A REVIEW OF BIMODAL BINAURAL HEARING SYSTEMS AND FITTING

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ABSTRACT: Cochlear implants and hearing aids are both suitable for use by people with severe to profound hearing loss (greater than 70 dB HL), and the "bimodal" combination of one of each device in opposite ears has become a commonly recommended option. This paper reviews some of the experimental evidence assessing the performance of bimodal hearing. To obtain the best bimodal performance, it is recommended that both devices are fitted together; that loudness of the two devices is balanced for a wide range of input levels; that the signal to noise ratio is maximised in each ear separately; that speech should be presented to both ears; and noise should be presented to one ear only if possible.

1. INTRODUCTION

Over the last 25 years, Australia has been at the forefront of sound processing research for cochlear implants (CI) and hearing aids (HA) for people with impaired hearing [1-4]. During this time, speech perception of severely-to-profoundly deaf people using CIs has improved until it is comparable or better (at least in some circumstances) than speech perception of people with severe hearing loss using HAs. It has been estimated that a cochlear implant user performs equivalently to a person with 70 to 80 dB HL hearing loss [5-7]. However, this does not mean that the same types of speech information are provided by a CI and a HA. HAs usually provide more low frequency information than CIs and CIs usually provide more high frequency information than HAs. Therefore the combination of a CI and HA is likely to provide access to information from a wider frequency range than either device on its own. The combination is called "bimodal stimulation" when the CI and HA are in opposite ears [8-10], and "hybrid stimulation" when the hearing aid acoustically stimulates the implanted ear [11].

CIs usually stimulate neurons in the basal part of the cochlea that produce relatively high-pitched sensations, so the addition of a HA with low-frequency amplification will usually sound more natural than a CI on its own [9]. Frequency discrimination and resolution are usually better for acoustic than for electric stimulation. This means that the HA can provide more accurate information about voice pitch and better performance in background noise [12]. These benefits are available to both bimodal and hybrid listeners, but bimodal listeners can also benefit from binaural effects.

It is well-known that two ears are better than one in many situations, and that the advantages of binaural hearing come from three main perceptual effects:

- The listener can combine information from the two ears,
- The listener can pay attention to the ear with the greater signal-to-noise ratio, and
- The listener can use the time and intensity differences between the two signals.

This paper makes recommendations for the design of a bimodal binaural sound processor that takes maximum advantage of these three effects.

2. COMBINING INFORMATION FROM HA AND CI

A clinical study of CIs for severely hearing-impaired adults was commenced by Cochlear Corporation in 1988. The first bimodal prosthesis was reported in 1993 [8]. Over the last 15 years there have been consistent reports that bimodal stimulation provides significant benefits over and above a unilateral cochlear implant. These benefits come partly from the fact that acoustic and electric stimulation provide complementary information, and partly from binaural effects.

Binaural information can only be combined if the sound can be heard in both ears at the same time. Psychoacoustic studies of loudness in CIs and HAs indicate that the range of sound input levels where this fundamental requirement is met can be quite limited because the dynamic range of acceptable sounds, classified as "soft" to "comfortable" is narrow with both types of device and varies widely across frequency and between individuals [13].

The vertically striped regions in Figure 1 show the input dynamic range that produced very soft to comfortable outputs with the HA. The loudness classifications were derived from a psychophysical experiment that used a loudness scale with seven categories: "too soft", "very soft", "soft", "medium/comfortable", "loud", "very loud", and "too loud" [13]. The horizontally striped regions show the input dynamic range that produced very soft to comfortable outputs with the CI. The grey region shows the input dynamic range that was comfortable and audible in both ears at once. This is the "sweet spot" for bimodal listening where information from both ears can be combined most easily. For these profoundly-deaf patients, the sweet spot was not very big for

