Speech Processing for Cochlear Implants and Bimodal Stimulation

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Introduction

An increasing number of cochlear implant (CI) recipients have usable acoustic hearing in one or both ears post-operatively. Several recent studies have shown that such people usually benefit from bimodal stimulation in comparison with separate use of either the CI or an acoustic hearing aid (HA). In general, the different devices function autonomously and are fitted to each user independently. However, improvements in performance are likely in future if the acoustic and electric modes of stimulation are designed to provide compatible and complementary information.

Previous research has related the pitch perceived with electric stimulation to that perceived acoustically (Boex et al., 2006). Although providing compatible pitch sensations may be beneficial with bimodal stimulation, it is also important to ensure that loudness is perceived appropriately via each mode of stimulation (Ching et al., 2004). The present study aimed to investigate loudness perception in CI subjects who had usable acoustic hearing. The specific aims included determining the dynamic range (DR) of perception for both acoustic and electric stimulation, estimating the shape of the loudness functions, and comparing the loudness perceived when similar signals are presented via each mode of hearing.

Materials and Methods

Eight subjects participated in the experiments. Relevant details about them are provided in Table 1. All were monaural users of 22-electrode Nucleus multi-channel CI systems. In the experiments, acoustic stimuli were presented to the non-implanted ear. Hearing thresholds in that ear, averaged across subjects, are shown in Figure 1. For all subjects, hearing thresholds were measurable at each frequency below 1 kHz shown on the graph.

The acoustic stimuli were designed to suit the residual hearing of these subjects. The stimuli consisted of a band of noise with a width of one octave presented at 10 different levels. The band-limited noise was created by filtering a white noise with a 10^{th}-order Butterworth band-pass filter having slopes of 60 dB/octave, a lower cut-off frequency of 250 Hz, and an upper cut-off frequency of 500 Hz. All acoustic stimuli had a duration of 500 ms, and were smoothed at the onset and offset with linear ramps of 30-ms duration.

The electric stimuli were constructed to emulate the output of a CI speech processor when the same type of acoustic stimulus was received at the microphone input. Thus, the stimuli consisted of activity on only the four most-apical electrodes (E22, E21, E20, and E19). In a typical speech-processor MAP, these electrodes are assigned to low frequencies (approximately 200-600 Hz). The relative levels on the active electrodes were set initially in relation to the DR on each electrode for each subject. These DRs were extracted from the MAPs that had previously been programmed into each subject's speech processor; that is, they extended from the threshold level (T-level) to the maximum comfortable level (C-level) on each electrode. The relative levels of the electric stimuli were specified within these DRs and held constant throughout the experiment. The duration of all stimuli was 500 ms. The stimuli were generated by a custom software system connected to an experimental sound processor. The software controlled the overall levels of the electric stimuli and collected the subjects' responses.

The experimental procedure comprised three parts. In the first part, the DR of the acoustic stimulus was determined separately for each subject by measuring levels corresponding to threshold and loudness discomfort (LDL). Subsequently, 10 levels were calculated spanning the DR for each subject. Ten stimuli at each of these levels were presented to each subject in a random order. The subjects were required to provide numerical estimates of the perceived loudness of each stimulus. The 10 estimates at each level were averaged for each subject.

Subject	Age (yrs)	Sex	Years of deafness	Aetiology	Months of CI experience	Implant type	Strategy	Rate (Hz)
S36	59	M	2	Progressive hereditary	4	CI24RE (CA)	ACE	900
S39	73	F	3	Unknown[1]	4	CI24RE (CA)	ACE	900
S42	67	F	2	Unknown[2]	6	CI24RE (CA)	ACE	900
S51	63	M	1	Unknown[3]	8	CI24R (CA)	ACE	720
S54	77	M	5	Unknown	29	CI24R (CS)	ACE	900
S55	78	F	2	Unknown	7	CI24R (CA)	ACE	900
S57	62	F	15	Unknown	24	CI24R (CS)	ACE	900
S59	82	F	8	Unknown	48	CI24R (CS)	SPEAK	250

Table 1. Relevant information about the subjects who participated in the experiments. Etiology: [1]progressive, possibly noise or ototoxicity; [2]possibly otoxicity or wide vestibular aqueduct syndrome; [3]possibly noise.

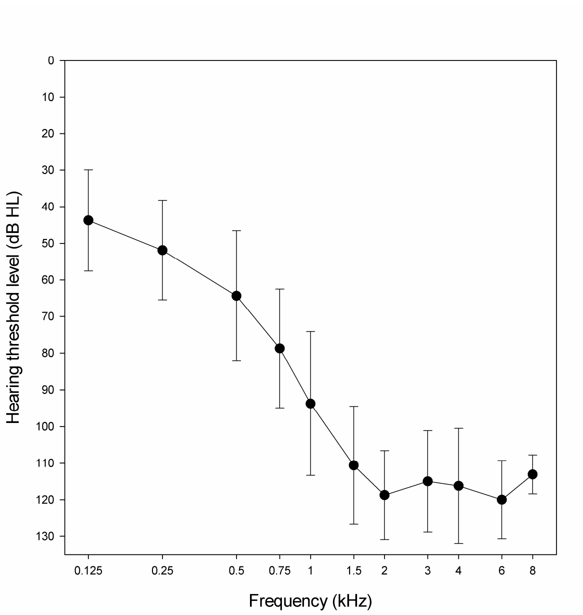

Figure 1. Average audiogram for the eight subjects who participated in the experiments. The error bars show ±1 standard deviation from the mean. For at least some subjects, hearing thresholds were not measurable at one or more frequencies above 750 Hz within the limits of the audiometer.

