Perceptual space induced by cochlear implant all-polar stimulation mode

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It has often been argued that a main limitation of the cochlear implant is the spread of current induced by each electrode, which activates an inappropriately large range of sensory neurons. In order to reduce this spread, a new stimulation mode, the all-polar mode, was tested with 5 participants. It was designed to activate all the electrodes simultaneously with appropriate current levels and polarities to recruit narrower regions of auditory nerves in the region of specific intra-cochlear electrode positions (denoted all-polar electrodes). In this study, the all-polar mode was compared to the current commercial stimulation mode: the monopolar mode. The participants were asked to judge the sound dissimilarity between pairs of 2-electrode stimuli that differed in the electrode positions and were presented in either monopolar or all-polar mode. The dissimilarity ratings were analysed using a multidimensional scaling technique and a three-dimensional stimulus perceptual space was produced. For both modes, the first perceptual dimension was highly correlated with the average position of the electrical stimulation and the second dimension moderately correlated with the distance between the two electrodes. The monopolar and all-polar stimuli were separated by a third dimension, which may indicate that all-polar stimuli have a perceptual quality that differs from monopolar stimuli.

INTRODUCTION

The cochlear implant (CI) is a biomedical device that can restore functional hearing for a large portion of people with severe to profound hearing loss (Blamey *et al.*, 2013). Despite this great success the sound quality produced by the device needs to be improved to help CI users to better understand speech in noise and to enjoy music. In the most common setup (for example, a Cochlear® device with the monopolar ACE strategy), the input signal is band-pass filtered. Then the envelope of the output of each filter is extracted to modulate a fixed-rate electric pulse train that activates specific electrodes. In order to avoid uncontrolled current interaction only one electrode is activated at a time (sequential interleaved stimulation). In the monopolar (MP) mode, each singly-activated intra-cochlear electrode is paired with an extra-cochlear return electrode.

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Recently a new stimulation mode has been designed to better control the current interaction and to create independent and focused places of electrical stimulation along the cochlea. In this mode, called all-polar (AP), all the electrodes are activated simultaneously. The current levels and polarities on each electrode are set in order to create a sum of all potentials that will confine the current field to specific and independent places within the cochlea. Recent behavioral experiments (Marozeau *et al.*, 2015) have shown that AP mode produces less current summation when 2 electrodes are simultaneously activated compared to MP mode. However, when the stimuli were matched in loudness, no significant advantage in terms of spread of neural excitation was found for the AP mode.

This study aimed to investigate the difference between MP and AP modes in the perceptual space generated by dual-electrode stimuli using a multidimensional scaling technique.

METHOD

Participants

Five CI users participated to the experiment (including 3 women). Their age ranged between 44 and 82 years old (mean: 67.2; std: 17) with a duration of deafness before first implantation ranging from 9 to 31 years (mean: 19; std: 8.5). All the participants were unilateral CI users who had received a second research implant on the contralateral side that could be connected to an external stimulator via a percutaneous connector. During an 18-month period, they participated in a number of experiments (for example Marozeau *et al.*, 2015). While not participating in experiments, the participants connected their research implant to a standard sound processor programmed with the ACE strategy (McDermott *et al.*, 1992; Vandali *et al.*, 2000) via a wearable adaptor (van den Honert and Kelsall, 2007). After the research period, participants were explanted and re-implanted with a standard commercial cochlear implant. This project conformed to The Code of Ethics of the World Medical Association (Declaration of Helsinki), and was approved by the Royal Victorian Eye and Ear Hospital Human Research Ethics Committee (Project 11-993H). Recruitment was conducted through the Cochlear Implant Clinic at the Royal Victorian Eye and Ear Hospital and the Hearing CRC.

Stimuli

The stimuli were generated by an experimental stimulator that was able to activate all 22 electrodes simultaneously to produce MP or AP stimuli. In this study we will refer to the electrode around which a focused current field is created in AP mode, by activating all the electrodes simultaneously, as an "AP electrode". Likewise, the term "MP electrode" designates the single intra-cochlear electrode activated in MP mode. AP electrodes were created by first measuring the impedances between all possible pairs of electrodes. Then a weight matrix that defined the relative current amplitudes across the array predicted to produce the focused current field at each electrode position was derived by inverting the impedances matrix (van den Honert and Kelsall, 2007; Marozeau *et al.*, 2015).