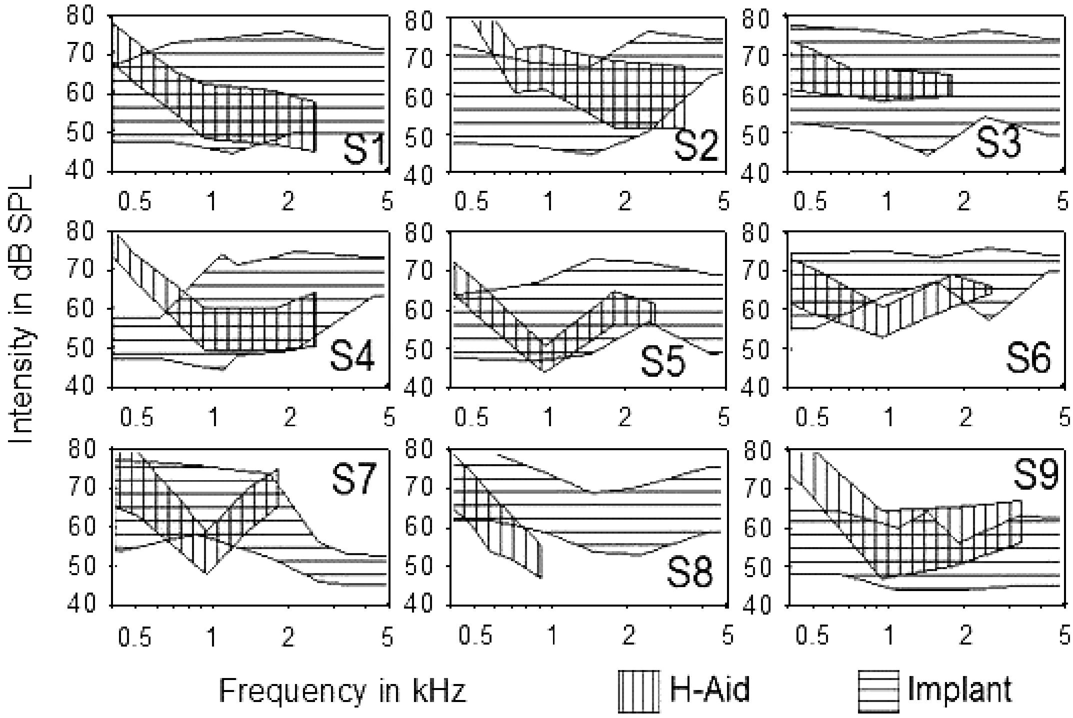

Figure 1. Acoustic and electric loudness scaling data for the CI and HA ears of nine patients overlaid on the same diagram. The "sweet spot" where sounds are audible and comfortable in both ears simultaneously is small and covers a narrow range of input levels.

conventional hearing aid fittings. Despite their limited range of hearing with conventional devices, most of these patients went on to become successful bimodal CI and HA users.

The ideal conditions for bimodal listening occur when the information presented to each ear is maximised, and this can be done by using an optimizing amplifier such as adaptive dynamic range optimization, or ADRO® [14-16]. ADRO keeps sound in both ears within the listener's optimal dynamic range in many narrow frequency bands using two fuzzy logic rules. The comfort rule says if the sound is too loud, make it softer by slowly decreasing gain. The audibility rule says if the sound is too soft, make it louder by slowly increasing gain.

The effectiveness of ADRO as a bimodal amplifier was illustrated in a study conducted at the University of Osaka [17]. The participants were six patients who used a cochlear implant in one ear and a hearing aid in the other. The Japanese version of the Hearing in Noise Test (the Japanese HINT) was used to compare two devices using ADRO with two conventional devices that did not use ADRO. The ADRO combination provided a 5.2 dB advantage for speech reception threshold in quiet and a 3.0 dB advantage for signal-

