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Preferred frequency response for two- and three-channel amplification systems

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Abstract—The purpose of these investigations was to compare the preferred frequency-gain responses obtained from two- and three-channel amplification systems. The current experiments were limited to a linear system in which the crossover frequency dividing the channels was systematically varied. The subjects for the experiment were nine individuals with mild to moderately severe sensorineural hearing loss with various audiometric configurations. The subjects listened to continuous discourse, in noise, via a computer-controlled digital master hearing aid containing two real-time data acquisition processors. Initially, a modified simplex procedure was used to obtain preferred frequency-gain responses using several different crossover frequencies. A round-robin procedure was then conducted in which each preferred response from the simplex was compared with every other preferred response. The frequency-gain responses chosen most often for the two- and three-channel systems were compared. The results showed no significant differences between the preferred frequency-gain response for the two- versus the three-channel system. In addition, the preferred response chosen most often was not consistently observed at the same crossover frequency for all subjects, with the exception of those with steeply sloping hearing loss who chose 1,120 Hz as the first or second preference for the two-channel system. The round-robin results were rank-ordered according to the number of times each frequency-gain response was chosen. In general, subjects chose several frequency-gain responses at various crossover frequencies, which were not significantly different from each other statistically. The results of a final experiment suggested that physical similarities in the preferred responses chosen at the various crossover frequencies played a role in the rank-ordering of the preference judgments obtained in the original investigation.

Key words: *amplification systems, digital hearing aids, hearing aids, preferred frequency-gain response, sensorineural hearing loss, two- and three-channel amplification systems.*

INTRODUCTION

The goal of most hearing aid selection procedures is to provide adequate gain so that speech cues important for intelligibility are audible. This general goal is not easily achieved for many patients with cochlear impairment who have elevated thresholds together with recruitment, which reduces the dynamic range. There is evidence (1,2) that an appropriate amplification system for such patients should restore the speech cues to normal loudness levels at each frequency and amplitude. For most hearing-impaired individuals, however, the loudness function and dynamic range of hearing varies over the frequency spectrum. Theoretically, the ideal amplification system would contain a sufficient number of frequency bands or channels, each acting independently, to accommodate the variations in dynamic range that exist at frequencies within the speech spectrum. In practice, several investigators (3,4) have advocated the use of two-channel amplification

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systems, in which the channels operate independently, and often contain some form of compression.

Currently, several digitally controlled, programmable hearing aids are available incorporating two or three independent channels. Often, the signals are split into a high- and low- frequency channel, allowing for relatively independent processing of consonant and vowel cues, respectively. A third channel, which allows for increased bandwidth flexibility, is also available in at least one digitally programmable hearing aid. This might be especially useful for individuals with large variations in both audiometric configuration and dynamic range across the frequency spectrum (e.g., patients with steeply sloping high-frequency loss). There is, however, no strong evidence that demonstrates the superiority of having three versus two independent channels. This paper contains results of our initial efforts to develop and test a digital master hearing aid with two and three independent, adjustable channels. Specifically, the digital master hearing aid was used to compare the preferred frequency-gain responses obtained from hearing-impaired individuals utilizing the two-channel versus three-channel systems.

An important characteristic of two- and three-channel systems is the flexibility to adjust the crossover frequency(ies) that divide the channels according to the preferences or requirements of the listener. No rules or recommendations for choosing the desired bandwidth of each channel have, as yet, been studied systematically. It is possible that the choice of bandwidths preferred by the individual hearing-impaired listener may interact with the preferred frequency-gain responses. In fact, an individual listener may potentially find more than one frequency-gain response acceptable as the crossover frequency is varied. Because of this potential interaction between the preferred frequency-gain response and the crossover frequency(ies), the current investigation incorporated two measurement techniques (one dependent on the other) to determine a final frequency-gain/crossover frequency combination that was preferred for the two- and three-channel systems. The first, a modified simplex adaptive strategy (5) was used to determine a preferred frequency-gain response for each of several predetermined crossover frequencies. This procedure resulted in a set of preferred frequency-gain responses, each obtained with a different crossover frequency. These responses were stored in a database for subsequent comparison with each other, using a second measurement technique, a round-robin paired comparison strategy. Since in that strategy, each preferred response was compared with each other response, it was possible to rank-order the number of times each frequency-gain/crossover frequency combination was preferred, as well as to determine the ultimate "winner(s)." From these results, comparisons could then be made between the preferred frequency-gain/crossover frequency combination for the two- and three-channel systems.

METHOD

Instrumentation

Figure 1 contains a block diagram of the basic components of the experimental system. The speech (continuous discourse) and noise signals used in this experiment were recorded on digital audio tape (DAT) recorders. These same recorders were then used to deliver the stimuli to the digital master hearing aid. The output of the recorders were attenuated (fixed attenuator, FATT) to achieve the desired signal-to-noise ratio (S/N), mixed, and then delivered to a compression/limiter device (having an attack time of 2 msec and release time of 45 msec) to reduce the effects of any spurious peaks that might have occurred in the speech or noise stimuli. The threshold of the compression/limiter was set at 85 dB sound pressure level (SPL). Following preamplification, the stimuli were delivered to an anti-aliasing filter to prepare the stimuli for digital processing. The stimuli were then converted from analog to digital form using 16 bit resolution with a sampling rate of 19.84 kHz. The digital processing system incorporated two real-time data acquisition processors (Ariel DSP-16+) operating in parallel under PC-AT control. The computer also controlled a programmable attenuator (PATT) to establish the overall SPL. The signals from the two Ariel boards were mixed and delivered to a reconstruction or anti-imaging filter to smooth the output of the digital-to-analog conversion. Both the anti-aliasing and reconstruction filters were programmed to low-pass filter the signals with a cutoff frequency at 7.0 kHz. The attenuation was 51.5 dB at the Nyquist frequency of 9.9 kHz.

