Suggested Crossover Frequencies and Compression Ratios for a Two-channel Wide Dynamic Range Compression Hearing Aid

Fréquences de coupures et rapports de compression proposés pour une prothèse auditive à compression dynamique large et à deux canaux

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Abstract

Forty hearing-impaired participants were fitted with the ReSound ED2 two-channel two-memory wide dynamic range compression hearing aid. After participants had worn the ED2 for six months, the final settings for crossover frequency (CF) and compression ratio (CR) for each channel were documented. There were statistically significant correlations between the slope of hearing loss and the programmed CF and CR. It was found that as slope increased, the CF increased and the low frequency CR decreased. No participant selected a CF for Memory 2 which was lower than the CF for Memory 1. It is recommended that the interactions between the channels of multichannel instruments and the settings of CF and CR not be overlooked.

Abrégé

Quarante participants se sont fait ajuster la prothèse auditive ReSound ED2 à compression dynamique large, à deux voies et à deux mémoires. Au bout de six mois, on a documenté les réglages définitifs de la fréquence de coupure (FC) et des rapports de compression (RC) de chaque canal. Des corrélations statistiquement significatives existaient entre la courbe de la perte auditive et la FC et les RC programmés. On a découvert qu'une augmentation de la courbe a entraîné une augmentation de la FC et une diminution des RC à basse fréquence. Aucun participant n'a choisi une FC de la mémoire 2 inférieure à la FC de la mémoire 1. Il est recommandé de tenir compte des interactions entre les canaux des instruments multicanal et de l'importance d'un réglage approprié de la FC et des RC.

Over the last decade there has been considerable interest directed toward determining the optimum frequency-gain response and compression characteristics for multichannel hearing aids. Early experiments yielded contradictory or inconclusive results concerning the number of channels, linear versus compression processing (Lippman, Braida, & Durlach, 1981; Plomp, 1988; Villchur, 1973, 1989), and the appropriate time constants. Some authors (Moore & Glasberg, 1986; Moore, Glasberg, & Stone, 1991; Plomp, 1988) have recommended slow time constants while others (Stone & Moore, 1992; Villchur, 1989) have recommended faster time constants.

Recently, several multichannel hearing aids have become commercially available. One such device is the ReSound ED2 two-channel two-memory wide dynamic range compression hearing aid. This hearing aid allows the clinician to program gain for soft and loud inputs, compression ratio (CR) and bandwidth for both a high and low frequency channel into two separate memories. This yields ten parameters for a single hearing aid and more than twenty parameters for a binaural fitting. A detailed description of the capabilities of the ReSound ED2 may be found elsewhere (see Johnson, Pluvinage, & Benson, 1989; Moore, Johnson, Clark, & Pluvinage, 1992; Moore, Lynch, & Stone, 1992).

Benson, Clark, and Johnson (1992), Moore, Johnson, et al., (1992), and Moore, Lynch and Stone (1992) have described clinical trials with the ReSound ED2 hearing aid. In two of these studies, participants were provided with ReSound hearing aids (Benson, et al.; Moore, Johnson, et al.). Benson et al. assessed 18 participants after a period of several months and Moore, Johnson, et al. evaluated 20 participants with multiple assessments over a period of

weeks after the initial fitting of the hearing aid. Benson et al. and Moore, Johnson, et al. demonstrated significant improvements in functional gain, real ear insertion gain, comfortable dynamic range, the ability to understand soft speech and subjective quality judgments with the ReSound aid compared to their previously worn linear devices. That is, two channel compression was superior to a linear device with respect to soft speech in quiet, comfortable dynamic range, subjective preference, and speech reception thresholds (SRTs) in noise.

