Evaluation of
A Protocol for Fitting
A Wearable Master Hearing Aid

ABSTRACT
An experimental protocol for the prescriptive fitting of a wearable master hearing aid was evaluated. The protocol consisted of four stages: (i) acquisition of baseline audiometric data, (ii) fixed test battery using speech-in-noise as the test material, (iii) adaptive adjustments, and (iv) evaluative comparative data. The results showed that systematic improvements in hearing-aid performance were obtained as a result of using the experimental protocol and that the largest improvements were obtained during the fixed-test-battery stage. The protocol in its present form is not clinically practical for most situations.

INTRODUCTION
An experimental protocol for the prescriptive fitting of a wearable master hearing aid (WMHA) has been developed and evaluated at the Communications Sciences Laboratory of the City University of New York. Although the protocol was applied specifically to the WMHA, the results of the evaluation of the protocol have implications for other sensory aids.

An assumption basic to the protocol design is that there exists an optimum setting for the device which will yield maximum performance. In this case, the device is the WMHA and the performance evaluated was the speech perception ability of hearing-impaired subjects. The present paper describes the final version of the protocol and the results of an evaluation of the protocol as applied to the WMHA.

DESCRIPTION OF THE PROTOCOL
In the final version of the protocol, "settings" which were manipulated were related to these frequency-gain characteristics of the hearing aid:
1. lower cutoff frequency, and
2. the slope of the gain function between the lower cutoff frequency the higher cutoff frequency.

In two earlier versions of the protocol, manipulations of higher cutoff frequency and of output-limiting characteristics were also carried out. Those two parameters were found to have less-significant effects on performance than lower cutoff frequency and slope; therefore, in the final version, only the latter factors were varied.

The protocol consisted of four stages of testing:
Stage I: Basic Audiometric Testing
Stage II: Fixed Test Battery
Stage III: Adaptive Sessions
Stage IV: Comparative Measurements
Basic audiometric testing during the initial stage included routine pure-tone, speech-reception, and speech-perception testing. Maximum comfort levels (MCL) and loudness discomfort levels (LDL) for one-third-octave bands of noise were determined. The latter two measures were used to set gain and maximum power output (MPO) on the WMHA for each subject. Impressions for custom earmolds were also made during the first sessions of this stage of the protocol.

Fixed Test Battery

The Fixed Test Battery involved testing of speech perception with predetermined settings of the WMHA. The setting which provided the highest score during this stage of testing was used as a starting point for the Adaptive Sessions. The Fixed Test Battery consisted of a statistically powerful factorial design with two levels of lower cutoff frequency (100 Hz and 500 Hz) and three levels of slope (-6 dB/octave, 0 dB/octave, +6 dB/octave). The results of the first two versions of the protocol were considered in selection of slope and cutoff frequency values used in the third (and final) version. Higher cutoff frequency was maintained at 4500 Hz in the final version.

Adaptive Sessions

The third stage of the protocol consisted of adaptive testing. A modification of the Simplical procedure (Box, 1957) was utilized. Lower cutoff frequencies of 100 Hz, 200 Hz, 500 Hz and 800 Hz were used in combination with slopes of -6 dB/octave, -3 dB/octave, 0 dB/octave, +3 dB/octave, +6 dB/octave, +9 dB/octave, and +12 dB/octave. This adaptive procedure involved exploring a surface (defined by slope value and lower cutoff frequency) for a peak in speech perception performance. The exploration was carried out by continually moving away from the setting yielding the lowest of three triangulated scores. (A description of the application of this procedure to hearing-aid evaluation may be found in Levitt, 1978.) During each of the six Adaptive Sessions, six to nine measurements were taken. The estimated optimum for each session was defined as the setting yielding in the highest score during the session.

Fixed Test Battery Materials

The test material used during the Fixed Test Battery and the Adaptive Sessions was the Nonsense Syllable Test (NST). This test was developed specifically to meet certain requirements such as low test-retest variability and minimal learning effects. Test items were designed to maximally differentiate between hearing-aid settings. The test employs stimuli which are of the vowel-consonant (VC) and consonant-vowel (CV) types, and responses are selected from a closed set. (See Levitt and Resnick, 1978, for a description of the test and its development, and Dubno and Dirks, 1980, for an experimental assessment of its reliability characteristics.)