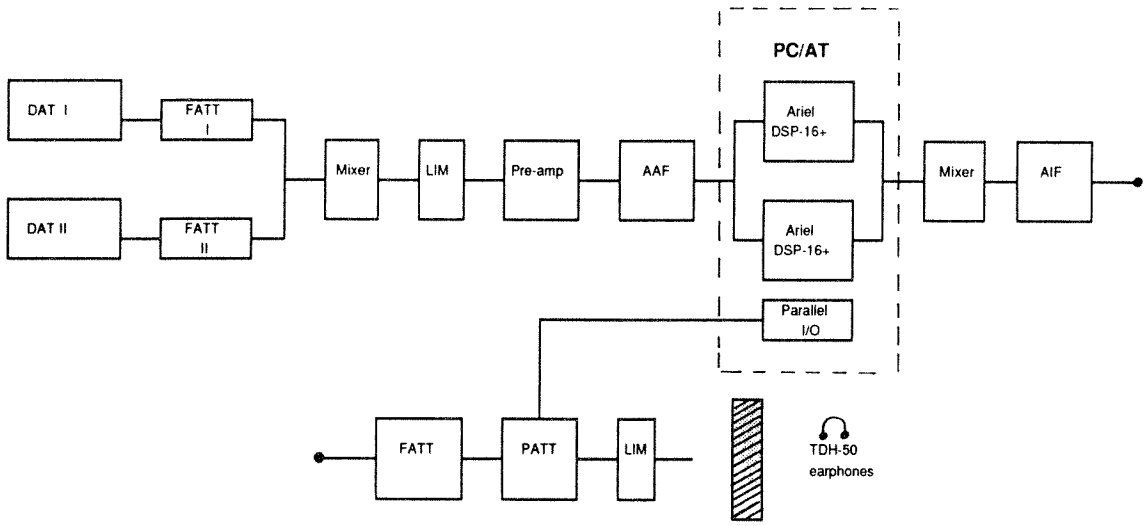

Figure 1.
Block diagram of the basic components of the digital master hearing aid system. DAT = digital audio tape recorder; FATT = fixed attenuator; LIM = limiter; AAF = anti-aliasing filter; AIF = anti-imaging filter; PATT = programmable attenuator; I/O = input/output board.

The processing system was programmed to produce four filter bands with the transition band between filters set at 500 Hz. Each band was spectrally shaped with a 127-tap finite impulse response (FIR) digital filter. The various experimental channels (or bandwidths) were formed by combining the one-third octave bands, starting with the band having a nominal center frequency of 0.315 kHz. The selection of the bandwidths of the desired channels was limited by the transition bandwidth of 500 Hz. Band SPL could be varied in 1 dB increments. The overall level of the stimuli delivered to the earphones was limited to an output level of 118 dB SPL (in a 6 cc coupler) by a second compression/limiter.

Subjects

For this experiment, nine subjects with mild to moderately severe sensorineural hearing loss participated. Three subjects had gradually sloping audiometric configurations, four subjects had steeply sloping audiometric configurations, and two subjects had flat or uniform audiometric configurations. Speech reception thresholds ranged from approximately 15 to 50 dB HL. Of the nine subjects, six subjects were binaural hearing aid users and three subjects had no prior experience with amplification.

Test Stimuli and Instructions

The principal test stimulus used in this experiment was continuous discourse (primary message) recorded by a male talker embedded in a small party noise (background message) containing a variety of male and female talkers. The continuous discourse was recorded on a DAT recorder in 45-minute segments. Each recording contained a complete story on various topics with vocabulary found in fifth-grade readers. **Figure 2** displays the long-term root mean square (rms) level of the stimuli at one-third octave bands from 0.125 to 6.3 kHz. During the experiment, the signals were presented at an S/N ratio of +3 dB. All subjects were able to understand the continuous discourse, because the information in the meaningful sentences contained many contextual cues.

Subjects in this experiment were instructed to base their judgments of preference on several dimensions of speech quality and intelligibility according to their individual standards. The instructions for making the preference judgments were, thus, broadly conceived, and permitted judgments based on the individual's own criterion of comparative importance of intelligibility and quality attributes. In our opinion, the preference judgment for speech in real-life situations is based on a variety of

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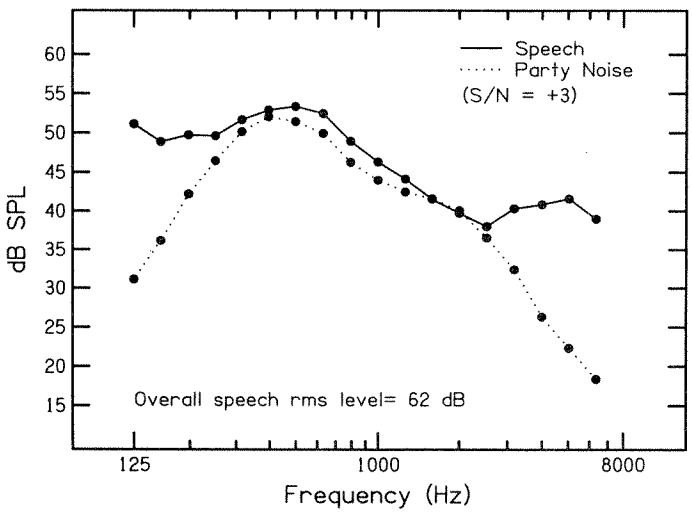

Figure 2.
Long-term rms spectrum of the continuous speech stimuli and the background party noise in one-third octave bands levels.

intelligibility and quality attributes that are highly related and not readily separated.

In addition to the speech and noise stimuli, threshold testing was administered to each subject for descriptive purposes using the modified Hughson-Westlake procedure (6) conducted in 5-dB steps. Loudness judgments were also obtained from each subject using the Loudness Growth in 1/2-Octave Bands (LGOB) method described by Allen, et al. (7). This procedure has been incorporated as part of the Resound Digital Hearing System (8) and was used in the study to describe the comfort loudness levels. In the LGOB procedure, one-half octave bands of noise, centered at 500, 1,000, 2,000, and 4,000 Hz are used as stimuli. The noise bands are presented to the subject (via an insert earphone), randomized over frequency and level, and the subject rates the loudness on a seven-point scale from "cannot hear" to "too loud." A rating of "3," reported in this study, is approximately equivalent to a judgment of most comfortable listening level.