Moore, Lynch, and Stone (1992) did not provide wearable hearing aids for their participants. They determined the precision required when adjusting the low level gain settings in each channel of a two-channel compression system for optimum performance. It is possible to assess the effects of gain and CR changes simultaneously if only the gain for soft inputs is modified. SRTs were obtained in quiet and in the presence of average level (65 dB SPL) speech babble and loud (75 dB SPL) speech babble. It was concluded that greater gain for soft sounds accompanied by increased compression ratios degraded performance in the presence of loud background noise. The authors acknowledged the multidimensional nature of the problem when fitting the ReSound device, but drew conclusions about fitting strategies based on the systematic alteration of only one parameter (i.e., low level gain settings). The effects of gain for soft sounds and CR were assessed, however, the interaction with crossover frequency (CF) was overlooked. Since the CF may be adjusted at half octave intervals from 400 to 4700 Hz and the transition between channels is determined by interactions between gain, CR, CF, and input signal level, the width of each channel might have a tremendous effect on performance in noise. While the authors' conclusion may have been correct, it could not be supported without this information. This information is important when fitting the ReSound device because the device has two programmable memories which are usually set for a quiet (Memory 1) and noise (Memory 2). If the actual hearing aids had been used in the study and the participants were properly fitted so that they could wear them comfortably through an acclimatization period, systematic effects due to differences in CF from one memory to another within each participant's hearing aid may have become apparent.

To provide guidelines for clinicians it may be helpful to scrutinize these multidimensional fittings and examine the interactions of the individual component parts. One way of doing this is to complete a long-term follow-up on a sample of satisfied users of a particular multichannel compression device. If individuals are categorized by configuration of hearing loss one may find systematic changes in participant preference. It would then be possible to examine specific

parameters of the fittings without inadvertently overlooking other programmable parameters that relate to the one in question. The hearing aid assessed in this study is commercially available. Using commercially available hearing aid models is crucial for clinical research if the results of the research are to be generalised to the hearing aids worn by consumers. It is possible that much of the ambiguity surrounding the efficacy of any compression hearing aid could be clearer if more specific results obtained with a given hearing aid model were available.

With that goal in mind, this study was undertaken to provide information of direct relevance to those who fit ReSound hearing aids. Specifically, the purpose of this study was to examine a relatively large number of hearing-impaired participants who had been fitted with the ReSound hearing aid for at least six months. Systematic changes in CF and CR required to fit a two-channel compression device (ReSound ED2) on participants with different audiometric configurations were examined.

Methods

Participants

Forty participants (10 females and 30 males) with sensorineural hearing loss, all of whom were previous hearing aid wearers, were fitted with the ReSound ED2 hearing aid. Their ages ranged from 32 to 85 years ($M = 68$, $SD = 12.7$). All participants had been monaural hearing aid wearers for a minimum of two years prior to their ReSound fittings. The participants were each fitted with one ReSound ED2 hearing aid at the Sunnybrook Health Science Centre in Toronto and were provided a 30-day trial period. All participants ultimately chose to replace their previous hearing aids with the ReSound device and expressed considerable satisfaction with their new hearing aids. They were all followed for at least six months and were encouraged to schedule programming adjustments to the hearing aids until satisfied that they were receiving optimum performance.

The participants were divided into three groups based on the configuration of their audiograms (see Figure 1). Configuration was defined as the difference in pure tone thresholds from 500 Hz to 2000 Hz in the participants' aided ear. Group 1 ($n = 12$) had a flat configuration in which hearing loss at 2000 Hz ranges from 20 dB less to 10 dB greater than the loss at 500 Hz. Group 2 ($n = 11$) had a gradual configuration in which the hearing loss at 2000 Hz is 15 to 25 dB greater than the loss at 500 Hz. Group 3 ($n = 17$) had a steep configuration where the hearing loss at 2000 Hz is 30 - 55 dB greater than the loss at 500 Hz.
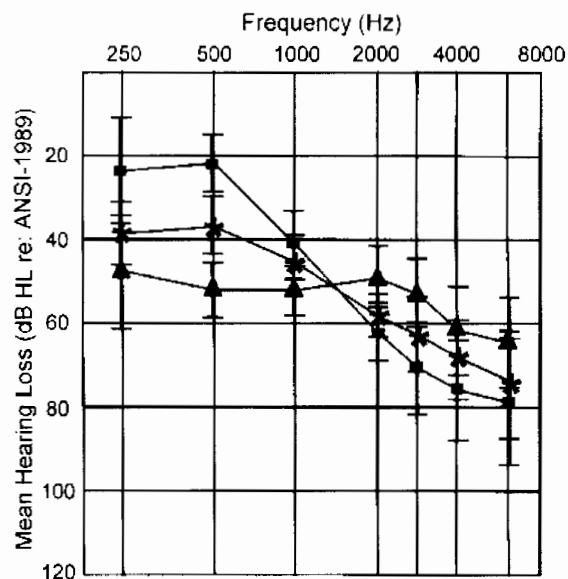
Hearing Device

