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On the evaluation of a new generation of hearing aids

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Abstract—Hearing aids with new technological features offer the promise of novel speech-processing and loudness-control capabilities. Full exploitation and assessment of these capabilities will call for the acceptance of fitting and evaluation strategies different from those currently used for traditional linear hearing aids. Until an appropriate set of procedures comes into relatively widespread use, it will be difficult to draw definitive conclusions about the desirability and effectiveness of the new options in amplification systems. This paper reviews some of the issues that should be considered as new evaluation procedures are explored.

Key words: *amplification systems, evaluation strategies, hearing aids, speech processing.*

INTRODUCTION

Technological advances have made it possible to build practical hearing aids with features never before available. For example, they may process the incoming signal in several independent bands; have flexible, adjustable compression capabilities; employ special algorithms and/or microphone arrays to improve signal-to-noise ratio; or contain different amplification characteristics (programs) for use in different listening environments. As instruments with these new and unproven capabilities become available, it is inevitable that we begin to ask how we can demonstrate the effectiveness of the new features. Clinicians and researchers need to know how these instruments compare with traditional single-band linear, single-microphone, single-program hearing aids. If these more capable but more costly devices are to be recommended for a large number of hearing aid wearers, it must be possible to demonstrate their advantages.

There is widespread recognition that appropriate evaluation and fitting procedures for the new generation of high-technology hearing aids will require an approach different from that considered satisfactory for traditional instruments. Changes are called for in many aspects of the fitting and evaluation protocol. This article will review some of the issues that should be considered in developing these procedures.

FITTING THE HEARING AID

It seems likely that full exploitation of the capabilities of many of the new hearing aid designs will require a more complete exploration of the auditory capabilities and disabilities of the hearing aid candidate than is found in current practice. New instruments offer potential for at least two features that could be valuable to the hearing-impaired: processing the entire range of input signal levels so that they are perceived with normal loudness relationships by the hearing aid wearer, and algorithms or microphone arrays to improve the signal-to-noise ratio in unfavorable listening situations. Appropri-

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ate application of these capabilities may call for an expanded fitting protocol.

Restoring Normal Loudness Relationships

Most well-known procedures for the prescriptive fitting of hearing aids were developed with linear, single-program instruments in mind. With this type of hearing aid, changes in gain can be achieved only by manual adjustment, and the instrument can have only one set of characteristics (frequency-response and maximum output). Given these limitations, it is expedient to choose the amplification characteristics to optimize performance under a limited set of conditions, usually assumed to be face-to-face communication in quiet or only moderately noisy backgrounds. The characteristics are typically chosen solely on the basis of auditory thresholds. To validate the fitting, measurements of real-ear gain are widely employed. Because the fitting is optimized for one set of conditions, measurement for a single input level is all that is needed. Usually, the data are obtained from insertion gain measurements for a swept pure tone input of 70 dB SPL.

This general approach, while practical and reasonably appropriate for linear instruments, does not take advantage of the capabilities of newly developed hearing aids that automatically adjust gain and/or frequency response as a function of input characteristics. Instruments that allow adjustment of compression thresholds or compression ratios in each of several frequency bands open up the possibility of remapping the whole range of likely inputs onto the dynamic range of the hearing-impaired listener. Thus, sounds that are soft, comfortable, or loud for normal-hearing listeners theoretically can be produced at levels that are correspondingly soft, comfortable, and loud for the hearing-impaired individual. It is no longer necessary to settle for optimizing amplification for a limited set of input conditions: new amplification devices potentially can deal appropriately with a large proportion of the input conditions experienced by the normal hearer.