Procedures

In two previous experiments (9), comparisons between the two- and three-channel hearing aid systems were made using a master hearing aid. For those investigations, the signal was presented via a loudspeaker and delivered to a microphone located in the shell of a behind-the-ear hearing aid. After modification by the digital master hearing aid, the signal was routed to a receiver, also located in the shell of the hearing aid, and delivered to the subject in the conventional manner via tubing and an earmold. This method, while realistic, led to several problems that may have interfered with the experimental results. Two of the problems were especially difficult to control. First, the input signal to the microphone was modified by the head diffraction effects and the position of the microphone on the listener, and the output signal varied with the fit and type of earmold. These factors often resulted in discrepancies between the frequency response in the center and surrounding cells of the simplex matrix relative to the desired levels. Various modifications (i.e., Libby horn, dampers, etc.) were needed for every subject in order to match the levels measured at the probe microphone to the desired levels. Second, in a significant number of the subjects, acoustic feedback problems were encountered, especially in cells of the simplex matrix where the gain in the high frequencies was increased by as much as 12 dB over the National Acoustic Laboratory (NAL) predicted gain (10) within the center cell (starting estimate). In order to eliminate these problems, it was decided to conduct the current experiments under earphone conditions. We did, however, incorporate modifications in the software so that the headphone SPL measured in a 6 cc coupler (via the master hearing aid system) simulated the SPL at the eardrum for a sound field hearing aid condition. To obtain the desired coupler response, correction values suggested by Bentler and Pavlovic (11) for the 6 cc-to-eardrum and soundfield-to-eardrum average transfer functions were applied to the long-term rms measured speech levels (**Figure 2**).

In order to obtain the preferred frequency-gain responses for two- and three-channel amplification systems, the modified simplex strategy was used, similar to the procedure described by Neuman, et al. (5), with the exception that the frequency responses in the matrix were not based on loudness. The simplex procedure consisted of a 5×5 matrix of cells for the two-channel system, and a $5 \times 5 \times 5$ matrix of cells for the three-channel system. Each cell contained a different frequency-gain response. The center cell of the simplex procedure was programmed to provide the frequency-gain characteristics predicted by the revised NAL prescription procedure (plus the correction values for simulating

a sound field hearing aid condition, as previously indicated) for each individual subject. The response characteristics in the remaining cells varied systematically, in 6 dB steps, relative to the response of the center cell (NAL). Thus, for the two-channel system, with a crossover frequency of 1,200 Hz, the cell on the vertex of the matrix immediately above the center cell changed by 6 dB in the high-frequency channel while the level in the low-frequency channel remained the same as in the center cell. For a cell on the abscissa adjacent to the center cell, the response was raised by 6 dB in the low-frequency channel, while the high-frequency channel remained unchanged. A similar arrangement was used for the three-channel system, with a 6 dB increase in one of the three channels for each cell in the matrix.

The simplex strategy was conducted in two trials. In the first trial, an initial estimate of the preferred frequency-gain response was obtained using a 12 dB step size. The starting point was always the response in the center cell of the matrix. For the two-dimensional simplex (two-channel system), paired comparisons were obtained between the responses in two cells on the vertical axis, and then a comparison was obtained between two cells on the horizontal axis. Depending upon the outcome, a new set of comparisons was presented, with the simplex moving back and forth between the cells depending upon the outcome of the previous comparisons, until a predetermined number of reversals was reached. A detailed description of the method and a graphic display of a two-dimensional simplex procedure can be found in Neuman, et al. (5) and is highly recommended for the interested reader. The comparative frequency-gain responses were varied by a manual switch controlled by the subject. The subject could switch back and forth between either of the two cells under evaluation as many times as he or she wished. Once the subject decided which response was preferred, a vote was made and then a new set of responses was automatically presented for comparison. Testing was terminated during the initial trial after three reversals in direction for both the horizontal and vertical axes.

After an estimate of the preferred frequency-gain response was made from the initial trial, that winning response then became the starting cell for the final estimate. The strategy just described was again utilized; however, a smaller step size (6 dB) was used, and testing was terminated after five reversals. The efficiency of the adaptive strategy method was improved by this use of a large step size to obtain an initial estimate of the response followed by the use of a small step size to obtain the final estimate.

The same design was used to obtain the frequency-gain response for the three-dimensional (three-channel) simplex, except that the addition of the third dimension required additional comparisons beyond those in the vertical and horizontal plane to accommodate the three components (low-, mid-, and high-frequency). The two-dimensional simplex procedure, in general, required 10–14 minutes for completion, while the three-dimensional required approximately 15–20 minutes.

Because of the potential interaction between the crossover frequency and the preferred frequency-gain response, several simplex procedures were conducted with various crossover frequencies. For the two-channel system, results were obtained with crossover frequencies at 0.562, 0.891, 1.12, 1.78, and 2.82 kHz. These crossovers were chosen because they appeared to provide a representative sample of frequencies across the important audible spectrum of speech.

For the three-channel system, the number of potential combinations for frequency crossovers were numerous; thus, it was necessary for practical purposes to delimit the combinations. Combinations were chosen that included one low-frequency crossover paired systematically with a mid- to high-frequency crossover. Using this rationale, four combinations of crossover frequencies were used: 0.562/1.120, 0.562/1.78, 0.562/2.24, and 0.562/2.82 kHz. Three additional conditions were also tested; 0.891/2.24, 0.891/2.82, and 1.12/2.82 kHz. These seven combinations, therefore, provided a reasonable sample of crossover frequency conditions that might be utilized by hearing-impaired listeners. In summary, there were five frequency-gain response conditions for the two-channel system and seven frequency-gain response conditions for the three-channel system.

In the second part of the experiment, a round-robin strategy, also incorporating a paired comparison method, was then used to compare each preferred response (within the two- or three-channel condition separately) obtained from the simplex procedure with every other preferred response a total of six times. This procedure produced a final

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"winner" from the preferred frequency-gain responses. In addition, the total number of times each competing response was chosen could be rank-ordered for more detailed analysis.

RESULTS

Overall Results

Several descriptive results will be reported initially to provide a general overview of the outcome of the round-robin procedure.

Figure 3 illustrates the average preferred frequency-gain response resulting from the round-robin procedure for the two- and three-channel systems in steeply sloping loss and gradual/uniform loss. Application of the analysis of variance to the data indicated that there were no significant differences between the preferred responses for the two- and three-channel systems. Included in the figures are the average predicted NAL responses for the same subjects at six major test frequencies. Similar to earlier data from this laboratory (9) and from data reported by French-St. George, et al. (12), each of the two groups of subjects in this study preferred slightly more gain in the low-frequency region than the NAL prediction. This result was somewhat more evident for the steeply sloping hearing loss group.