All of the participants were fitted with the ReSound ED2 in-the-ear hearing aid. The device has been described by Moore, Johnson, et al. (1992). The ED2 has three compression amplifier stages. The preamplifier uses automatic gain control output limiting for signal inputs of 85 dB SPL or above. Signal input is split into high and low frequency bandpass filters. Each band uses a fast acting compression amplifier (attack time < 1 ms; release time 50 to 100 ms) with a kneepoint of 45 dB SPL. The CF between the two filters can be adjusted in ½-octave steps from 400 - 4700 Hz. The signals from both bands are then mixed and passed through an output limiting amplifier stage.

The device has two programmable memories that can be accessed by the wearer using a pen-shaped remote control. When using the remote control, the wearer may switch back and forth between Memories 1 and 2 at any time. The wearer may, to a limited extent, adjust the gain of the hearing aid up or down at any time. Several parameters of each memory can be independently programmed by the fitter of the device. The gain for soft (50 dB SPL) and loud (80 dB SPL) inputs for both the low frequency and high frequency channels as well as the CF between the two channels are adjustable for each memory. Compression ratios for each channel are indirectly adjusted when the gain for high and low level

inputs are adjusted. For example, the gain in the low frequency channel may be set at 10 dB for both a 50 dB and 80 dB input. Then the output of the aid would increase from 60 dB SPL to 90 dB SPL as the input changed from 50 dB to 80 dB SPL. Therefore, for the 50 to 80 dB SPL input range every 1 dB increase of input yields a one dB increase of output or a CR of 1:1. If, however, the gain in the low frequency channel is set at 30 dB for a 50 dB SPL input and at 10 dB for an 80 dB SPL input, then for the 50 to 80 dB SPL input range the output of the aid would go from 80 to 90 dB SPL. It would then require a 3 dB input increase to yield a one dB output increase or a 3:1 CR. The maximum CR for each channel is 3:1.

Fitting Protocol

The goal of each fitting was to program the first memory for optimum performance in "quiet" or "moderately-noisy" situations. For example, moderate noise in this case is intended to mean small groups of people (i.e., 10 or less) or possibly riding in a car. The second memory was programmed for optimum performance in situations of more "extreme" background noise. Situations, for example, with far more people such as a full restaurant, a wedding, or a large bridge club. A description of the hearing aid and a detailed description of the fitting protocol have already been published elsewhere (Allen, Hall, & Jeng, 1990; Benson et al., 1992; Moore Johnson, et al., 1992; Moore, Lynch, & Stone, 1992). The protocol used in this study was virtually identical to those cited above.

