Prescriptive Hearing Aid Fitting by Parameter Adjustment and Selection

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Abstract

We describe the rationale for the development of a psychophysical procedure that allows individual listeners to adjust the frequency-gain characteristic of a programmable hearing aid on a unidimensional scale, based on a target-gain reference value. The listener's task is to adjust the frequency response and select the parametric value judged to optimize the intelligibility or quality of speech. Originally described as the Sliding Scale, the procedure has been modified for use in reliability and validity studies of hearing aid fitting at Michigan State University. The modified approach is referred to as the Parameter Adjustment and Selection (PAS) procedure. Primary immediate goals for the procedure are ease of use, high reliability, and rapid clinical administration. The procedure, which may offer potential advantages over a paired-comparison approach, appears to be generally applicable to the fitting of digitally programmable hearing aids.

Key Words: Hearing aids, programmable hearing aids, hearing aid selection, hearing aid fitting

Work is currently underway at Michigan State University to refine a hearing aid fitting procedure originally developed by a staff team at Nicolet Instrument Corporation when the first author was associated with that company's digital hearing aid division. We would like to begin by providing a glimpse into the background of this work, and into the motivation for doing it.

The Nicolet group first implemented a version of the Simplex procedure to select the characteristics for programming the Nicolet Phoenix digital hearing aid. This preference-based, paired-comparison procedure has been developed and researched by Levitt and associates, and described most recently by Neuman et al (1987). Nicolet's original implementation, which used a 5 x 5 matrix, but otherwise differed in several ways from the version described in the literature, proved relatively unreliable in clinical trials. Furthermore, it required dispensers about 1.5 hours or more to administer tests of frequency shaping and noise reduction in fitting the Phoenix aid. A substantial number of revisions in the procedure were subsequently made at Nicolet, one of which was to use a 2-stage testing strategy. This strategy treated the 5 x 5 matrix as nine overlapping 3 x 3 matrices, or areas. These areas of overlap are depicted in Figure 1. A sequential test strategy monitored the stability of responses by continuous calculations of the proportion of times a given cell was preferred with respect to the number of times that particular cell was visited. In addition, a five-reversal stopping rule was implemented, in which five reversals in both the horizontal and vertical dimensions were required to end the test. These dimensions were low-frequency and high-frequency gain, respectively, with each adjacent cell representing a 3-dB change in gain in either dimension. Two-step comparisons were first administered to the listener to establish which one of the nine 3 x 3 areas was preferred. This was followed by 1-step comparisons within the winning 3 x 3 area. In general, if a winning area could not be established, the center cell of the 25-cell matrix (the selected target-gain rule) was chosen as the final winner by default. If a winning 3 x 3 area could be identified, but a
Figure 1 A 5 x 5 matrix used in a Revised Simplex hearing aid fitting procedure, showing overlapping 3 x 3 areas. Relative low and high frequency values, referenced to target gain, are represented on the abscissa and ordinate, respectively. The highlighted 3 x 3 area in the top matrix, four corner areas of the type represented in the middle matrix, and four mid-peripheral areas of the type represented in the bottom matrix constitute a total of nine overlapping areas.

winning cell within the 3 x 3 area could not be established, the center cell of that smaller matrix was taken as the final winner.

Although concerns about reliability and administration time were substantially alleviated by this Revised Simplex procedure, the Nicolet group began work to develop another method that might offer more dramatic improvements. Initially described as the Sliding Scale procedure by Benedict et al (1989), it was proposed and tested in 1988 and early 1989, and preliminary work with it was reported at the 1989 ASHA Convention by Benedict, Punch, Lasky, and Chi (1989). This preference-based procedure was found to be not only more reliable than the Revised Simplex procedure, but also substantially faster. Encompassing both frequency shaping and noise reduction testing, the Sliding Scale could typically be administered in a clinical test protocol in about 30 minutes.