In regard to the preferred frequency-gain/crossover frequency combination, no single frequency(ies) was consistently chosen by all subjects, with one exception. Among subjects with steeply sloping hearing loss, a crossover frequency of 1,120 Hz was chosen as either the first or second preference for the two-channel system. For the gradually sloping/uniform loss group, although no single crossover frequency was favored consistently, in general, the preferred frequency-gain response incorporated one of the mid-frequencies rather than a crossover at the lowest (562 Hz) or highest (2,820 Hz) frequencies available.

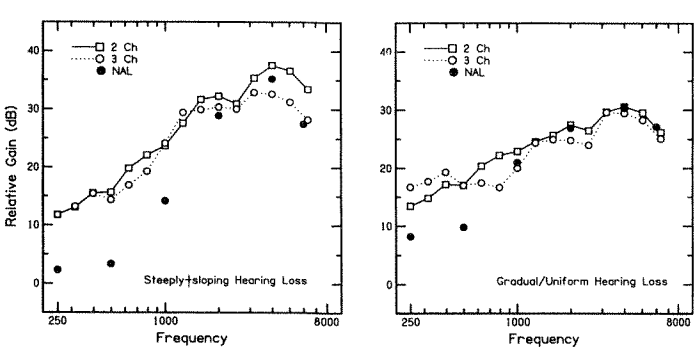

Figure 3.
Average preferred frequency-gain responses resulting from the round-robin procedure for the two- and three-channel systems. The left panel shows the results for the steeply sloping hearing loss group. The right panel shows the results for the gradually sloping/uniform hearing loss group. Included also are the average predictions for both groups from the NAL method.

It is not uncommon in experiments where preferred frequency-gain responses are obtained to instruct the subjects to make judgments on the basis of speech intelligibility and quality factors. Because this study was conducted with a linear system, both the speech and noise changed proportionally as subjects varied the frequency-gain responses within the matrix available. As a consequence, the Articulation Index predictions of intelligibility remained the same for all frequency responses available for an individual subject. It is assumed then that intelligibility was generally constant for the comparisons made by an individual subject; thus, it was reasoned that speech-quality factors may have played a larger role than speech intelligibility in the preference judgment of the subject.

While it was not possible to determine what quality factors were critical to each subject in his or her judgment process, it was possible to estimate one factor, the loudness level of each preferred frequency-gain response, and determine whether preference was dependent on loudness level. (Examples of the five preferred frequency-gain responses for the two-channel system and the seven preferred frequency-gain responses for the three-channel system, from two individual subjects, can be seen in **Figure 6** and **Figure 7**.) The loudness level of each preferred response was estimated in the following manner. First, the preference judgments were rank-ordered in terms of the number of times each preferred frequency-gain response was chosen during the round-robin procedure. Second, the loudness level of each preferred frequency-gain response was estimated using the Zwicker loudness summation model incorporating software based on Zwicker's original programs for calculating loudness in one-third octave bands (13). Frequencies lower than 200 Hz and higher than 6,300 Hz were eliminated from this calculation because of the restricted frequency range of the master hearing aid. The loudness level

of each frequency response was calculated from the aided or amplified speech spectrum obtained from measurements of the long-term rms values of the speech for each preferred frequency response. These loudness levels for each response were rank-ordered from the highest to lowest in terms of loudness for each subject. The rank-ordered results from each subject were then averaged in contingency tables, and chi-square analysis was conducted separately for the results from the two- and three-channel systems. The group results from both analyses were found to be nonsignificant, indicating that the preference judgments made during the round-robin procedure were independent of loudness level.

Rank-order correlations between loudness level and preferred frequency-gain response from the round-robin procedure were also conducted for each individual subject. The relationships varied greatly from an inverse correlation of −0.90 for one subject to a +0.50 for another subject. As a group, no clear trend could be found relating loudness level to the "winner" of the round-robin procedure.

Detailed Results

As indicated previously, the results of the round-robin procedure were rank-ordered according to the number of times each competing preferred response (at the various crossover frequencies) was chosen. These results indicated that most subjects preferred several frequency-gain responses at various crossover frequencies that statistically (chi-square analysis) were not significantly different from each other. Since this general result was applicable to each subject, results from two subjects will be detailed as a representative demonstration of group data.

Figure 4 shows the descriptive results from a subject (BH) with a steeply sloping hearing loss. The panel on the left illustrates the audiogram described in SPL values at the eardrum. Also included in the left panel are the results of the LGOB test. Recall that the loudness test incorporates loudness ratings from "cannot hear" to "too loud"; however, the results shown on the graph are only those rated as "comfortable." The top right panel shows the preferred aided speech spectrum response for the two- and three-channel systems (these results were obtained by adding the preferred gain to the long-term rms speech spectrum at one-third octave intervals), while the relative gain is depicted in the

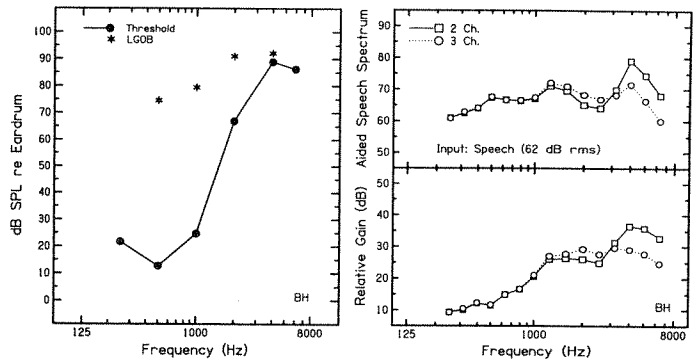

Figure 4.
Descriptive results from a subject (BH) with a steeply sloping hearing loss. The left panel includes the pure tone audiogram and comfort levels from the loudness test. The upper right panel shows the aided speech spectrum and the bottom right panel shows the relative gain for both the two- and three-channel systems.

lower right panel. Similar results are shown in **Figure 5** for a typical subject (LH) with gradually sloping hearing loss.

