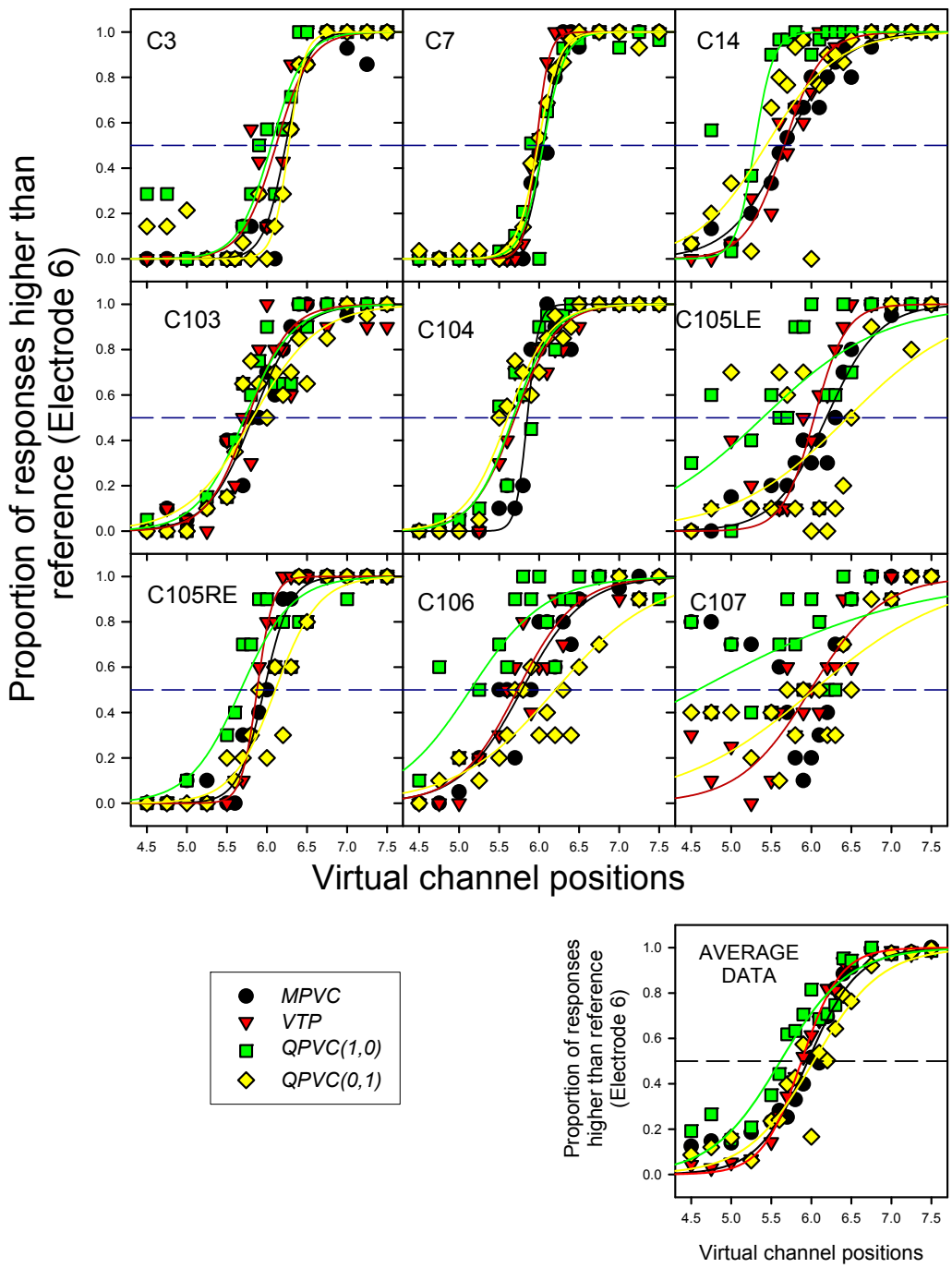

Fig. 4. Psychometric fitting to the data for all subjects tested. Separate plots for each subject are presented with all four stimulation configurations used in this experiment. Average response for all subjects are plotted in the lower right corner.

point are presented in Fig. 7. Variability between subjects is large for the slope of the sigmoidal functions. In fact, the variability in slopes across subjects is much larger than the variability across stimulation modes. A one-way repeated measures ANOVA detects no statistically significance difference across the slopes for each of the stimulation modes ($F(3,31) = 0.57$, $p = 0.642$).