Despite the fact that the Phoenix digital aid is no longer commercially available, the procedure remains a viable means of fitting any digitally controlled or fully digital hearing aid. The development of digital hearing aid fitting procedures is the primary emphasis in our Hearing Aid Research Laboratory at Michigan State University. Our initial work has involved the modification of the Sliding Scale, which we prefer to call Parameter Adjustment and Selection (PAS) because the latter term is more descriptive of the listener's task. This report focuses on a description of the procedure and recent refinements to it, as well as its potential utility in the fitting of digitally programmable hearing aids, both in research and clinical applications. The procedure could conceivably be used with a number of signal processing schemes, including noise reduction. Our present focus, however, is limited to frequency shaping.

**PAS PROCEDURE**

Originally, the Sliding Scale was based on the idea that listeners should be able to adjust frequency response on a unidimensional scale ranging from low-frequency emphasis to high-frequency emphasis, and to indicate a preferred response while listening to connected discourse. The name Sliding Scale derived from the notion that the method might be implemented by asking a listener to slide a moveable horizontal scale to the right to change the frequency emphasis of a digital hearing aid from low to high, and to the left to change the response from high to low. Alternatively, a mechanical dial might be rotated to accomplish the same goal. It is also conceivable that a listener could point a finger along a horizontal scale on a touch-screen monitor to change a hearing aid's frequency response. To our knowledge, none of these specific approaches has been implemented. Nicolet's implementation involved use of a 3-button response box accompanying the Nicolet Aurora audiometric work station, while our version uses a 3-button computer mouse. Given the actual task, therefore, Parameter Adjustment and Selection seems to be a more appropriate name for the procedure. In our version, the listener presses the left-hand button of a mouse to adjust the frequency re-
sponse slope to a more negative value, the right-hand button to adjust the slope to a more positive value, and the middle button to indicate the preferred value.

The procedure is currently being implemented on an 80386-based microcomputer, operating at 16 MHz and containing a digital signal processing board (Ariel DSP-56). Signals are digitized at a 16 kHz sampling rate, at 16-bit quantization. The signals are then convolved with a 128-point finite impulse response (FIR) filter, resulting in 64 discrete filters centered at 125 Hz and its multiples. The octave frequencies between 125 and 8000 Hz are routinely programmed, with interoctave frequencies being logarithmically interpolated. A wearable behind-the-ear assembly (Nicolet Phoenix earpiece) containing a hearing aid microphone, volume control, and receiver interfaces with the laboratory unit. The system, therefore, incorporates real-time, computer-controlled, signal-processing techniques to allow a hearing-impaired individual to select the preferred frequency response characteristic. While listening to connected discourse in quiet or against a background of speech babble, the listener is instructed to indicate the preferred option from among the available options, based on either speech clarity or speech quality.

In our implementation, five discrete frequency shapes are made accessible to the listener, with step 3 (the middle step) representing the Revised NAL formula (Byrne and Dillon, 1986). As most of our current work is developmental, we use the version of the NAL formula that calculates desired gain in a 2cc coupler rather than in the real ear, to simplify verification of our results. The two steps on the scale above the NAL reference curve create successively steeper positive slopes, while the two steps below the reference provide successively steeper negative slopes. Changes in response occur simultaneously at frequencies below and above a fulcrum frequency that can be selected by the examiner. Adjacent steps differ by a frequency response slope specified in dB/octave. This slope characteristic can also be controlled by the examiner. Preliminary tests suggest that each of the five adjacent slopes may differ by 5 dB/octave or more over a relatively wide range of degrees and configurations of hearing loss without significant distortion. This slope is effective over a frequency range of 250 to 5000 Hz, with frequency limits at either end imposed by analog components in the earpiece.

Figure 2 illustrates the changes that occur as the frequency response is varied along the 5-step continuum. These responses occur specifically in conjunction with the audiogram in Table 1. Measurements were performed with the Fonix 6500 hearing aid analyzer, using that system's tone composite signal, and specified in a standard 2cc coupler. In this example, the frequency shape tilts around a fulcrum of 1000 Hz.