A set of 20 dual-electrode stimuli were created: 10 in AP mode and 10 in MP mode. Each MP stimulus was a 500-ms-duration pulse train, with two biphasic pulses per period of 10 ms. The two pulses were presented sequentially with an onset to onset delay of 232 µs to two different MP electrodes. Each biphasic pulse had a phase width of 100 µs and an interphase gap of 20 µs. The current levels of each electrode were adjusted so that each electrode contributed equally to the overall loudness, and all the dual-electrode stimuli were adjusted to have an equal comfortable loudness (using a loudness balance method described in Marozeau *et al.*, 2015). The MP electrodes were selected in order produce different electrode separations and different average electrode positions: 17/15, 17/13, 17/11, 17/9, 15/13, 15/11, 15/9, 13/11, 13/9, and 11/9[1,2]. Stimuli presented in AP mode were similar in all aspects other than the mode, and were loudness balanced to the MP stimuli.

Task

Participants were presented, first, with each of the 20 stimuli in random order to acquaint them with the range of perceptual differences in the set of stimuli. They were allowed to hear them as many times as they wanted. Then, they were informed that the goal of the experiment was to estimate the similarity in sound quality between pairs of sounds. Remaining small differences of loudness were to be ignored. They were presented with every possible pair of the 20 stimuli in random order, totalling 380 pairs (excluding pairs with repeated stimuli). In each trial, the participants were instructed to judge how similar the pairs were, and to respond by moving a cursor on a slider bar labelled from “most similar” to “least similar”. Participants could listen to the pair as many times as they wanted, by pressing a “listen again” button. When they were satisfied with their judgment, they pressed a “validate” button, and the next trial began.

RESULTS

An MDS solution was derived based on the dissimilarity scores averaged across the five participants. In order to reduce space distortion due to a bound dissimilarity scale, dissimilarity scores were transformed with a hyperbolic arctangent transformation (as in Marozeau and de Cheveigné, 2007). The scores were then analysed using the MDSCAL procedure, implemented according to the SMACOFF algorithm (Borg and Groenen, 1997). A three-dimensional solution was selected because higher-dimensional solutions did not significantly decrease the stress of the model. As the MDSCAL solution is rotationally undetermined, the solution was rotated with a procrustean procedure in order to maximize the correlation between the MDS dimensions and some physical descriptors (described below).