4. Discussion

Analysis of data from individual subjects suggest that the asymmetric pulse shape (QPVC) provides a shifted percept across electrode boundaries relative to the symmetric pulse shapes (MPVC and VTP) for some subjects (e.g. C105 and C106). The QPVC(1,0) stimulation mode tends to bias the equal pitch point towards the apex while QPVC(0,1) stimulation tends to bias the equal pitch point towards the base. However, for other subjects (e.g. C7 and C103), pitch discrimination across electrode boundaries is similar for the symmetric and asymmetric modes. There is considerable variability in the equal pitch location for QPVCs across subjects and in the case of bilaterally implanted C105, across ears. This variation could be caused by differences in current flow from local electrode placement and variations in anatomical structure or from physiological differences such as local neural survival and structural damage from surgery. Although a one-way ANOVA found a

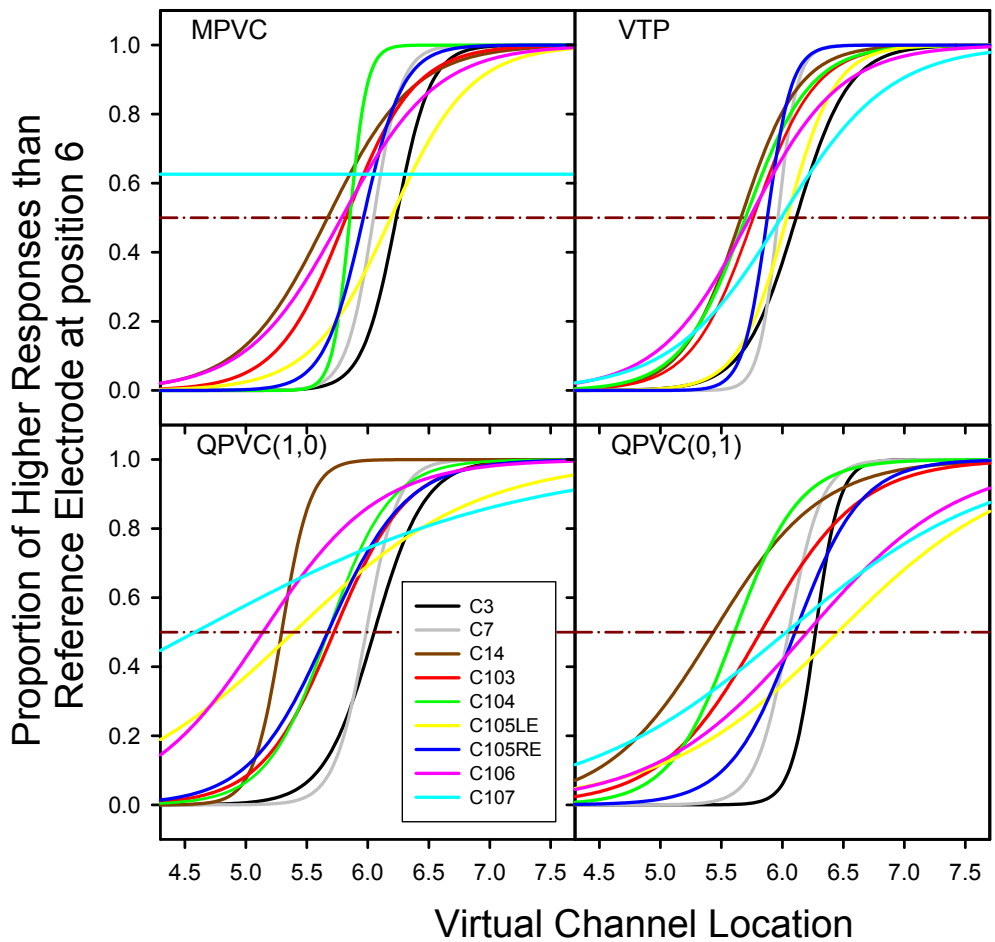