To fit these hearing aids, two types of data are needed that are frequently not included in currently popular prescriptive fitting methods. First, data are needed to describe the auditory area or long-term listening range of the hearing aid candidate. In other words, the ear canal sound-pressure levels required to elicit judgments of soft, comfortable, somewhat loud, very loud, etc., must be determined. There are at least three fairly well-known measurement procedures that can be used to describe the long-term listening range of a hearing-impaired person as a function of frequency (1,2,3). Second, validation of the fitting calls for real-ear measurement and adjustment of hearing aid characteristics until input levels with a given loudness for normal-hearing listeners are delivered to the ear canal at the corresponding loudness for the hearing-impaired individual. This aspect of the fitting procedure has not been fully investigated. In contrast to currently popular validation procedures that focus on insertion gain for a single input level, this type of validation involves consideration of the real-ear-aided response (REAR) for a series of input levels. Cox and Alexander (4) reported implementation of this type of validation system. The most significant problem they encountered was achieving precise control of the spectrum of a speech-shaped broad-band input signal. Further research is needed to describe workable REAR-based validation systems, and development of commercial instrumentation to facilitate this approach would be a valuable contribution.

Improving Signal-to-Noise Ratio

New technology has been employed to develop hearing aids with adaptive frequency responses that are intended to improve speech intelligibility in unfavorable listening conditions. The approach is grounded in the assumption that reduction of low-frequency gain under high-noise conditions will produce the dual benefits of removing a substantial proportion of the noise components (because background noise is often low-frequency) and reducing upward spread-of-masking effects. Some studies have supported the efficacy of this approach (5), while others have suggested that it is largely ineffective (6). Those employing hearing-impaired listeners have tended to indicate that some individuals appear to benefit from an adaptive frequency response while others do not (7,8). The explanation for the lack of consistent results among hearing-impaired listeners may lie in the differing auditory resolution capabilities of these individuals. For instance, it is clear that there is considerable variation in auditory filter shapes across hearing-impaired listeners (9) as well as a wide range of temporal processing abilities (10). Clinically practical approaches to the measurement of auditory resolution abilities have been explored by several investigators (11,12,13,14). Future developments in this arena may provide evaluation tools that will permit prospective selection of appropriate candidates for hearing aid features such as adaptive frequency response and syllabic compression.

The ultimate goal in hearing aid fitting should be to develop prefitting psychoacoustical tests and postfitting acoustic validation methods that can be used with confidence to select an appropriate amplification system for each hearing-impaired individual. This goal probably will not be achieved in the near future. In the meantime, the efficacy of features such as putative loudness normalization, adaptive frequency responses, and signal-to-noise ratio improvement through multimicrophone arrangements will often need to be evaluated using performance testing after the fitting. Performance tests can be conducted in either laboratory or field settings, or both, as described below.

PERFORMANCE EVALUATION IN THE LABORATORY OR CLINIC

In the short history of hearing aids, it has been customary to fall back on speech intelligibility testing to evaluate instruments with previously untried capabilities. The practice of using speech understanding as the ultimate standard of efficacy is easily justified because improved speech communication is the main goal of most hearing aid wearers (15,16). As attempts are made to describe applicability and refine new features of hearing aids employing technological advances, a resurgence of interest in speech intelligibility testing seems likely. The clearest applications for such tests at present are to evaluate the effectiveness of technology that attempts to improve signal-to-noise ratio, and to establish program parameter values for multiprogram hearing aids.

Although monosyllabic word tests have been widely used to evaluate hearing aids, their basic unsuitability for this task has been recognized for many years. Monosyllabic words (and nonsense syllables) do not resemble natural speech, and the relationship between understanding of these types of stimuli and understanding of everyday conversational speech is not known. Many newly introduced hearing aids are adaptive in their performance, adjusting their characteristics with varying attack and release times, on the basis of the ongoing input. Because of this, it is especially important that they be evaluated and compared using speech that is as natural as possible. Ideally, the speech test material would be long enough to include contextual cues and would develop a familiar topic over several sentences, as normal conversations do. It would be delivered with natural inflection in a conversational manner and be produced by several different normal talkers. Competing noises and other environmental influences would resemble those encountered under everyday conditions. Finally, the results would be highly reliable and there would be a large number of equivalent forms to allow testing of many conditions.