In all instances, the speech materials were presented in the sound field at 70 dB SPL. The subject adjusted the gain control of the hearing aid for maximum comfort of the test stimuli immediately prior to each test. During the Fixed Test Battery and the Adaptive Sessions, the materials were presented against a background of equalized cafeteria noise at a 20-dB signal-to-noise ratio. (Other signal-to-noise ratios were used in the Comparative Measurements, but the data presented in this paper will be limited to those obtained with the 20-dB signal-to-noise ratio.)

At the end of the adaptive stage, the final estimate of the optimum was derived using the data from all of the Adaptive Sessions. This setting was used during the final stage of the protocol (Comparative Measurements), which served primarily to evaluate the success of the experimental fitting procedure. Specifically, the subjects' performance with the WMHA (at the final estimated optimum setting) was compared to performance with the subjects' own aids. Performance was evaluated with the NST; the Pascoe High Frequency Word List (Pascoe, 1975); the Central Institute for the Deaf (CID) W-22 word test (Hirsh et al, 1952); and the CID sentences of everyday speech, also known as the CHABA sentences (Silverman and Hirsh, 1955).c

Aided thresholds for one-third-octave bands of noise were determined with both the WMHA and with the subjects' own aids. Unaided thresholds for the noise bands were also obtained, so that functional gain could be computed for both the WMHA and the subjects' own aids. Additionally, testing was done with the CHABA sentences at settings one step removed in all directions from the estimated optimum slope and lower cut-off frequency.

SUBJECTS

Subjects who participated in the study were

cThe results presented in the present paper will be limited to results obtained with the NST. For results obtained with other materials, see Levitt and Collins (1980).
adults who were experienced hearing-aid users. Experienced users were desirable so that adjustment to amplification would not be a factor during testing. Satisfied hearing-aid users were selected so that comparisons would be made to satisfactory fittings rather than to inappropriate fittings. All subjects had measurable speech perception, and English was their first language. The latter criteria were used for subject selection in order to avoid biases in speech perception testing.

Although sensorineural hearing losses predominated, some subjects exhibited conductive components. The degree of hearing loss varied from mild to profound, with a variety of contours of loss. The group might be described as representative of the spectrum of types and degrees of hearing loss encountered in a clinic.

A total of 27 subjects participated in the study. The first 10 subjects were run on the early versions of the protocol. Of the 17 subjects run on the final version of the protocol, 1 completed only 3 sessions of the adaptive testing rather than the 6 completed by the other 16 subjects.

RESULTS AND DISCUSSION

The first step in the evaluation of the protocol was to determine whether, in fact, a "good" estimate had been made of the theoretical optimum. This was done in part by comparing performance with the estimated optimum setting to performance with the subject’s own hearing aid. Figure 1, showing NST scores obtained with the WMHA at estimated optimum setting plotted against NST scores obtained with the subject’s own aid, illustrates that in almost all cases, performance with the WMHA was superior. (Data points falling above the diagonal indicate superior performance with the WMHA, data points falling along the diagonal indicate equal performance, and data points falling below the diagonal indicate inferior performance with the WMHA.) Since the subjects were satisfied users, any improvement seen in Figure 1 takes on additional significance. Note also the relatively large improvements obtained for subjects who had scores lower than 60 percent with their own aids.

The next step in the process of evaluating the protocol was to determine which aspects of the protocol were most efficient and effective. The stages to be evaluated were the Fixed Test Battery and the six Adaptive Sessions. The NST scores obtained at successive estimates of the optimum setting would be expected to reveal the degree of proximity to the hypothesized optimum and to provide an indication of the rate of progress toward optimum performance. The successive estimates are obtained at the end of the Fixed Test Battery and at the end of each Adaptive Session. Figure 2 shows the average NST scores at the estimated optimum settings at the end of the Fixed Test Battery, at the end of each Adaptive Session, and during the final stage of the protocol. The data point on the far left is for the subject’s own aid and was also obtained during the final stage of the protocol. As can readily be seen from this graph, the greatest improvement in performance is obtained during the Fixed Test Battery, although additional small gains are observed during the Adaptive Sessions. (Statistical analyses were performed on the repeated measurements with given settings to rule out learning effects as the source of the improvement over time.)

Having determined that the Fixed Test Battery was of major significance—but that, on the average, additional improvements in performance were
observed during the Adaptive Sessions—it was considered important to further evaluate each step in the protocol in terms of approximation of the estimated optimum setting. How similar would the estimated optimum setting have been if testing had been terminated earlier? Was the estimate obtained during the Fixed Test Battery or the early Adaptive Sessions the same as the final estimate?