Fig. 5. Psychometric fits for each subject organized by stimulation mode. Each panel indicates one of the four stimulation modes while each color indicates a subject. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

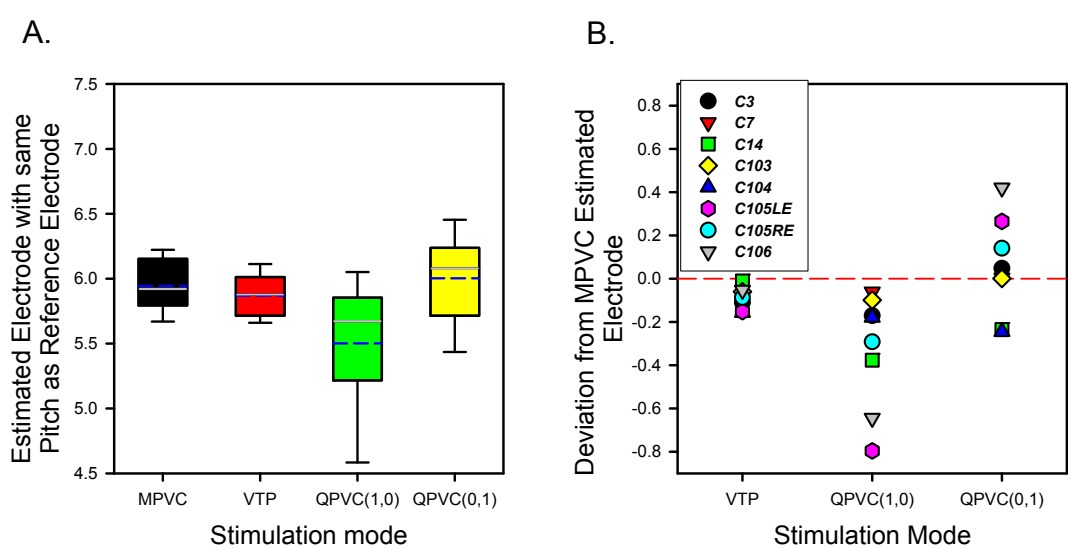

Fig. 6. A) Estimated position with the same pitch as the reference electrode at location 6. Estimates were made by extracting the points where the sigmoidal functions in Fig. 4 cross the value of y = 0.5 for each subject. The process was repeated for each tested stimulation mode. Solid grey lines indicate the median value and the dashed blue lines indicate the mean value. B) Electrode deviation for each stimulation mode (i.e. VTP, QPVC(1,0) and QPVC(0,1)) from the estimated electrode for MPVC stimulation mode. Within a stimulation mode, each point represents a different subject. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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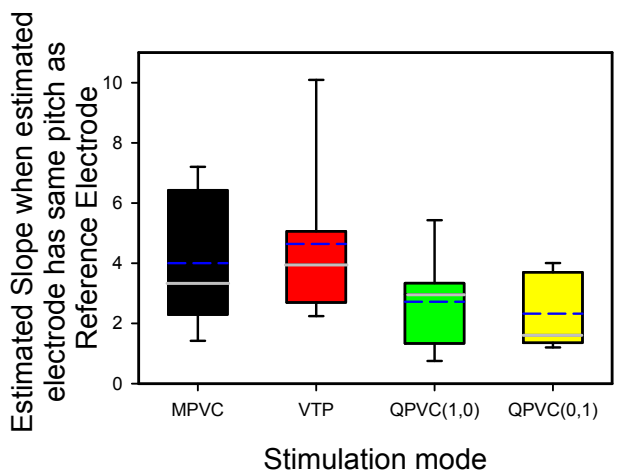