In administering the procedure, most comfortable listening level (MCL) is first established as the subject listens to connected discourse at the NAL target frequency response. Next, the subject is given a set of instructions that emphasizes the response task (Appendix). The procedure is then started by randomly presenting one of the five frequency response alternatives. Subsequent values are selected by the subject through use of the mouse. Although discrete changes in values occur as a result of button-pressing, the successive changes are perceived as a pitch shift along a unidimensional.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
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<td>25</td>
<td>30</td>
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<td>65</td>
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Hearing thresholds are in dB HL, and are data used as the basis for Figures 2 and 3.
continuum. Each click of the mouse advances the processing by one step; keeping a button depressed will not change the frequency response. No appreciable delay occurs as a result of changes in signal processing. Once the listener determines the preferred value, the selection is registered and stored immediately after the middle button is pressed.

**Pertinent Research and Clinical Issues**

Four issues are currently being addressed in our laboratory with respect to refinements and uses of the PAS procedure. Although we are in the process of exploring these issues experimentally, none of them has been sufficiently evaluated to be considered firmly resolved at this point in time.

1. **Variable-Fulcrum Frequencies.** The software used in Nicolet’s procedure controlled the relative gain around a fixed fulcrum frequency of 1000 Hz. Our software allows any multiple of 125 Hz to serve as the fulcrum. Only fulcrum values of 500 Hz, 1000 Hz, and 2000 Hz, however, are currently being used in the fitting procedure. A fulcrum of 1000 Hz is illustrated in Figure 2, and results of using the optional frequencies of 500 Hz and 2000 Hz are shown in Figure 3. The somewhat limited bandwidth of the system causes use of these extreme fulcrum values to alter the gain substantially on one side of the fulcrum, but not on the other. Having this option available ostensibly enhances individualized fitting in cases of precipitous configurations where there are sharp breaks in the audiometric pattern. The clinical value of using a variable fulcrum, however, remains to be determined.

2. **Optimum Step and Interstep Interval Size.** Ideally, the number of scale steps should cover the range of frequency slope options available in the hearing aid of interest, with interstep intervals large enough to be discriminably different for a substantial proportion of the hearing-impaired population. This latter concern was the primary reason we are not using the 11-step procedure originally developed at Nicolet. The hearing aid literature is replete with examples that attest to the relatively poor ability of hearing-impaired listeners to discriminate among electroacoustically diverse conditions.

There should also be a reasonably high correlation between differences in subjective preferences across the scale and differences in objectively measured speech intelligibility.

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**Figure 3** Graphic illustration of optional fulcrums (500 and 2000 Hz) in the PAS procedure, using the Revised NAL formula in conjunction with the audiogram in Table 1. Only the reference value, step 3, and extreme steps 1 and 5 are shown, based on 2 dB/octave changes between the five available adjacent steps. Gain is specified in a 2cc coupler.

These relationships are currently being investigated in our laboratory.

Generally, the larger the interstep intervals, the fewer the total number of steps that can be made available. Interstep value is variable in the procedure. Although slope differences of up to about 5 dB/octave are possible without distortion, a typical interstep interval size is 3 dB/octave on either side of the fulcrum. Working with a fulcrum of 1000 Hz, the five available filter slopes are typically accommodated well within the system’s dynamic range. An unusually steep or unusually flat audiometric configuration, or extreme fulcrum values, can result in the need to adjust the interval size.
to accommodate the electroacoustic limits of the system.

3. Procedural Rules. Procedural rules are those rules governing when and how the procedure is started, executed, and stopped. The starting rule, as noted above, is that the initially presented frequency response is randomized across the five alternatives.

In large measure, execution of the PAS procedure is a relatively simple matter because the subject adjusts the parametric value (i.e., frequency response) and indicates which is preferred, thereby ending the trial. The time required to execute the procedure is under the listener's control. A potentially problematic component of the execution, however, has to do with the fact that the listener may occasionally prefer a frequency response that is beyond the limits of the system. An alternative to limiting the frequency shaping options at either end of the scale would be to make the scale circular rather than linear, causing the response to revert to the other end of the scale when a limit is reached. This alternative was rejected because of the desirability to have the listener experience a perceptual shift along a pitch continuum in response to button-pressing activity.