The following is a brief description of the protocol that was used: Initial settings for all parameters of Memories 1 and 2 were obtained with the ReSound stand alone programmer (DHS) using the fitting algorithm therein. Male and female running speech presented in a sound field from a compact disk supplied with the DHS was then used to fine-tune the hearing aid for each wearer. Gain settings for low level speech were set using a presentation level of 50 dB SPL in quiet. Gain for loud speech was set using 75 dB SPL running speech. Participants were asked to rate the speech for comfort, clarity, and sound quality while the indicated parameters were adjusted. The sequence was repeated while adjusting the CF of Memory 1 until the highest ratings were reached. Memory 2 was fine-tuned using competing noise from the same compact disk which best represented the type of situation each participant reported they most commonly experienced. Typical choices included parties, restaurants, and traffic. Once again, gain, CR, and CF were systematically adjusted to obtain the highest subjective ratings for speech clarity and overall comfort. Speech was presented at 75 dB SPL at zero degrees azimuth. Background noise was presented at +10, +5, or zero dB signal-to-noise ratio at zero degrees azimuth. Signal-to-noise

ratio was varied throughout the fine-tuning procedure in an effort to maintain a clarity of at least 50% with participants. If the clarity was very high, the signal-to-noise ratio was reduced and vice versa. Memory 2 was considered to be set when further parameter adjustments ceased to yield increased subjective ratings.

After the initial fitting session all of the participants were seen at one-month and six-month follow-up appointments. Some participants required additional visits for programming adjustments prior to the six-month visit and were seen as the need arose. All of the participants received their final program settings by the six-month appointment, at which time the final program settings for each participant were recorded.

Real-ear measurements were obtained at the end of the one-month follow-up visit. If, as a result of that visit, significant changes were made to the hearing aid parameters, the real-ear measurements were obtained again at the six-month visit. If, for example, the entire fine-tuning protocol had to be repeated, that would be considered a significant change. Those measurements were made for both low and high level inputs (i.e., 50 and 80 dB SPL) on Memories 1 and 2. All measurements were obtained using a probe-tube microphone system (Fonix 6500-CX Real Time Hearing Aid Test System) with a composite noise signal. The real-ear measurements were obtained to ensure adequate amplification had been provided and to troubleshoot complaints about sound quality and clarity. The primary purpose for the real-ear measurements was to locate anomalies in the real ear insertion response (REIR). A large peak in the REIR at a narrow band of frequencies or a larger than expected vent-related resonance would require reprogramming the aid, particularly if the participant had a related complaint with respect to sound quality or clarity. As always, high level inputs of 80 dB were used to ensure that aided outputs for such input levels did not cause discomfort for the wearer.
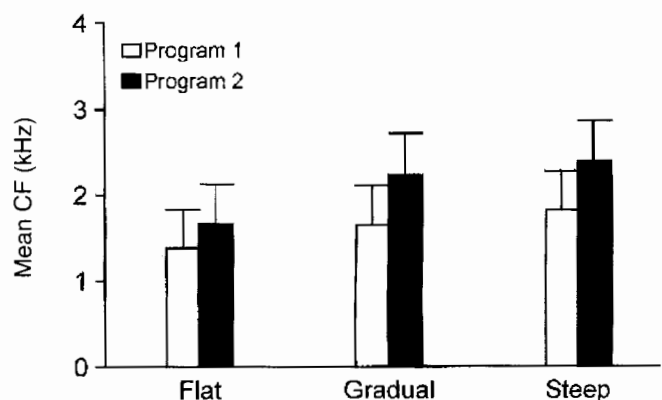
Results

Crossover Frequency.

Pearson Product Moment correlations were performed to determine which factors of a participant's hearing loss might be related to the final setting of the hearing aid parameters. Using the previous description of audiometric slope configuration (i.e., hearing level at 2000 Hz relative to hearing loss at 500 Hz), correlations of configuration to CF were calculated for both memories. The correlations were not strong, but they were statistically significant. The configuration of the hearing loss correlated positively with

the CF of Memory 1 ($p < .05$, $r = .346$) and Memory ($p < .05$, $r = .485$). An analysis of variance was performed to calculate any possible interaction between chosen crossover frequencies between groups (group X condition). There was a significant main effect for group, $F(2,37) = 6.56$, $p = 0.0036$. A Tukey pairwise comparison by group for CF_1 (crossover frequency for Memory 1) revealed a significant difference between all three groups ($p < .05$). The CF_2 chosen for Group 2 was significantly different ($p < .05$) from the CF_2 chosen for Group 1. The Group 3 CF_2 was also significantly different ($p < .05$) from the Group 1 CF_2. There was also a main effect for CF_1 versus CF_2, $F(1,37)=68.32$, $p < 0.0001$, CF_2 ($M = 2125$ Hz), was higher than CF_1 ($M = 1640$ Hz).