Fig. 7. Estimated slope for the psychometric curve at the same pitch as the reference electrode. Solid grey lines indicate the median value and the dashed blue lines indicate the mean value. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

difference between stimulation modes, post-hoc tests only detected differences between the two QPVC configurations and MPVC and the QPVC(1,0) configuration. Therefore, it cannot be conclusively determined that the point of equal pitch for QPVC and VTP are different or that the QPVC(0,1) configuration provides a different point of equal pitch than the MPVC configuration. Nevertheless, because QPVC(0,1) is ranked higher than QPVC(1,0) at a fixed channel location, there is reason to be concerned about place pitch distortions with the QPVC stimulation mode.

The effects on outcomes of using QPVC or VTP stimulation modes in speech processing strategies are unknown as these strategies have yet to be implemented or evaluated. As the results of the present experiment were variable, it is unclear if there would be a difference between these strategies and an MPVC strategy. When implemented in a speech processing strategy, other current focusing modes, such as pTP and phased array, have been shown to provide improved spectral resolution relative to MP stimulation (Berenstein et al., 2008; Smith et al., 2013). Presumably, similar benefits would be observed with focused virtual channel stimulation modes relative to MPVCs in a sound coding strategy, although this has yet to be evaluated. It has been previously shown that QPVC stimulation steered halfway between two physical electrodes (i.e. $\alpha = 0.5$) provides a sharper peak of stimulation (Srinivasan et al., 2010), but the reductions have not been evaluated for QPVCs with α values other than 0.5. Similarly, the reductions in spread of excitation with VTP have not been evaluated. Furthermore, even if reductions in spread of excitation are consistent with QPVC and VTP stimulation, the benefits of a reduced spread of excitation are still inconclusive. Srinivasan et al. (2013) found subjects using pTP maps performed significantly better with speech in noise than subjects using MP maps while Bierer and Litvak (2016) only found consistent benefits of pTP stimulation for poorer performing subjects. Therefore, even if the only functional difference between unfocused (MPVC) and focused (QPVC and VTP) virtual channels is that the spread of excitation is reduced (and the monotonic nature of place pitch is not distorted), the benefits of implanting a current focused virtual channel in a sound coding strategy still need to be evaluated.

The results of the present experiment suggest that changes in place pitch are similar between MPVC and VTP stimulation modes and therefore VTP stimulation could be easily substituted for MPVC stimulation. However, with QPVC stimulation, it appears that for some (but not all subjects), replacing MPVCs with QPVCs may lead to place pitch distortions. It is unclear how this would effect speech in noise understanding. There is reason to be concerned that when placed into a sound coding strategy, QPVC place coding variability will yield either poorer spectral resolution or spectral distortions for some subjects. Therefore, although results are likely to be similar for some subjects, the use of a VTP stimulation mode instead of a QPVC mode in a speech processing strategy is encouraged.

Before implementing VTP or QPVC stimulation in a speech processing strategy, there are a few aspects of the current experiment that should be considered. One is that of the large phase duration (226 μs) used in this experiment is not clinically practical. Larger phase durations limit the maximum rate of stimulation that can be used with an interleaved processing strategy, but may be necessary to achieve sufficiently loud stimuli with current focused stimulation. The large phase duration was selected for this experiment to ensure a constant phase duration for all subjects. However, it remains to be determined how short of a phase duration can be used consistently with QPVC and VTP stimuli.

Another assumption is that linear interpolation of amplitude between physical electrode locations is sufficient to maintain loudness. Previous work (Snel-Bongers et al., 2011, 2013) have suggested that interpolation is sufficient for MPVC stimulation. Analysis of loudness balancing data from Landsberger and Srinivasan (2009) suggest that linear interpolation is similarly appropriate for QPVC stimuli. Modeled spreads of excitation at different virtual channel locations (Fig. 2B) suggest that behavior across virtual channel locations should be similar for MPVC and VTP stimulation. However, this has yet to be measured.