Despite the large differences in hearing loss for each subject, especially in the low- and mid-frequency region, the preferred gain responses are similar; therefore, the preferred aided speech spectrum values for the two subjects are nearly equivalent. It has been shown that hearing-impaired subjects require amplification such that the amplified speech spectrum corresponds roughly to the loudness contour of comfort loudness levels rather than to audiometric configuration (10,14). Interestingly, despite large differences in audiometric thresholds, the comfort loudness levels as well as the preferred amplified speech spectrum for both subjects are similar. The preferred amplified speech spectrum values for both subjects, shown in the right upper panels of **Figure 4** and **Figure 5**, are slightly lower than the comfort loudness levels measured with the LGOB procedure. Assuming that there should be general correspondence between the comfort loudness level and the preferred amplified speech spectrum, the discrepancy between these values for our subjects is of interest. Recall that the loudness levels in this study (using the LGOB) were based on frequency-specific narrow-band signals, while the preferred aided-speech spectrum was based on broad-band continuous discourse. No allowance has been made for the loudness summation most hearing-impaired subjects experience when listening

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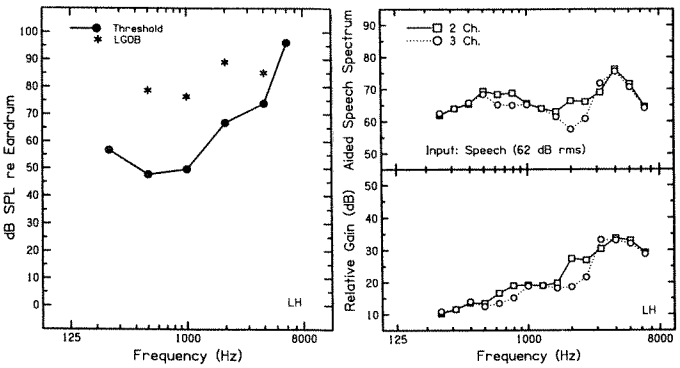

Figure 5.
Descriptive results from a subject (LH) with a gradually sloping hearing loss. The left panel includes the pure tone audiogram and comfort levels from the loudness test. The upper right panel shows the aided speech spectrum and the bottom right panel shows the relative gain for both the two- and three-channel systems.

to broad-band stimuli as compared with narrow-band stimuli. This loudness summation effect varies with input level and the individual hearing-impaired listener but, in general, can be quite large (2), and is probably responsible for the reduced levels of the aided speech spectrum relative to the frequency-specific comfort loudness levels.

Figure 6 shows the preferred frequency-gain responses at the various crossover frequencies for the subject (BH) with the steeply sloping hearing loss. The upper panel of the figure illustrates the results from the two-channel system, while the bottom panel contains similar data from the three-channel system. Also shown in each panel is the number of times each preferred frequency-gain response was chosen during the round-robin procedure. Similar results for the subject (LH) with gradually sloping hearing loss are shown in **Figure 7**.

Two observations from the data in **Figure 6** and **Figure 7** are noteworthy. First, the results of the round-robin procedure do not lead to a clear-cut "winner" within the two- or three-channel systems for either subject. Chi-square analysis was applied to the number of times each preferred response was chosen. In each of the four comparisons (two for each subject), the chi-square was significant (<0.01). This significant result was attributed to the lowest rank-ordered preferred response. (When this latter preferred response was removed from the analysis, the chi-square was not significant.) Thus, the results would suggest that for both the two- and

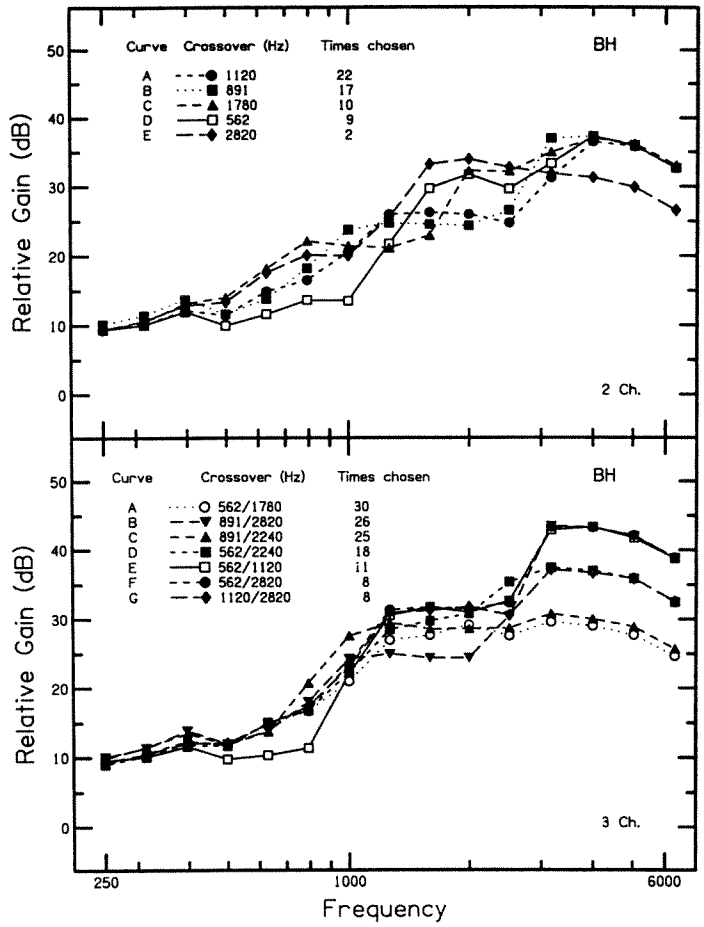

Figure 6.
Preferred frequency-gain responses, at various crossover frequencies for the two- and three-channel systems, for subject BH. Also included are the number of times each response was chosen, at the various crossover frequencies, during the round-robin procedure.

three-channel system, several preferred frequency-gain responses, with different crossover frequencies, might be acceptable to the subjects. Second, it was observed that within each condition, the preferred frequency-gain responses were often quite similar. The similarity between the physical characteristics of many of the preferred responses prompted us to question whether or not subjects could, in fact, appreciate the differences among the responses when comparing the samples. Thus, an additional experiment was conducted to determine the degree to which the subjects, who participated in the initial experiment, could appreciate the differences between the preferred responses using the continuous discourse stimuli.