Figure 2 shows the mean CFs for Memories 1 and 2 as a function of Group. As the configuration of the hearing loss became steeper the CF increased for both memories. The CF for Memory 2 was consistently higher than Memory 1 for each of the three groups. Figure 3 shows the distribution of the selected CF for both memories as a function of Group. The most common CFs for both memories were 1300 Hz and 2000 Hz for Groups 1 and 2, respectively. For Group 3, the most common CF for Memory 1 was 2000 Hz, but increased to 2800 Hz for Memory 2. As evident in Figures 2 and 3, the difference in CF from Memory 1 to Memory 2 increased as the configuration of the hearing loss increased (see Figures 2 and 3). There was a weak positive correlation between hearing loss configuration and the difference in crossover frequency between Memory 1 and Memory 2 ($p < .10$, $r = .303$).
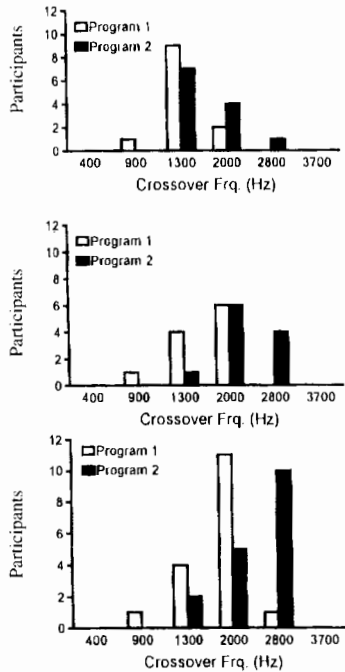
Percentage incremental differences in chosen crossover frequency from Memory 1 to Memory 2 as a function of hearing loss slope are presented in Figure 4. This figure

Figure 2. Mean crossover frequencies for Memories 1 (open bars) and 2 (solid bars) as a function of hearing loss slope. Error bars represent plus/minus one standard deviation of the mean.


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Figure 3. Individual crossover frequencies for Memories 1 and 2. Groups 1 (flat configuration), 2 (gradual configuration), and 3 (steep configuration) are represented in the top, middle, and bottom axes, respectively.

shows that not one participant preferred a lower CF for Memory 2 than for Memory 1. Only one participant chose a CF for Memory 2 that was greater than one increment above the CF selected for Memory 1. Finally, as the configuration of the hearing loss increased from flat to steep, the percentage of participants who chose to raise the CF for Memory 2 by one increment also increased.

Figure 4. Percentage incremental differences in chosen crossover frequency from Memory 1 to Memory 2 as a function of hearing loss slope. Positive increments indicate that the crossover frequency for Memory 2 was higher than that for Memory 1. Bars represent the percentage of the total within each group.
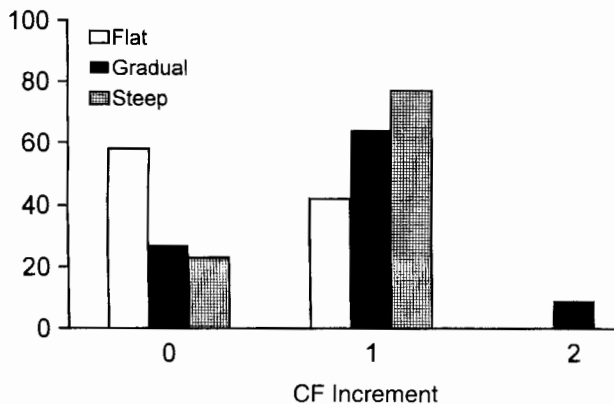