As the data were analyzed to answer these questions, subjects divided naturally into two categories:

1. those whose final estimated optimum was included in the Fixed Test Battery, and
2. those whose final estimated optimum was not included.

Figure 3 illustrates how much more rapidly the former group of subjects converged on the final estimated optimum setting than did the latter group. (Data are shown for 16 subjects only, since one subject completed only 3 Adaptive Sessions.)

The solid line (for subjects whose final estimated optimum setting was included in the Fixed Test Battery) shows steady progress throughout the protocol. The dashed line (for subjects whose final estimated optimum setting was not included in the Fixed Test Battery) indicates that even at the end of the fourth Adaptive Session, less than half of those subjects had converged on the final estimate. Thus, the major contribution of the lengthy adaptive procedure was to counteract effects of a less-than-ideal selection of settings for the Fixed Test Battery on an individual basis. In this regard, the importance of a good initial estimate of the optimum setting cannot be over-emphasized. Individualized adaptive procedures can get around the problem of a poor initial estimate, but at the expense of valuable testing time. Procedures for improving the quality of this initial estimate (using individually determined psychoacoustic data) are currently being investigated.

Further support for the notion of the need for individualized frequency-selective amplification is derived from the distribution of final estimated settings of the WMHA which were found to be “optimum”. Figure 4, a grid showing each subject’s NST score obtained with the WMHA at the estimated optimum setting, and the frequency-gain...
characteristics of this setting (optimum lower cut-off frequency by optimum slope), shows the range and variety of settings selected as optimum. It should also be noted that for 3 of the subjects the estimated optimum slope of the frequency response was 12 dB/octave. This was the highest setting of slope available on the WMHA. It is possible that the optimum setting for these subjects may have involved slopes steeper than 12 dB/octave—that is, had higher slope settings been available on the instrument, several of the subjects might have shown even greater improvement.

We recognize that the experimental protocol in its present form is not clinically practical for most situations. It appears that the most efficient stage of the protocol is the Fixed Test Battery, in that the greatest improvement is achieved in the least time.

It appears to be reasonable to state that in order to make the protocol clinically feasible, it is necessary to be able to select, on an individual basis, the settings which are most likely to be similar to the final estimated optimum for inclusion in the Fixed Test Battery. In order to do this a priori, rules for selection on the basis of audiometric and/or psychoacoustic data may be determined. A variety of rules have been previously proposed and used with varying degrees of success: mirroring the audiogram, paralleling the MCL, paralleling the LDL and bisecting the dynamic range, to name a few. If the protocol were to be applied to other sensory aids, rules could similarly be established which would be appropriate to the modality being “aided” and the performance measurements available.

In summary, we would recommend the retention of all stages of the experimental protocol, but with certain modifications. The initial stage of Basic Audiometrics is needed. It should include testing to determine settings, for each individual, to be included in the Fixed Test Battery. For example, if one were to place the speech spectrum just below the LDL curve (Hertzano, Levitt, and Slosberg 1978), LDL measurements would be made during the first stage of the protocol. Then, the Fixed Test Battery, taking the form of a 3x3 factorial design, would have the LDL-shaped gain function in the central cell with variations of that curve (steeper and less steep slopes) contained within the other cells of the experimental design.

If performance is considered to be satisfactory
and near optimum at the end of the Fixed Test Battery for a given subject, the Adaptive Sessions can be eliminated. However, if the settings in the Fixed Test Battery do not lead to satisfactory performance with amplification, an additional single session of adaptive testing would result in an improved estimate of the optimum setting. The Final Stage can be modified to include testing with various other materials than those used during the Fixed Test Battery, in order to verify the final selection. (Testing can also be done at this time to compare performance with the commercial aid to be fitted with the master hearing aid.)

It should also be pointed out that the application of the original protocol or its suggested revised form is not dependent on the performance measure utilized. Any performance measure which fits the criteria of low test-retest variability and minimal learning can be used. For example, rank-ordered judgements of clarity could be used in place of a speech discrimination score. Similarly, even though in the present study lower cutoff frequency and slope were the independent variables, the protocol could be extended to include different or additional variables such as peak frequency, bandwidth, ripple in the frequency response, or any other index of hearing-aid performance.

ACKNOWLEDGEMENTS

This research was supported by the National Institutes of Health (Contract No. NIH-NO1-NS-4-2323). The wearable master hearing aid used in the study was designed and constructed by Bolt, Beranek, and Newman under contract to the NIH.

REFERENCES