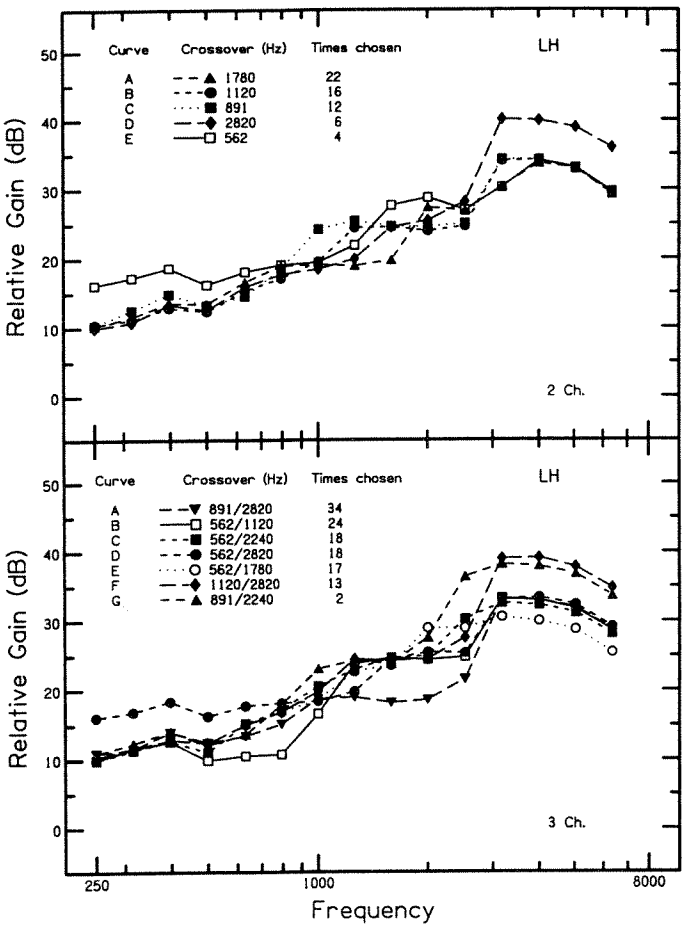

Figure 7.
Preferred frequency-gain responses, at various crossover frequencies for the two- and three-channel systems, for subject LH. Also included are the number of times each response was chosen, at the various crossover frequencies, during the round-robin procedure.

Supplemental Experiment

For this investigation, the round-robin procedure was again utilized, but instead of making a preference judgment, the subjects were instructed to provide a "same/different" judgment between the speech samples heard for the various preferred frequency-gain responses that had been chosen in the first experiments. Each frequency-gain response was compared with every other response a total of four times.

A control condition was included in this experiment in order to verify that the subjects could readily perform the same/different task. Two foil frequency-gain responses (two NAL responses) were paired against each other in the round-robin procedure. Within the experiment, these two foil responses were the only ones that were identical in physical characteristics. No subject had difficulty identifying the two foil responses as the same.

Results. For data analysis, given that each response was compared four times with every other, judgments were considered as "same" if a subject rated three or four of the four comparisons between any two frequency-gain responses as identical. Judgments were considered "uncertain" if two of the comparisons were rated the same and two different. A judgment of "different" was used if the subject rated three or four of the comparisons as different from each other. Subjects were instructed to ignore the obvious fact that each segment of the continuous discourse contained different sentences. Similar to the earlier instructions for making preference judgments, each subject judged the comparative frequency-gain responses as same or different depending on his or her own internal criteria of variations in the quality or intelligibility of the speech.

The results of the same/different task for the nine subjects revealed two somewhat discrete patterns of judgments. One, represented by the results for subject BH, indicated that a majority of the comparisons were judged to be the "same." The results of BH are shown in **Figure 8** in terms of the percent of occurrence of the various ratings for the two- and three-channel systems. Note that the "same" judgment was predominant among the preferred responses for the two-channel system.

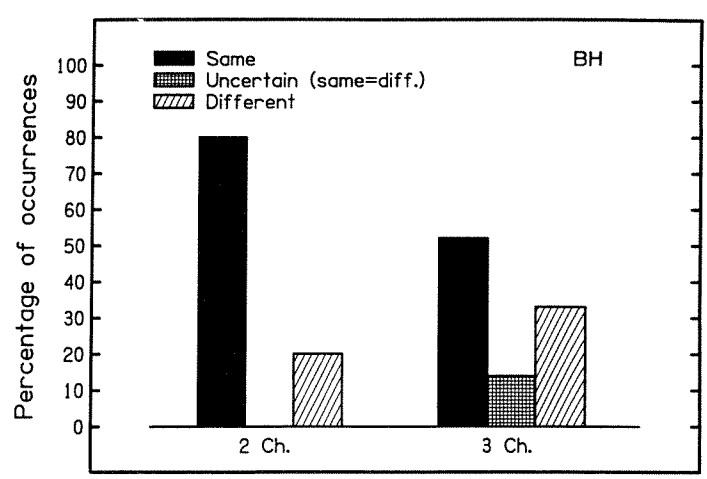

Figure 8.
Percentage of occurrences of the various ratings from the same/different task for subject BH.

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While the "same" judgment continued to be in the majority for comparisons made with the three-channel system, the difference in the ratings between "same" and "different" were somewhat more evenly divided. This result seems reasonable if the earlier data (**Figure 6**), which illustrated the preferred frequency-gain responses, are reviewed. Those data indicated relatively little difference in the physical characteristics of the preferred frequency-gain responses chosen for the two-channel system. For the three-channel system, however, the spread in the physical characteristics of the preferred frequency-gain responses was relatively large in the high-frequency channel, and most likely accounted for the more evenly divided same/different ratings for that condition.

Five subjects in this experiment followed the general pattern of BH, implying that the lack of a distinct preferred frequency-gain response (from the round-robin procedure) may be closely related to the inability of these subjects to differentiate perceptually among many of the competing frequency-gain responses. With one exception, the subjects in this group were those with the steeply sloping hearing loss.

Figure 9 contains the pattern of same/different judgments for subject LH. As can be seen, a majority of the comparisons were judged to be "different," especially for the three-channel system. Inspection of the preferred frequency-gain responses of LH (**Figure 7**) again shows relatively large differences between the responses for the three-channel system, not only in the high-frequency region but also in the low- and mid-frequency regions. For the two-channel system, variations between the preferred responses in both the low- and high-frequency regions are observed; however, the differences are not as large as those found for the three-channel system. Four subjects, with gradually sloping or uniform loss, followed the pattern of LH. For those subjects it appeared that even though they were able to perceptually differentiate between the responses, a clear-cut preference still did not result from the round-robin procedure. This result may suggest that a range of frequency-gain responses would be acceptable for that subset of subjects.