To expedite execution of the procedure, the listener should be alerted when an unavailable value is desired. A number of options are available to the programmer for alerting the listener. The Nicolet group activated a light, signaling that values in the direction the listener wishes to move are not available and that the listener's options are either to move in the opposite direction or select the extreme value as the preference. We activate an audible beep (a default 250 Hz tone, with frequency a variable) when processing is at an extreme scale value and the listener indicates that an even more extreme value in the given direction is desired.

Use of any such warning signal could result in artificially inflated reliability of a listener's preference judgments over repeated trials. This might occur if a listener were to monitor the current position on the scale by counting the number of steps from an extreme value (i.e., the audible beep). The Nicolet group did not observe any evidence of such monitoring behavior using its 11-step scale. Our use of a 5-step scale, however, requires more caution in this regard.

To reduce the likelihood of this occurrence, we employ a random skip in the program whereby pressing the left or right buttons sometimes results in no step change. This is accomplished according to a probability determined by the examiner. For example, the frequency response might fail to change 20% of the time in response to button-pressing activity. Use of this feature is intended to reduce the association between awareness of step location and repeatability of preferences. This part of the procedure may have the disadvantage of slightly prolonging test time.

The procedure typically consists of multiple trials, each of which ends when a listener indicates a preference by pressing the middle of three buttons. The stopping rule must also terminate the procedure. With respect to determining the total number of trials and terminating the test, the following rule has been adopted, pending evaluation of its clinical efficacy. This rule has been modified from that used at Nicolet for use with a 5-step scale as follows.

A minimum of four test trials are administered. After the fourth trial, the preference on the fourth trial is compared to preferences on the first three trials. If the listener’s fourth preference falls within 1 step of that on each of the first three trials, results are considered reliable, and the fourth selection is accepted as the listener's preferred frequency shape. If the fourth preference is two or more steps from any one of the first three preferences, the results are considered unreliable, and the listener is administered two additional trials, for a total of six trials. In this case, the last three selections are then averaged and the mean step value (rounded to the nearest whole number) is taken as the listener's final choice. This value is used for programming the hearing aid.

4. Relative Loudness of Frequency Response Alternatives. In real life, listeners normally have the opportunity to turn a hearing aid's volume control up or down. In a fitting procedure, therefore, the realistic way to deal with this fact seems to be to allow the overall gain of the aid to vary according to levels determined to be equally loud. Not to make such an allowance could result in preferences based primarily on loudness rather than frequency response per se. Unfortunately, any such adjustment may have two undesirable effects: (1) reduction of the electroacoustic differences among frequency response alternatives, and (2) prescribed levels that are relative rather than absolute at given frequencies.

Figure 4 illustrates how such an adjustment might be made. The low-frequency portion of the scale is illustrated in this example. Curves A and B are frequency-gain functions representing relatively low-frequency empha-
sis steps 1 and 2, respectively, on the 5-step continuum. If a signal processed by Curve A is perceived as louder than a signal processed by Curve B, Curve A might be preferred on the basis of loudness rather than frequency shape. Curve A1, a curve parallel to Curve A and adjusted slightly to account for presumed loudness differences with Curve B, might be presented instead of Curve A. We are currently evaluating the degree of such loudness differences and whether they should be taken into account as frequency response is varied in the fitting task.

Potential Uses of the PAS Procedure in Hearing Aid Fitting

On a prima facie basis, digitally programmable hearing aids do not require fitting techniques that differ from those used with traditional analog aids. Real-ear probe-tube measurements, for example, can be used in conjunction with any number of prescriptive formulas to determine optimum frequency response. In fact, the fitting task is substantially simplified by use of a programmable aid in conjunction with real-ear measurements. Several manufacturers of digitally programmable aids currently advocate real-ear measurements in fitting their aids. In such an approach, the desired real-ear insertion gain is determined by a formula selected by the dispenser, and the aid is programmed to match that specification. This general strategy is considered prescriptive, implying an individualized fitting. In fact, it applies to all hearing-impaired listeners a single theoretical notion about the relationship between a given audiometric loss and the desired gain of a hearing aid. Although such an approach is generally regarded as state-of-the-art, it represents less than an ideal model for individualized fitting (Hecox and Punch, 1988).