Single channel electrical dynamic ranges (defined as the difference between threshold and loudest acceptable sound in dB re: 1μa) are similar for MP, Bipolar (BP; Landsberger and Galvin, 2011), pTP (Berenstein et al., 2008), and QPVC (Landsberger and Srinivasan, 2009) stimulation modes. Therefore, one would expect that most new stimulation modes would provide a similar electrical dynamic range. With all stimulation modes, when multiple channels are presented (as in a speech processor), the perceived sound is louder than any of the channels in isolation. This phenomenon is known as loudness summation. However, as spread of excitation and channel interaction change with different modes, the degree of loudness summation may change. Specifically, it has been shown that depending on the configuration, BP (McKay et al., 2001) and pTP (Padilla and Landsberger, 2014) stimulation can have different loudness summation than MP stimulation. It is therefore possible that loudness summation with MPVC, QPVC, and VTP stimulation are different. Differences in loudness summation could manifest as changes in audibility of certain sounds or spectral contrasts. Thus, without careful consideration of loudness summation, differences between MPVC, QPVC, and VTP stimulation modes may not be due only to changes in spectral resolution and/or deviations from monotonic place pitch.

A speech processing strategy incorporating QPVC parameters is still possible to implement, regardless of the potential problem of shifted pitch percepts present mostly at the borders. To avoid this issue, the strategy could use values of α ranging from 0.3 to 0.7 for example, similarly to the Advanced Bionics Optima strategy. By not presenting stimuli at the borders, the strategy will avoid the biggest switching points that occur when grounds for the same physical electrode are different. This will also reduce power consumption, increasing battery life, because stimulation will always be restricted to between two physical electrodes. The limitations with a QPVC strategy come from the fact that the shape of the spread of excitation is asymmetric and changes as a function of place. A similar limitation will take place with other current steered stimulation

modes producing asymmetrical, such as the steered pTP proposed by Wu and Luo (2013) and the Dynamically Compensated Virtual Channel (DC-VC) proposed by Nogueira et al. (2017). A range for the steering coefficient would have to be selected to make sure that pitch changes monotonically within that range and does not overlap between electrodes.

If we want to take advantage of a focused strategy with pitch percepts that change monotonically over the whole electrode array, a VTP configuration would be more beneficial than a QPVC implementation, as is shown in Fig. 2C. We hypothesize that VTP stimulation, like QPVC stimulation (Landsberger and Srinivasan, 2009; Srinivasan et al., 2012), will provide less channel interaction than MPVC stimulation. However, this still needs to be verified. A complication of implementing a VTP strategy is that two ground contacts are required on either side of the stimulation configuration preventing stimulation at locations represented by electrodes 1, 2, 15, and 16 while QPVC (and pTP) only restrict stimulation for locations represented by electrodes 1 and 16. An alternate stimulation mode, such as an MPVC or phantom electrode configuration can be used to represent the locations along the electrode array for which VTP is unable to stimulate. Therefore, the use of a VTP stimulation mode in a cochlear implant processing strategy seems more desirable than a QPVC strategy for providing current focused virtual channels.

5. Conclusions

Pitch ranking results with QPVC stimuli suggest that there are place pitch distortions when using this stimulation mode. Presumably, these distortions are produced by the asymmetric nature of the QPVC stimulation mode. This conclusion is consistent with the observation that the two symmetric virtual channels (MPVC and VTP) evaluated in this manuscript do not demonstrate these deviations from tonotopic place pitch representation. Although they have not been evaluated in the present manuscript, it is presumed that other asymmetric stimulation modes, such as the steered pTP (Wu and Luo, 2013) and the DC-VC (Nogueira et al., 2017), have similar limitations. Therefore, the data in the present manuscript suggest that a symmetric mode (such as the VTP) may be a better choice for use in a sound coding strategy.

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