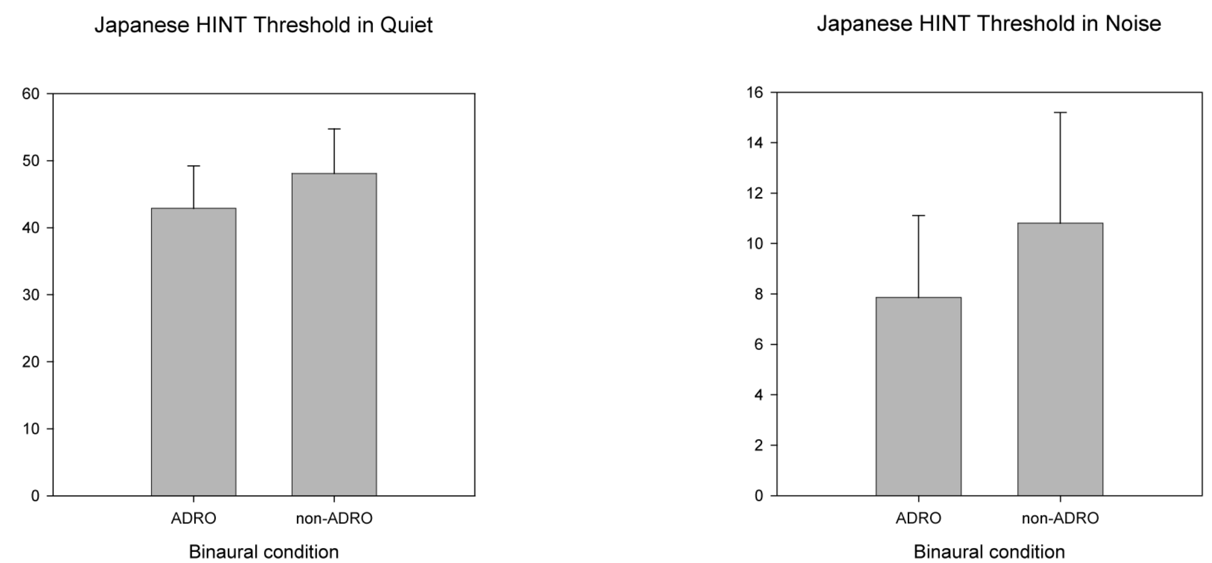

Figure 2. The ADRO bimodal combination provided a 5.2 dB advantage for speech reception threshold in quiet and a 3.0 dB advantage for signal-to-noise-ratio in background noise compared to the non-ADRO bimodal combination..

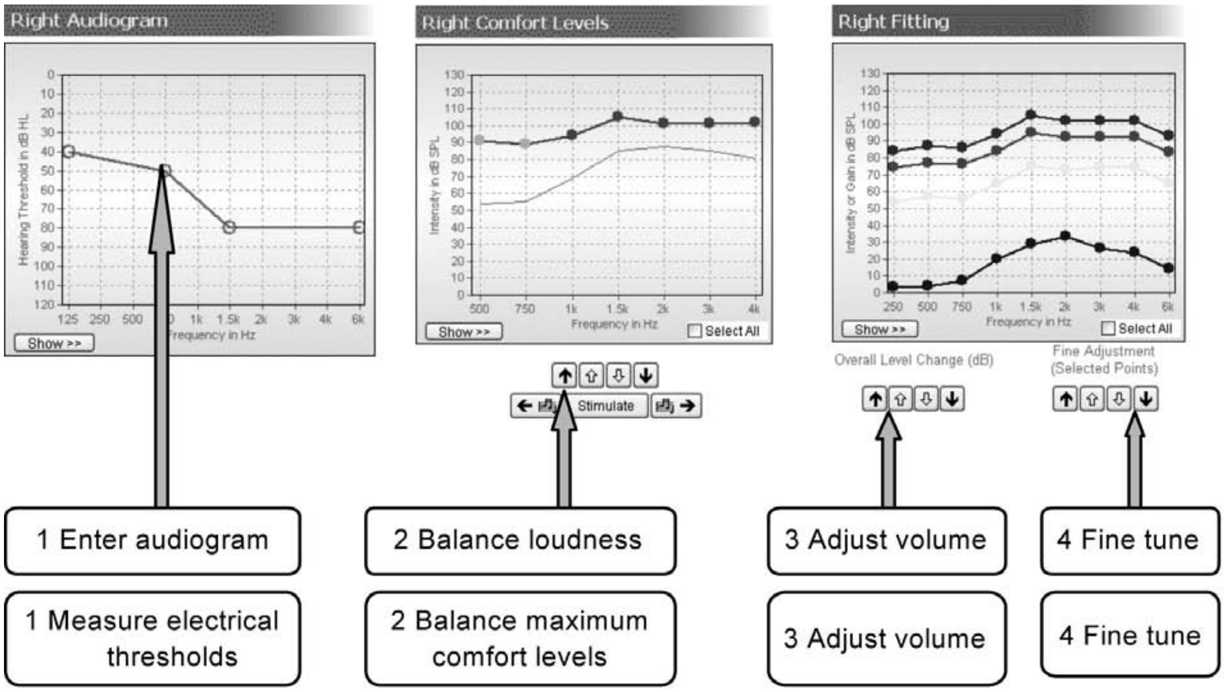

Figure 3. The four basic steps for fitting ADRO are the same in a CI (lower boxes) and HA (upper boxes).

to-noise-ratio in background noise (see Figure 2). The data were non-normally distributed, and a Wilcoxon signed rank test indicated that the differences between ADRO and non-ADRO conditions were statistically significant ($p < 0.05$). These advantages are attributed to the combined additional information delivered by the ADRO devices compared to the non-ADRO devices.

The effectiveness of bimodal fittings has now been more widely recognised [10,16] and special fitting methods for hearing aids have been devised to maximise bimodal benefit [18]. When ADRO is used, the same fitting method is used for each ear, and a binaural balance of loudness across frequencies is automatically achieved. Figure 3 summarises the four basic fitting steps for CI and HA [19]. It has also been shown that ADRO can improve speech perception scores and sound quality in unilateral CIs [20, 21] and unilateral and bilateral hearing aids [15, 22].