Programmability offers a degree of flexibility not previously available in hearing aids, and this capability virtually demands that new procedures be developed to individualize the fitting of hearing aids. The PAS procedure could be utilized in current and future approaches to the individualization of hearing aid fitting, as illustrated by the following examples.

Some manufacturers of programmable hearing aids offer separate memories, in which are stored multiple frequency response characteristics presumed to provide differential benefit in different listening situations. Few guidelines are available, however, with respect to determining the most appropriate frequency responses in programming these multiple memories. Several manufacturers advocate the use of target-gain formulas, but few commercially available aids allow the listener to vary frequency response around a specific target-gain formula. Such a formula might be used as a starting point, allowing the hearing-impaired individual to listen to other values and to indicate a preference based, for example, on judgments of speech intelligibility.

The programming of separate memories, as described above, could be based on listening tests conducted under different acoustic conditions, simulated either in the hearing clinic or in the real world. Programming based on everyday use conditions in which the listener selects preferred settings in different acoustic environments would ostensibly give the user an opportunity to select frequency responses that would ultimately be found optimal and acceptable. Some commercial devices already offer several default characteristics that are initially programmed without any fitting per se, and the user is free to select the value that seems most beneficial in a listening situation at home, work, or in a social gathering. This approach could be combined with a target-gain fitting strategy in which listener preferences are determined directly under a variety of listening conditions, using a default target-gain response as the basis for further adjustments. Such an approach could move hearing aid fitting procedures out of the sound booth and into the real world, where they may justifiably belong.

When hearing aids become a bit more intelligent, programmed values can be provided based on adaptive selection strategies. An intelligent hearing aid could monitor the listener's acoustic environment and modify its response.
adaptively to achieve optimum benefit for the listener. It is difficult to imagine, given our present state of knowledge of speech perception in the hearing impaired, that this goal could be achieved without some form of individualized fitting. An adaptive version of the PAS procedure could serve a useful role in such a fitting paradigm.

CONCLUSION

The key components of the PAS procedure are that it utilizes a target-gain rule only as a starting point, and allows a listener to select an individually preferred frequency response. Used in conjunction with wearable digitally programmable hearing aids, or devices that simulate such aids, the procedure offers the potential of obtaining listener preferences under real world conditions that can be used to program the hearing aid. Its potential advantages in the fitting process have encouraged us to continue development.

In the long term, digital technology will presumably offer many characteristics to fit, based on new developments. Researchers working to formulate fitting procedures for the future should not underestimate the importance of the time required for clinical testing. Relatively short test times are critical in the minds of dispensers. Of course, any new fitting procedure that might be developed must also have high reliability. There is a pressing need for fitting procedures that are, at a minimum, fast and reliable. Hopefully, any procedure meeting these requirements will also achieve a reasonable degree of concurrent or predictive validity. Audiologists need to be assured that hearing aid fitting procedures incorporated into a clinical protocol will result in user acceptance, benefit, and satisfaction. To devise a truly valid fitting procedure would mean, de facto, that the procedure would be far superior to any used in the past or present. The use of digital technology will not necessarily guarantee a fitting procedure to be more reliable or valid than existing fitting methods. This technology, however, offers an unprecedented opportunity to develop a reliable and valid fitting procedure.

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REFERENCES


APPENDIX

Instructions for Parameter Adjustment and Selection Procedure

The purpose of this test is to determine the features of a hearing aid that best meet your individual needs. You will be hearing a man (woman) reading from a book. You have in front of you three buttons, two that you will use to change the sound of the aid, and one to tell us the sound you prefer. Pressing the left button will make the pitch of the sound lower, and pressing the right button will make the pitch higher. You should try to make the man's (woman's) speech as understandable as possible. When the aid makes the speech as clear as possible, press the middle button to indicate the current sound as your choice.

It is important especially in the beginning that you explore the whole range of sound available to you before you begin to focus in on the particular sound that you prefer.

Remember—to change the aid's settings, press either the left or right button. These buttons will change the pitch of the man's (woman's) voice. Then, when the voice sounds its clearest, press the middle button to let me know that the setting is the one you prefer. The procedure will be repeated several times.

Do you have any questions?