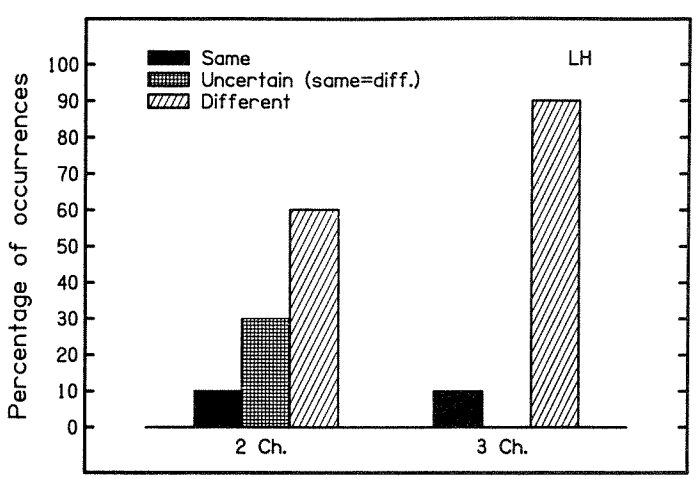

Figure 9.
Percentage of occurrences of the various ratings from the same/different task for subject LH.

As indicated previously, the simplex procedure resulted in five preferred frequency-gain responses for the two-channel system and seven for the three-channel system. From the round-robin procedure a winner was identified, although inspection of the data showed that several frequency-gain responses were chosen nearly as often as the winner. It seems clear from the results of the supplemental experiment that some subjects found it difficult to discriminate between several of the frequency responses that were physically similar. Therefore, for those subjects, the round-robin results may have been significantly influenced by this factor.

An additional analysis was performed on the results from the supplemental experiment. Of interest was the degree to which the frequency-gain curves differed from each other before the curves were judged to be dissimilar. To obtain this information, the percent of same or different judgments was analyzed as a function of the rms differences between the preferred frequency-gain responses. The differences were quantified in the following manner. First, the difference between each frequency-gain curve was calculated at each one-third octave band. The rms difference was then calculated as the square root of the mean of the sum of the differences squared. This calculation provided us with distributions of rms differences for the two- and three-channel systems. The distribution of rms differences ranged from 1 dB to 11 dB. The percent of times a "same" (three or four out of four times) or "different" (three out of four times) judgment occurred was calculated for each rms difference. A rating of "uncertain" was given to comparisons

where the "same" and "different" rating occurred equally.

Figure 10 (two-channel system) and **Figure 11** (three-channel system) illustrate the percent of times subjects judged two comparative frequency-gain response curves as the "same," "uncertain," or "different" as a function of the distribution of rms differences. As might be anticipated, for small rms differences between curves (1–4 dB), a majority of the comparisons were judged the same. For 4 dB rms differences, the same/different judgments were either equal (three-channel system) or approaching equality (two-channel system). For larger differences (>4 dB), a majority of the comparisons were judged to be different. Some irregularities occurred at the highest rms difference principally because of the small number of samples on which to base the estimates. These results suggested that at least one-half of the hearing-impaired subjects could perceptually distinguish rms differences of 3–4 dB of continuous speech in noise. Interestingly, for the simplex procedure we chose a 6 dB step size, based *a priori* on preliminary observations. Given the results from the same/different task just reported, the 6 dB step size appeared in retrospect to be a reasonable choice. For many subjects, a smaller step size would have led to indecisive behavior and thus test poor test efficiency. A larger step size, however, may not have yielded sensitive enough data.

DISCUSSION

The results from this experiment demonstrated no significant differences between the preferred frequency-gain responses for two- or three-channel amplification systems. This observation applied to both a group of subjects with steeply sloping hearing loss and to a group with gradually sloping or uniform hearing loss. It should be stressed, however, that these studies were conducted under linear amplification conditions, and it is quite possible that a different set of results will apply for systems with various types of compression amplification. Conducting investigations similar to the current study, but incorporating compression parameters, would be especially timely because of advances in technology that have already made two- and three-channel hearing aids commercially available.

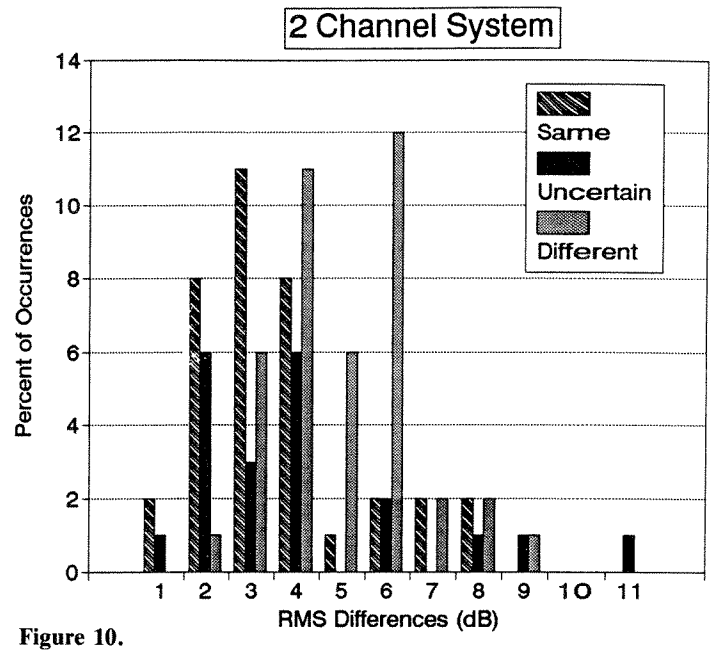

Figure 10.
Percentage of times subjects judged comparative frequency-gain response curves in the two-channel system as "same," "uncertain," or "different" as a function of the rms differences between any two preferred frequency responses.