Unfortunately, the ideal speech intelligibility test does not exist. However, several tests have been developed that incorporate some of the required features. For example, the Connected Speech Test, or CST (17,18,19) employs 10-sentence passages of speech about familiar topics, produced with fairly natural rate and inflection. The intelligibility of the talker was found to be average among a group of normal talkers (20). The competing noise is a six-talker babble similar to the murmur of voices in a crowded room. The 48 passages may be combined into empirically equated sets of 2, 4, 6, or more. This test is scored objectively in terms of the proportion of scoring words correctly repeated from each sentence. Benefit from linear hearing aids, measured using the CST, has been consistent with subjective reports of hearing aid wearers indicating that benefit is dependent on acoustic environment (21). The speech intelligibility demands produced by the test in three different environmental configurations have been rated by hearing aid wearers as quite similar, though not identical, to those of daily life (22). The principal disadvantages of the CST are the relatively long administration time and a number of equivalent forms that may be fewer than desired. Because substantial learning occurs for natural speech with a single exposure, there are limitations on the reuse of passages with the same subjects.

Administration time of connected speech tests can be substantially shortened if subjective ratings of intelligibility are used instead of objective scoring. Early work on this approach to intelligibility testing with fairly natural speech samples was reported by Speaks, et al. (23). The Speech Intelligibility Rating (SIR) test, based on subjective intelligibility ratings, was developed by Cox and McDaniel (24,25). For the SIR test, the subject listens to a 35-second passage of connected speech about a familiar topic and then estimates the proportion of words understood on a percentage type of scale. The final score for a given listening condition is based on the ratings for from three to five passages. Several investigators have reported the use of this test with hearing-impaired subjects to evaluate and compare both traditional hearing aids and instruments with novel processing abilities (26,27,28). Because it employs continuous, reasonably natural speech, and can be administered in a short period of time, the SIR test is well-suited to clinical comparisons of hearing aids or hearing aid features. Furthermore, Cox, Alexander, and Rivera (29) found that, although subjective intelligibility estimates similar to those generated by the SIR test were somewhat less reliable than objective intelligibility scores such as those obtained using the CST, the overall ranking of hearing aid conditions produced by the two types of tests was similar. The major drawback of the SIR test is that its set of equivalent passages is limited to 20. Because of the essentially instantaneous learning that occurs for natural speech, the effects of passage repetition are difficult to predict. As a result, the SIR test is best suited to applications with comparisons of four or fewer conditions so that passage repetition will not be necessary.

It is well-known that traditional linear hearing aids deliver the least benefit for listening conditions where they are most needed—the unfavorable conditions produced by the degradations of background noise and reverberation. Perhaps the most eagerly anticipated advantage of new technology in hearing aids is an improvement in the benefit obtained in unfavorable conditions, either through adaptive frequency response algorithms, multiprogram instruments, or other approaches. Simulation of unfavorable listening environments will be an integral part of speech intelligibility test evaluations with hearing aids employing these technologies. Given the considerable importance of environmental acoustics in the evaluation of technologically advanced instruments, it is essential to consider the validity of the acoustic environment used for clinic and laboratory testing. The degradations employed in the test setting should have a known relationship to those encountered in daily life. Simulations that are both traditional and intuitively reasonable may not be as satisfactory as anticipated. For example, Cox and Alexander (22) reported that a multitalker babble used to simulate the competing noise in a "cocktail party" situation was rated as less disturbing than noises encountered at real cocktail parties, despite the use of an appropriate signal-to-babble ratio. Similarly, in an investigation of the accuracy with which a reverberant environment could be simulated in an audiometric test room, Cox, Alexander, and Rivera (30) reported that although the results for two normal talkers indicated that the simulation was quite accurate, the results for a third normal talker indicated that the simulated reverberant environment was different in some respects from the real reverberant environment. These types of data reveal that more research is needed to explore methods of accurately simulating everyday noisy and reverberant environments under controlled conditions. Successful simulations may make an important contribution to valid and useful comparisons of noise-reduction hearing aids as well as providing a suitable milieu for establishing parameter values in multiprogram instruments.