3. IMPROVING SIGNAL-TO-NOISE RATIO IN EACH EAR

In binaural listening, SNR at each ear can be improved by the head shadow effect and by directional microphones. Figure 4 shows the results of the HINT test for eight listeners with impaired hearing using ADRO behind-the ear hearing aids on both ears [23]. Speech was presented from the front and noise was presented from 3 different positions to the side and behind the listeners. Three different microphones were used: omni-directional, fixed directional with a supercardioid response pattern, and adaptive directional microphone. The adaptive directional microphone adopted an omni-directional response pattern for sound levels below 65 dB SPL. Above 65 dB SPL, an omni-directional pattern and a figure-eight dipole pattern were formed from the signals from two omni-directional microphones mounted on the hearing aid with a separation of about 1 cm. The omni-directional and dipole patterns were combined in a manner that kept the response gain from the front of the hearing aid constant, while minimising the total input sound level [24].

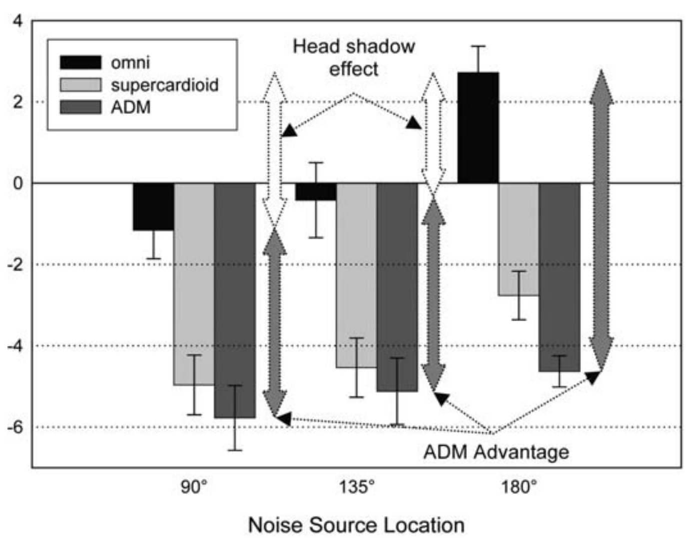

Figure 4. HINT thresholds using omni, fixed directional and adaptive directional microphones in background noise.

When noise came directly from behind the listener, the signal-to-noise ratio was the same at both ears and there was no head shadow effect. When the noise came from one side, there was a head shadow advantage of 3 to 4 dB in the omni-directional microphone condition. When the ADM was turned on, it improved the signal-to-noise ratio at both ears, giving an additional advantage of about 5 dB when noise was coming from the side, and about 7 dB when noise was coming from behind the listener. The combination of binaural hearing and adaptive directional microphones allowed these listeners to understand speech at -5 dB signal-to-noise ratio in these three noise conditions, which is similar to the performance of listeners with normal hearing. Paired t-tests showed that the fixed directional microphone performed significantly better than the omni-directional microphone in every noise condition ($t=10.15$, $p<0.001$ at 90º; $t=6.48$, $p<0.001$ at 135º; $t=8.57$, $p<0.001$ at 180º), the ADM performed better than the omni-directional microphone in every noise condition ($t=4.7$, $p<0.05$ at 90º; $t=6.09$, $p<0.001$ at 135º; $t=8.04$, $p<0.001$ at 180º), and the ADM performed better than the fixed directional microphone in noise from 180º ($t=2.59$, $p<0.05$). The head shadow effect (differences between HINT scores for the 90º, 135º and 180º noise directions in the omni-directional condition) were statistically significant: head shadow effect = 3.9 dB, paired-t = 6.27, $p<0.001$ for 90º; head shadow effect = 3.1 dB, paired-t = 5.00, $p<0.001$ for 135º.

These data clearly illustrate that binaurally aided hard-of-hearing listeners can benefit by listening to the ear with the better SNR. A similar head shadow effect was found in the Japanese bimodal study [17] where behind-the-ear microphones were used. The Japanese HINT thresholds in noise were 7.86 dB (SD 3.25 dB) with noise from the front, 5.62 dB (SD 4.26 dB) with noise from the implant side, and 2.37 dB (SD 8.68 dB) with noise from the HA side. These SNR values correspond to head shadow effects of 2.24 dB for noise from the CI side, and 5.49 dB for noise from the HA side. Although they were not statistically significant in the bimodal study, the observed head shadow effects were of the same order of magnitude as the statistically significant effects in the ADM study.