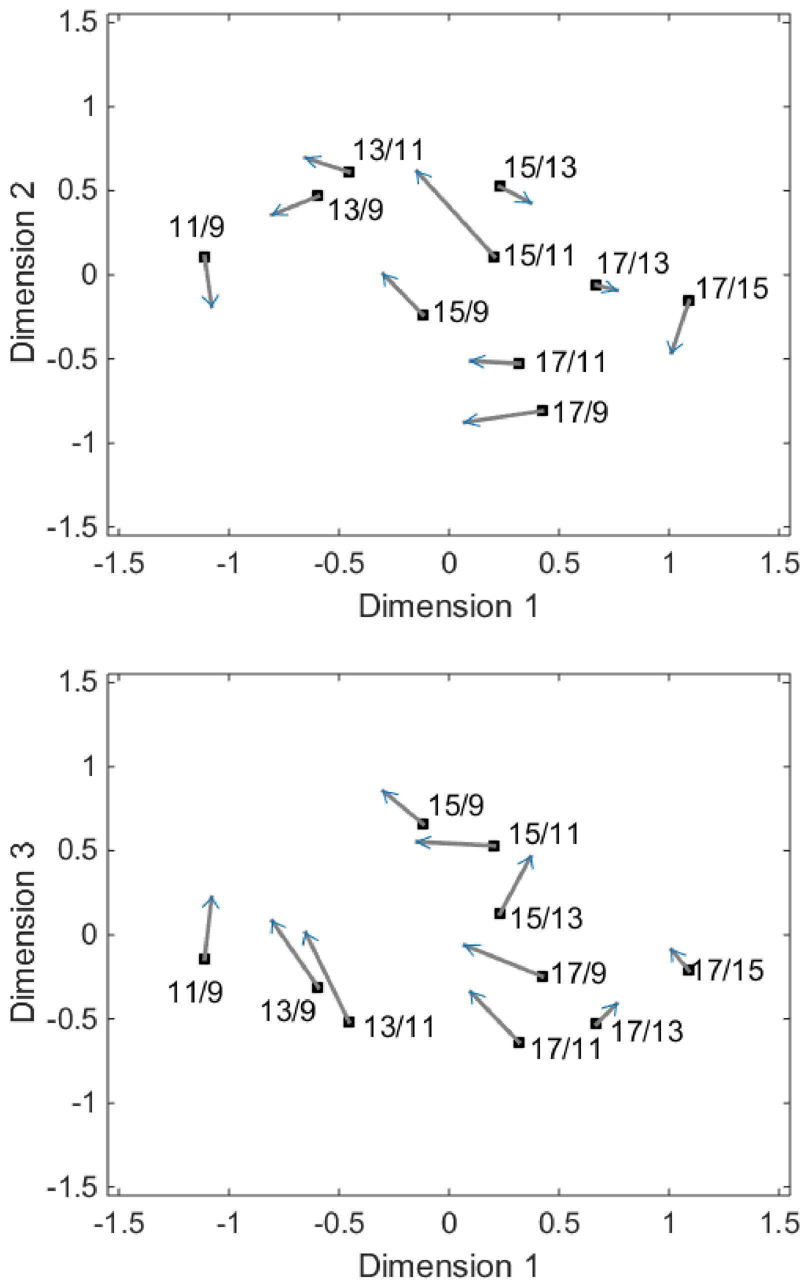

Fig. 1: MDS solution. Each MP stimuli is represented by a square and each AP stimuli is represented by the end of the arrow. The two numbers next to each stimulus indicate the "AP" and "MP" electrodes activated. Each MP and AP stimulus that shared the same activated electrodes are linked by an arrow.

Figure 1 shows the 3-dimensional solution. Each MP stimulus is represented by a square and each AP stimulus is represented by the end of the arrow. The two numbers next to each stimulus indicate the AP and MP activated electrodes. The MP and AP stimuli that shared the same activated electrodes are linked by an arrow. The figure shows that the stimuli are grouped into clusters based on the most apical electrode. The projection on the first dimension is highly correlated with the average activated electrode position [$R^2 = 0.93$, $df = 19$, $p < 0.0001$]. The second dimension is significantly correlated with the distance between the two activated electrodes [$R^2 = 0.44$, $df = 19$, $p = 0.001$]. Two features can be observed on the third dimension: first, the stimuli with electrode 15 as the most apical (15/13, 15/11, and 15/9) are separated in that dimension from the other stimuli; secondly, the AP stimuli are consistently separated from the MP stimuli (i.e., the arrows are always pointing upward).

Figure 2 shows the average difference of the projection on each dimension between the position of the MP stimuli and their AP counterparts. On average, in the first dimension, AP stimuli are located on the left of the MP stimuli [$t(9) = 2.42$, $p = 0.0389$], and upward on the third dimension [$t(9) = -5.3008$, $p < 0.0001$]. No significant difference can be observed on the second dimension [$t(9) = 0.0780$, $p = 0.9395$].