Compression Ratio

Hearing loss configuration correlated negatively with the CR of the low frequency channel for both Memory 1 ($p <$ .001, $r = -.550$) and Memory 2 ($p < .05$, $r = -.462$). The one frequency that was always within the bandwidth of the low frequency channel, regardless of the chosen CF, was 500 Hz. The correlations between the hearing loss at 500 Hz and the CR for the low frequency channel in Memories 1 and 2 were .691 (p < .001, r) and .492 (p < .005), respectively. The two frequencies that consistently fell within the bandwidth of the high frequency channel were 3000 and 4000 Hz. The correlations between the hearing loss at 3000 and 4000 Hz and the high frequency CR for Memory 1 and 2 were significant, albeit weaker ($p < .05$, $r = .364$ and $r=.358$).

Bivariate scatter plots and respective linear regression line CRs as a function of hearing loss at 500 and 3000 Hz for Memories 1 and 2 and are shown in Figure 5. A statistically significant correlation was found between hearing threshold level and CR for both Memory 1 ($r = .695$, $p < .001$) and Memory 2 ($r = .688$, $p < .001$). Only three participants chose a CR of 1:1 (i.e., linear amplification) for the low frequency channel of Memory 1 (see top of Figure 5). All three had normal hearing at 500 Hz with HTLs less than 25 dBHL (see top of Figure 5). The lowest possible setting for the low frequency channel of the ED2 is 2 dB of amplification with no compression. Those participants who chose linear amplification all chose 2 dB of gain in the low frequency channel for both 50 and 80 dB inputs.

Figure 5. Combined compression ratio setting for high and low frequency channels by hearing threshold level (HTL) within each channel for Memory 1 (Top) Memory 2 (Bottom).
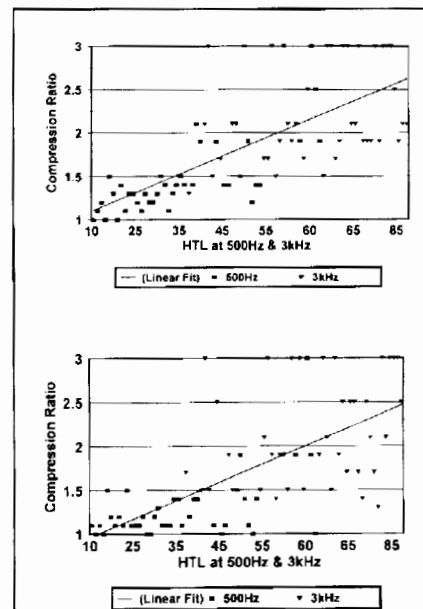
Discussion

Thirty-seven of the 40 participants chose a CF of either 1300 Hz or 2000 Hz for Memory 1. Those with a flat audiometric configuration preferred a 1300 Hz CF and those with gradual to steep configurations preferred a CF of 2000 Hz. The choices of CF may have been related to the configurations of the hearing loss within the participant population. Figure 1 shows that low frequency pure tone thresholds decrease as configuration increases and the thresholds for all three groups intersect close to 1300 Hz. The lowest mean CF was chosen by the group with the flattest audiometric configuration. This group has the most hearing loss below 1300 Hz and the least hearing loss above 1300 Hz of all three groups in Figure 1. Participants with steeper configurations require less amplification below 1300 Hz, but more amplification above 1300 Hz than those with flat configurations. This point is critical to a multichannel hearing aid fitting in ways that are not relevant for a single-channel device. The reason for the difference lies in the way that frequency shaping can be done by changing the CF and CR of each channel relative to the other channels. The following is an explanation of the interaction of CF and CR relative to hearing loss configuration.