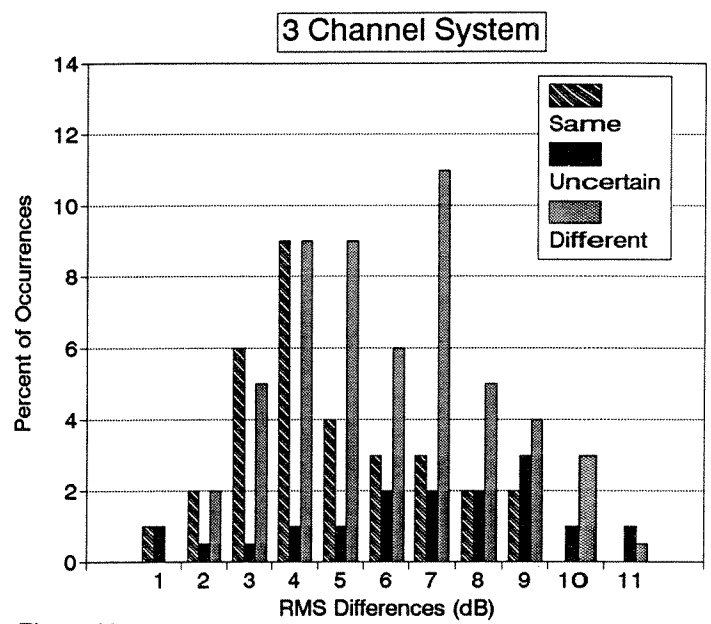

Figure 11.
Percentage of times subjects judged comparative frequency-gain response curves in the three-channel system as "same," "uncertain," or "different" as a function of the rms differences between any two preferred frequency responses.

Although a representative sample of crossover frequencies was available to the subjects, no single crossover frequency was consistently chosen by all subjects even when grouped by audiometric configuration. This result, however, does not imply that all

available crossover frequencies and the resultant frequency-gain responses were equally acceptable. That frequency-gain curves from several crossover frequencies were chosen approximately the same number of times may imply that the choice was more closely related to the suprathreshold loudness contour (which was observed at more equivalent SPL levels across the frequency range than at threshold) rather than the more varied audiometric shape at threshold. While the round-robin procedure appears to be a very useful technique for establishing an acceptable crossover frequency, this adaptive method is not highly efficient for clinical purposes. In our opinion, no systematic clinical procedure by which to select an appropriate crossover frequency for two- or three-channel hearing aids is currently available. It would be especially useful, however, if principles could be established possibly employing the shape of the loudness contour at comfort level as the means by which to establish an appropriate crossover frequency in the individual case.

As a group, the subjects preferred an average frequency-gain response (**Figure 3**) that approximated the NAL predictions, except in the low frequencies where more gain was routinely preferred than predicted by the NAL. This finding is in agreement with results reported by French-St. George, et al. (12). There are several factors that may have contributed to this preference of more low-frequency gain than predicted by NAL. First, the speech signal in the current study, and that of French-St. George, et al., were both presented at relatively low input levels (55–62 dB SPL). While it is implied that the NAL prediction is applicable at all input levels, there is evidence that the preferred frequency-gain response may change with input level (15). Second, as reasoned previously in the current paper, it appeared that sound quality may have played a larger role than intelligibility in the preference judgments. In the validation studies of the NAL (16), both perceived intelligibility and pleasantness (quality) of the speech were considered to be of importance. Generally, the importance of the mid- and high-frequencies has been associated with improvements in intelligibility. However, evidence (17,18) is also available indicating that increasing the amount of low-frequency gain resulted in judgments of better sound quality. Since the continuous discourse in the current study was generally understood by the subjects, perhaps they chose increased low-frequency gain in order to improve sound quality.

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REFERENCES

1. Villchur E. Signal processing to improve speech intelligibility in perceptive deafness. J Acoust Soc Am 1973:53:1646-57.
2. Khalil E, Skinner M, Andrews S, Miller J. Monaural and binaural loudness summation of speech. ASHA 1989:Oct:126.
3. Moore B, Laurence R, Wright D. Improvements in speech intelligibility in quiet and in noise produced by two-channel compression hearing aids. Brit J Audiol 1985:19:175-87.
4. Pluvinage V, Benson D. New dimensions in diagnostics and fitting. Hear Instrum 1988:39(8):28-9.
5. Neuman A, Levitt H, Mills R, Schwander T. An evaluation of three adaptive hearing aid selection strategies. J Acoust Soc Am 1987:82(6):1967-76.
6. Carhart R, Jerger J. Preferred method for clinical determination of pure tone thresholds. J Speech Hear Disord 1959:24:330-45.
7. Allen J, Hall J, Jeng P. Loudness growth in 1/2-octave bands (LGOB)—a procedure for the assessment of loudness. J Acoust Soc Am 1990:88(2):745-53.
8. Johnson J, Pluvinage V, Benson D. Digitally programmable full dynamic range compression technology. Hear Instrum 1989:40(10):26-30.
9. Dirks D, Lee L, Ahlstrom J, Noffsinger PD. Application of simplex adaptive test strategies for hearing aid selection. ASHA 1990:Oct:156.
10. Byrne D, Dillon H. The National Acoustic Laboratories' (NAL) new procedure for selecting the gain and frequency response of a hearing aid. Ear Hear 1986:7:257-65.
11. Bentler R, Pavlovic C. Transfer functions and correction factors used in hearing aid evaluation and research. Ear Hear 1989:10(1):58-63.
12. French-St. George M, Metzger H, O'Connell M, Engebretson M. Level effects on hearing-impaired listener's preferred frequency/gain functions. ASHA 1990:Oct:69.
13. Zwicker E, Fastl H, Dallmayr C. BASIC program for calculating the loudness of sounds from their 1/3-oct band spectra according to ISO 532 B. Acoustica 1984:55:63-7.

14. Skinner M. Hearing aid evaluation. Englewood Cliffs, NJ: Prentice Hall, 1988.
15. Sullivan J, Levitt H, Hwang J, Hennessey A. An experimental comparison of four hearing aid prescription methods. Ear Hear 1988:9:22-32.
16. Byrne D. Effects of frequency response characteristics on speech discrimination and perceived intelligibility and pleasantness of speech for hearing-impaired listeners. J Acoust Soc Am 1986:80(2):494-504.
17. Punch J, Beck E. Low frequency response of hearing aids and judgements of aided speech quality. J Speech Hear Disord 1980:45:325-35.
18. Punch J, Montgomery A, Schwartz D, Walden B, Prosek R, Howard M. Multidimensional scaling of quality judgements of speech signals processed by hearing aids. J Acoust Soc Am 1980:68:458-66.