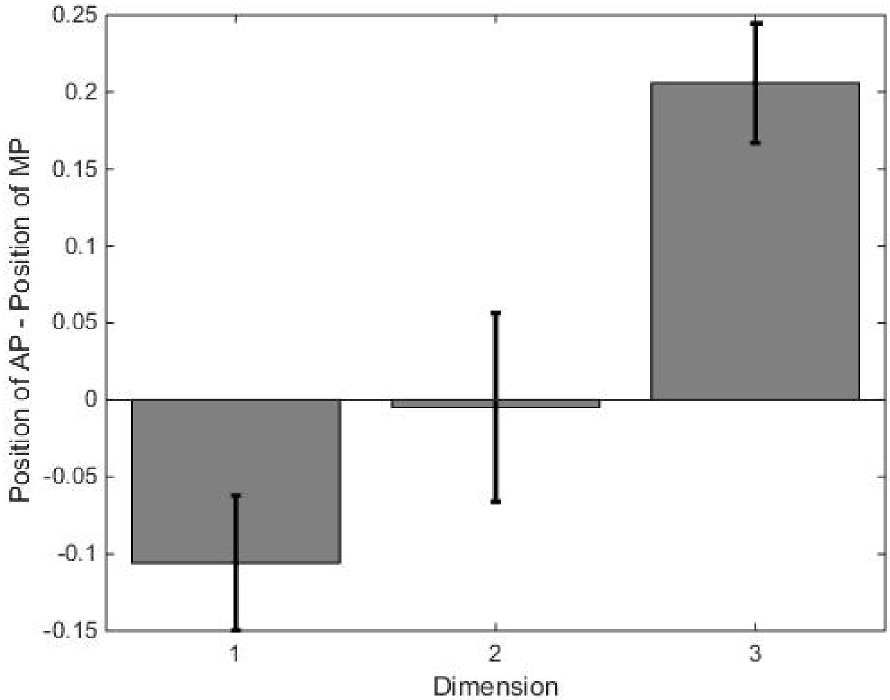

Fig. 2: Average difference of the projection on each dimension between the position of the MP stimuli and their AP counterparts.

DISCUSSION

The main aim of the experiment was to study the effect of stimulation mode (AP vs MP) on a perceptual space. Overall, the AP stimuli and their MP counterparts are always located closely to each other on the three dimensional space. However, two clear effects can be observed. First, as showed in Fig. 2, on average AP stimuli are shifted toward the left of first dimension compared to the MP stimuli. As this dimension is clearly correlated with the average activated electrode position, it can be interpreted as a dimension linked to the perception of pitch, ranging from high pitch stimuli on the left to lower pitch on the right. This will indicate that AP stimuli are perceived as higher in pitch than MP stimuli. Second the effect of mode can be seen on the third dimension as an upward shift. It is unclear why on that dimension the stimuli 15/13, 15/11 and 15/9 are also shifted upward in both modes compared to the other electrode positions. However, it is possible that the 3-D solution is composed of bended 2-D plans like a half cylinder (or a horse saddle). This kind of distortion is often found in MDS studies, where a 1-D solution is represented as a horse shoe in a 2-D solution (for example McKay *et al.*, 1996). If this distortion is ignored, then the third dimension clearly separated the MP and AP stimuli. This result would indicate that the AP mode differed from the MP mode along a perceptual dimension that was independent of electrode position and separation.

The first two dimensions of the 3-D solution can be strongly correlated with simple physical descriptors. Those descriptors are the CI equivalent of common acoustical descriptors of timbre: the spectral centroid and the spectral spread (see Marozeau *et al.*, 2003 for a complete description). This indicates that the perception of those dimensions might be similar to the perception of timbre by normal hearing listeners (Kong *et al.*, 2009; Kong *et al.*, 2012).

Similar results were previously found by McKay *et al.* (1996). They asked four CI participants to rate the dissimilarity between pairs of dual-electrode bipolar stimuli that varied in electrode separation and overall position. The bipolar stimulation widths were also varied with two distances between the active and return electrodes of the bipolar pair in order to test the effect of current spread. They found that for most CI participants a two dimensional solution related to the average activated electrode position and the activated electrode separations. They also found similar MDS solutions with the two bipolar stimulation widths. However, as this parameter was not varied within the same session, it was not possible to assess whether the width of the bipolar stimuli produced an isometric shift along a specific dimension as observed in the current experiment.

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ENDNOTES

[1] The electrode will be identified by the Cochlear Ltd convention in which electrode 22 is the most apical electrode, and electrode 1 the most basal.

[2] The stimuli were shifted basally by 2 electrode positions for one participant in order to avoid high AP threshold regions. The relative electrode positions were identical to those of the other subjects.

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