In the ReSound ED2, the low frequency bandpass filter has a -12 dB/octave slope and the high frequency bandpass filter has a -18 dB/octave slope. In Figure 6 (top) the CF is 1300 Hz. In this example, the output of the low pass filter is set at 30 dB and provides 30 dB of output for all frequencies below 1300 Hz. Starting at 1300 Hz, the output of the low frequency channel decreases at a rate of 12 dB/octave. The high frequency channel is also set at 30 dB and the output of the high frequency channel is 30 dB at frequencies above 1300 Hz. The output of the high frequency channel drops at a rate of 18 dB/octave as frequency decreases from 1300 Hz. Since the two bandpass filters have different slopes, the amount of amplification provided by each filter effects which middle (transition) frequencies are within the bandwidth of each of the two channels. The transition frequency (TF) is the point at which both channels of the device provide the same amount of amplification. At any instant, when both channels are providing exactly the same amount of output, the TF from the low frequency channel to the high frequency channel is the chosen CF. In this case it is 1300 Hz. In Figure 6 (top) the low frequency channel provides more output than the high frequency channel (30 dB) at all frequencies below 1300 Hz. The high frequency channel provides more output than the low frequency channel (30 dB) for all frequencies above 1300 Hz.

If, at any instant, the output of one channel decreases, the transition frequency shifts to the direction of the channel with lower output. The amount that the transition frequency

Figure 6. Example of crossover frequency versus transition frequency when the output of both channels is equal (Top). Change in transition frequency relative to crossover frequency as the output of the low frequency channel is reduced relative to the high frequency channel (Bottom).
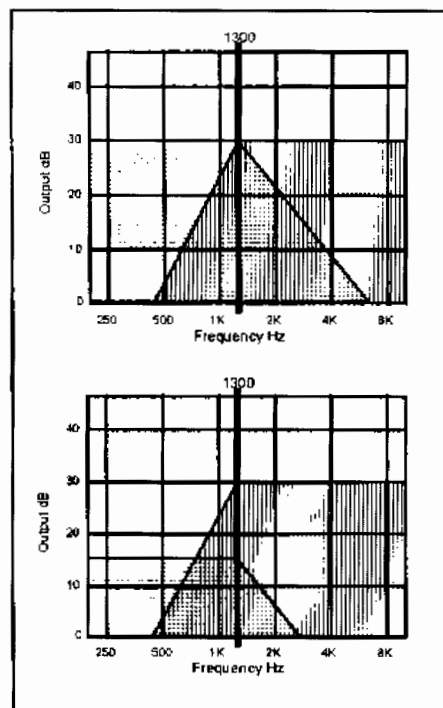
shifts is determined by the slope of the opposing channel. For example, if the CF remains at 1300 Hz, but the output of the low frequency channel is reduced to 15 dB (Figure 6, bottom) the TF would shift from 1300 Hz to 700 Hz. This is the point in Figure 6 (bottom) where the low frequency and high frequency hatched lines cross in the low frequency channel. The low frequency channel provides the most output, 15 dB, for all frequencies below 700 Hz. The high frequency channel would provide the most output at frequencies above 700 Hz. The output from 700 Hz to 1300 Hz would rise from 15 dB to 30 dB at a rate of 18 dB/octave and then remain at 30 dB for all frequencies higher than 1300 Hz.

The output of the low frequency channel may be reduced relative to that of the high frequency channel if the configuration of the hearing loss was to get steeper. Steeper hearing losses require more gain for soft sounds in the high frequency channel than the low frequency channel to provide appropriate frequency response shaping. Flatter configurations require more balanced gain between the channels to properly shape the frequency response. Furthermore, the CR of each channel, at each instant in time, determines the output for that channel based on the level of the input to the hearing aid within the bandwidth of the channel. In other words, increasing the input to the low

frequency channel with a loud steady state noise (e.g., car motor or large group of people) will reduce gain in that channel by the amount determined by the CR and temporarily have the same effect on the transition frequency as described above, if the noise is outside the bandwidth of the high frequency channel. The shift in CF for steeper sloping losses from 1300 Hz to 2000 Hz may be compensating for a downward shift in TF. The decreased TF is due to changes to gain and compression ratio in each channel that are necessary for appropriate frequency response shaping. For participants with steeper hearing loss configurations the choice of a crossover at 2000 Hz shifts the TF to a higher point, allowing gain reduction for a larger bandwidth of low frequency energy.