In the second part of the procedure, the level of the electric stimulus was varied until the loudness perceived by each subject corresponded to the categories of ‘soft,’ ‘comfortable,’ and ‘loud but OK’. In addition to these three levels, thresholds and LDLs for the same stimulus were determined for each subject.

Finally, in the third part of the procedure, subjects heard the acoustic stimulus alternating with one of the electric stimuli, which was presented at each of the levels mentioned above (i.e., eliciting loudness responses of ‘soft,’ ‘comfortable,’ and ‘loud but OK’). The subjects adjusted the level of the acoustic stimulus until its loudness was judged equal to that of each of the electric stimuli.

The data obtained in these experiments that were levels (i.e., thresholds, LDLs, and levels corresponding to the three intermediate loudness categories) were scaled in relation to the DR for each type of stimulus in each subject. This made it possible to compare results for the acoustic and electric stimuli, and across subjects, despite the differing modes of hearing and absolute signal levels. Thus, most results presented below are on a scale of sensation level, with units of percent dynamic range.

Ethics approval for this project was provided by the Human Research and Ethics Committee of the Royal Victorian Eye and Ear Hospital, Melbourne, Australia.

Results

In the first part of the procedure, thresholds and LDLs were determined for each subject for the acoustic stimulus. Figure 2 shows the DRs calculated from these levels plotted as a function of the threshold for each subject. The straight line, which is a good fit to these data (R^2 = 0.72), shows that, on average, DR decreased with increasing severity of hearing impairment.

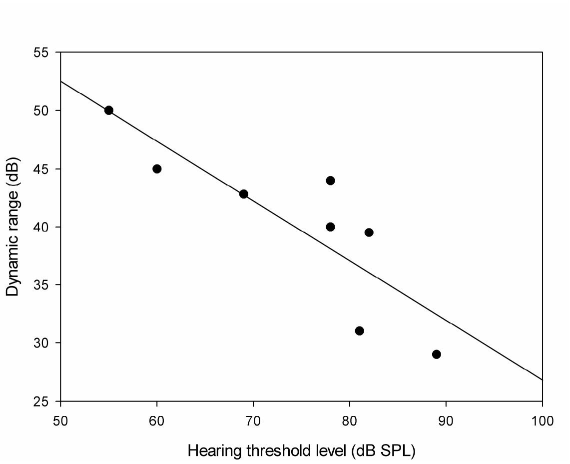

Figure 2. Dynamic range of the experimental acoustic signal for each of the eight subjects, and a straight line fitted to those data. Levels were measured in an ear simulator.

The results of the loudness-estimation experiment are shown for each subject in Figure 3. The subjects' numerical loudness estimates are shown on the ordinate, while the levels of the acoustic stimuli, scaled between threshold (0%) and LDL (100%), are shown on the abscissa. The line fitted to all of the data is based on a cubic function. The results show that loudness increased more steeply, on average, for levels in the lower 30% of the DR than in the upper 70% of the DR. In the latter region of the DR, the fitted curve is almost straight, suggesting that loudness on a logarithmic scale is a linear function of stimulus level on a logarithmic (dB) scale.

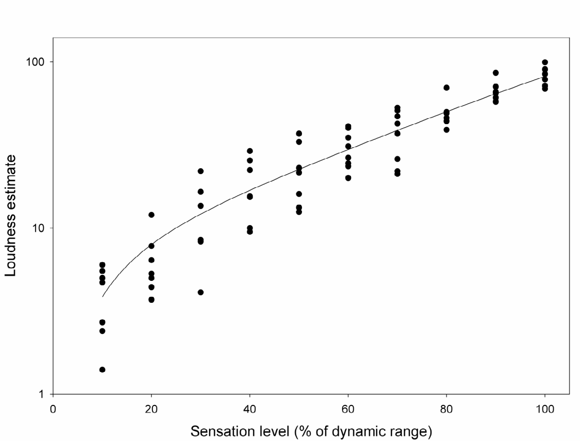

Figure 3. Average loudness estimates for the acoustic stimuli for each of the eight subjects, and a line fitted to those data.

The results of the remaining part of the experiment are shown in Figure 4. That graph shows the relative levels, averaged across subjects, of the acoustic and electric stimuli that were matched in loudness. In addition, a fitted line and levels corresponding to threshold and LDL are shown. As is evident in the figure, the straight line is an almost perfect fit to these data ($R^2 \approx 1$).

This suggests that when acoustic and electric levels are scaled in relation to their corresponding DRs, the perceived loudness of each type of signal is very similar.