4. SEPARATING SPEECH AND NOISE

Listeners with a cochlear implant and a hearing aid in opposite ears can also separate speech from noise using binaural cues. This is illustrated by a study in which speech and noise were presented in seven different binaural conditions as shown in Table 1 [25]. The noise was a white noise presented at a comfortable level. The speech stimuli were a small closed set of spondee words spoken by a female speaker and chosen so that every listener could score 100% recognition of the words with either hearing aid or cochlear implant when they were presented at the same comfortable level in quiet.

Condition	Voice	Noise
HA-0	HA	none
CI-0	CI	none
HA-HA	HA	HA
CI-CI	CI	CI
Diotic	HA+CI	HA+CI
HA-CI	HA	CI
CI-HA	CI	HA

Table 1. Seven conditions in which speech and noise were presented to the HA and CI ears of the participants.

Figure 5 shows the results averaged for the three listeners. In each of the seven conditions, the level of presentation of the noise was kept constant and the level of the voice was varied to find the level at which the listener scored 70% correct word recognition. In this graph 0 dB corresponds to the comfortable level of the noise for each participant. Negative levels mean that the speech was softer than the noise at the 70% correct level. ANOVA with subject and condition as independent variables was followed by post-hoc t-tests using the Bonferroni method to compare the SNRs in the different conditions. The mean SNRs for the HA-HA, CI-CI, and Diotic conditions were not significantly different from one another ($p>0.05$). The mean SNRs for CI-HA, HA-CI, HA-0, and CI-0 conditions were not significantly different from one another ($p>0.05$). However, all the SNRs for the first three conditions were significantly different from all the SNRs in the second group ($p<0.001$).

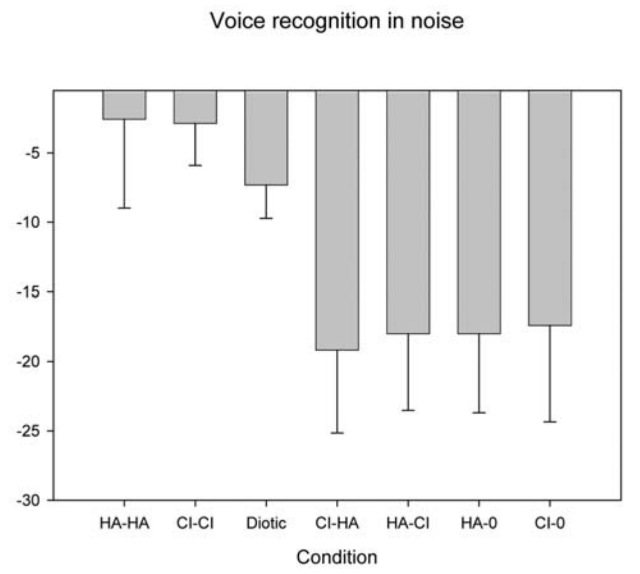

Figure 5. SNR for 70% correct recognition of words in seven monaural and binaural conditions.

The best results were for the four conditions on the right where there was no noise or the noise and voice were in opposite ears. There was no significant difference between these four conditions, showing that the subjects could easily separate the speech and the noise in opposite ears even when the noise was 15 to 20 dB louder than the speech.

The two monaural conditions on the left with speech and noise in the same ear gave signal-to-noise ratios of about -3 dB. The diotic condition gave a mean signal-to-noise ratio of -7 dB, indicating that there was a 4 dB advantage from combining the information from the two ears.

5. RECOMMENDATIONS

These three experiments together suggest that large improvements in the binaural perception of speech in noise can be obtained by using a combination of ADRO to provide ideal conditions for the combination of speech information from two ears, by using adaptive directional microphones to maximise the SNR in each ear, and by trying to keep speech and noise in opposite ears if possible. A 3 dB advantage was obtained with ADRO in the Japanese bimodal study, with a further 7 to 8 dB advantage from the head-shadow / ADM combination depending on the direction of the noise obtained in the microphone study. If complete separation of speech and noise into opposite ears is achieved, the total advantage may increase to 15 dB or above, as in the third experiment. It is our vision that one day implants and hearing aids will be fitted at the same time by the same person, with the same fitting software, and patients will have the freedom to choose two hearing aids, two implants, one of each, or even two of each. It is time to recognise that people have two ears and need to use them both in a coordinated way for maximum benefit.

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