Note that the CF increases as audiometric configuration increases. Also note that the CF for Memory 2 (i.e., the background noise memory) is always higher than the CF for Memory 1. The distribution for Memory 2 demonstrates the effect to an even greater extent (see Figure 3). The flat configuration group preferred a 1300 Hz CF, the gradual configuration group preferred 2000 Hz CF, and the steep configuration group preferred a CF of 2800 Hz. Furthermore, the CF chosen for Memory 2 is always equal to or one increment higher than the CF for Memory 1. These choices of CF demonstrate a major weakness in the previously cited study by Moore, Lynch, and Stone (1992) regarding intelligibility of speech in quiet and in noise. That paper did not account for the possible effects of hearing loss configuration on CF, nor the effects of CF on intelligibility in noise. Future studies on multichannel hearing aids should not ignore this important interaction, since changes in CF are a necessary part of frequency response shaping.

There were statistically significant correlations between the CR for each channel and hearing loss for frequencies within the bandwidth of those channels for all cases except the high frequency channel of Memory 1. The presence of acoustic feedback may have been a mitigating factor in that case since many of the participants had hearing losses of 70 - 80 dB HL at 3000 and 4000 Hz. Attempts to provide adequate amplification in the high frequency channel of Memory 1 for soft sounds (50 dB) were sometimes limited by acoustic feedback. In order to provide gain for average levels of speech while limiting feedback, the gain was decreased for soft high frequency sounds (i.e., 50 dB) which in turn decreased the CR of the high frequency channel. Since the necessity for such modifications was not consistent from participant to participant, the correlation for the high frequency channel of Memory 1 was reduced. The same problem did not occur in Memory 2 as that memory was used for situations where significant background noise was present. As it has been shown by Moore, Lynch, and Stone (1992), intelligibility in background noise improves if there

is less high frequency amplification for soft sounds (i.e., 50 dB input) in Memory 2. There was less acoustic feedback in Memory 2 because there was less amplification.

For Memory 1, only three participants chose linear amplification for either channel. Those three participants all had normal low frequency hearing and required the minimum possible amplification in that channel. There were 10 other participants with normal HTLs at 500 Hz who preferred nonlinear amplification in the low frequency channel (i.e., CR > 1:1).

Given the relationships found between the fitting parameters of the ReSound ED2 hearing aids and the hearing losses of the 40 participants in this study the following conclusions were reached:

1. The choice of CF for Memories 1 and 2 was systematically and significantly related to the configuration of the pure tone hearing loss.

2. Thirty-seven of 40 participants chose a CF for Memory 1 of 1300 Hz or 2000 Hz. Participants with flat hearing loss configurations most often chose 1300 Hz and, as the slope of the configuration increased, the percentage of participants who chose the 2000 Hz CF increased.

3. No participant chose a CF for Memory 2 that was lower in frequency than the CF chosen for Memory 1. Participants with flat losses tended to choose the same CF for both memories. As the configuration of hearing loss increased so did the percentage of participants who chose a CF one increment higher for Memory 2 than that selected for Memory 1.

4. Given the range of CF by hearing loss for both memories and the relationships shown here for the CF in Memory 2 relative to Memory 1, future studies of the performance of multichannel compression hearing aids should not ignore the importance of CF.

5. The CR increased as hearing thresholds increased.

6. Wide dynamic range compression was unanimously preferred, except where the preference was for minimal amplification in the range of normal hearing ($n = 3$).

One caveat remains in that the results and conclusions of this paper were obtained after a series of monaural hearing aid fittings. If the fittings had been binaural, the results and conclusions reached herein may have been different.

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