Discussion

As shown in Figure 2, there was a wide range of DRs among subjects for the acoustically presented signal. Across the eight CI users with acoustic hearing who participated in this study, the DR varied from 29 to 50 dB. Smaller DRs corresponded to higher (worse) hearing threshold levels. This finding is consistent with that of Dillon and Storey (1998), who found that, on average, DRs decrease with increasing hearing threshold levels.

The growth in perceived loudness with increasing physical level of the acoustic stimulus followed a non-linear function, as shown in Figure 3. On average, loudness grew more steeply at levels near the threshold of detection than at higher levels. The loudness growth function was found to be approximately linear in the upper 60-70% of the DR when subjective magnitude estimates were plotted on a logarithmic scale against sound levels on a dB-like scale. Thus, at these higher levels, loudness followed a power function of intensity. These perceptual characteristics are consistent with results published previously (Humes and Jesteadt, 1991).

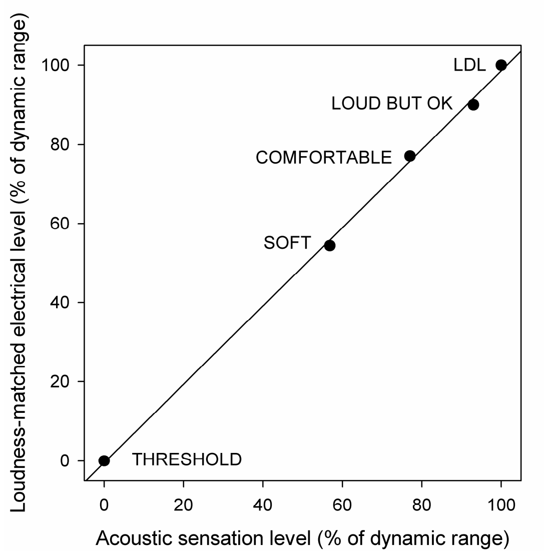

Figure 4. Levels matched in loudness between the acoustic and electric stimuli, averaged across subjects, and a straight line fitted to those data.

The results in Figure 4 suggest that the loudness of a complex signal is perceived as similar when presented either acoustically or electrically provided that the levels are at similar proportions of the dynamic range. For example, a signal at a level of 80% of the acoustic DR has about the same loudness, on average, as the corresponding signal at a level of 80% of the electrical DR.

Taken together, these findings have important implications for the design of CI systems and for the fitting of

HAs to recipients of CIs who have usable acoustic hearing. Most CI sound processors convert the level of acoustic input signals to an electric stimulation level by means of a function that is approximately linear when both levels are represented on logarithmic scales (McDermott, 2006). The input DR may be adjusted when the CI sound processor is programmed, but it is not related to the electrical DR measured at the recipient's electrodes. For instance, recent sound processors used with the Nucleus CI system have an input DR of 35-45 dB, which is selected independently of the T- and C-levels applied in the recipient's MAP. However, today's CI recipients often have usable acoustic hearing, at least in the ear opposite to the one that is implanted. The DR of that hearing may vary over a wide range. Furthermore, when an acoustic HA with amplitude-compression sound processing is fitted, the input DR will be different from the DR related to the unaided hearing (Dillon, 2001). In contrast to the usual fitting of CI sound processors, the fitting of acoustic HAs often results in an input DR that is related to the perceptual characteristics of the impaired ear.

The findings reported above suggest that any differences in input DR for sounds processed by the two types of device may result in differences between the loudness perceived with each mode of stimulation. For example, a sound that is presented from a CI system at 80% of the electrical DR will be perceived as having the same comfortable loudness as the same sound amplified by an acoustic HA only if the output of the HA is close to 80% of the listener's acoustic DR. This depends on an appropriate setting of the gain and compression functions of the HA for individual CI users. In general, the HA's input DR, aided threshold, and shape of the compression function should be adjusted to match the CI in terms of output signal levels relative to the user's perceptual DR.

The signals used in the experiments described above were chosen specifically to be audible via both modes of stimulation. Because CI users with usable acoustic hearing generally have most hearing sensitivity at low frequencies, the signals were noise-bands limited to the frequency range 250-500 Hz. For the present group of subjects, the loudness-matching procedure between the two modes of stimulation would not be feasible with only a single type of signal limited to a higher frequency range. For example, a narrow noise-band centred on 4 kHz would be audible via the CI, but not via the HA, even if the HA was programmed to a gain that was unrealistically high. Therefore, it is unclear from the results of the above experiments exactly how loudness should be controlled for input signals containing frequencies corresponding to acoustic and electric stimulation that overlap only partially or not at all.

Conclusions

The results of the present experiments are consistent with previous reports about the dynamic range of acoustic hearing in subjects with severe to profound sensorineural impairment. They are also consistent with published data and models describing the relationship between perceived loudness and sound pressure level in such listeners. Although the acoustic DR varied widely (i.e., 29-50 dB) across the subjects, CI sound processors are typically programmed such that the DR for acoustic input signals is approximately constant (e.g., 35-45 dB). Therefore, to optimise loudness perception with bimodal stimulation, amplitude compression functions in HAs should be programmed individually so that the acoustic signals are perceived appropriately relative to the electric stimuli delivered by the CI.

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