Even assuming that an appropriate speech intelligibility test is used and accurate environment simulations are developed, at least one other variable will play an important role in laboratory evaluations of hearing aids with new technological features. Two recent investigations have shown that a substantial period of normal use is required before the benefit available from a newly fitted hearing aid is fully mature. Cox and Alexander (22) assessed laboratory-measured hearing aid benefit immediately following the fitting and again after 10 weeks of normal daily hearing aid use. The results indicated that over the 10-week adjustment period, benefit improved significantly in certain listening environments but not in other environments. Furthermore, the amount of improvement was more predictable in some listening conditions than in others. The results were consistent with a hypothesis that full utilization of newly audible speech cues cannot be achieved by many individuals without considerable practice. Gatehouse (31) also reported that laboratory-measured hearing aid benefit increased over the 12 weeks following a new hearing aid fitting. This study also clearly supports the existence of a substantial adjustment period before hearing aid benefit stabilizes.

Both of these investigations employed traditional linear hearing aids which do not substantially alter the cues available in natural speech. It is possible that the adjustment period would be even longer for hearing aids that recode speech cues by compressing or enhancing them. In addition, the interaction between the benefit maturation process and the employment of multiprogram hearing aids has yet to be investigated. Because multiprogram instruments may provide different speech cues depending on the program being accessed, it is possible that maturation of benefit for one program may interfere with maturation of benefit for another program (for example, if one program compresses speech and the other does not). Clearly, more research is needed to delineate the process of benefit maturation and to determine whether, and to what extent, the amount of improvement in benefit is predictable. Unless long-term benefit can be predicted with reasonable accuracy from initial measurements, the validity of benefit data obtained very soon after hearing aid fitting must be seriously questioned.

PERFORMANCE EVALUATION IN THE FIELD

Questionnaire-based approaches have a long history in the evaluation of hearing aids and the verification of their effectiveness. Typically, the instrument under investigation is fitted to each of a group of hearing-impaired listeners and they use the device in their daily lives for a period of days or weeks. Following this, each subject responds to a series of questionnaire items concerning his/her experiences with the amplification system. This type of evaluation has already been employed by several investigators to quantify the benefits of hearing aids employing technologically advanced features (32,33,34). Acquisition of data through the process of asking the hearing aid wearer about the help provided by the instrument has an appealing simplicity and relevance to the issues in question. Nevertheless, field types of evaluations have their own set of limitations.

One especially troublesome problem is the lack of comparable results across studies. Investigators have tended to develop their own inventories, relying on the content validity of the items to address the issues of interest, and employing measurement scales varying from estimated percentages to binary choices. In addition, psychometric data describing means, variability, reliability, and item interrelationships are generally not reported for these single-use inventories. Because of differences in data structures and a lack of reference data, it is often difficult to compare the results of studies evaluating different instruments or opposing technologies. The utility of field evaluations would be enhanced considerably if a standard inventory with established psychometric properties could be used by the various investigative teams as well as by clinicians.

The fundamental property of most innovative hearing aids at this time is their ability to adapt their performance to accommodate a range of inputs or acoustic environments. To assess the effectiveness of these types of instruments, an inventory that quantifies benefit in several subscales relating to different environments or input conditions is appropriate. Several inventories that might be suitable have been reported. The Hearing Aid Performance Inventory (HAPI), developed by Walden, Demorest, and Hepler (35) quantifies the magnitude of hearing aid benefit in four subscales. The Profile of Hearing Aid Benefit, or PHAB (36) quantifies the frequency of benefit in seven subscales. The Profile of Hearing Aid Performance, or PHAP (37) is similar to the PHAB but reports performance with the hearing aid in terms of frequency of problems in various situations. Mean subscale scores, variability, and interitem relationships are available for all three inventories for subjects using traditional hearing aids. In addition, test-retest data and subscale critical differences have been reported for the PHAB (38) and the PHAP (37). These data applying to traditional hearing aids could provide a basis for evaluation of the effectiveness of new technological features.

One of the most attractive applications of self-assessment inventories is the potential for evaluating opposing technologies or fitting strategies on the same individual. In this type of investigation, the subject is furnished first with one proposed amplification system, and then with the other. Responses to self-report inventories are obtained to evaluate each system. However, several investigators have reported the test-retest reliability of self-assessment inventories used with hearing-impaired listeners (37,38,39,40), and these studies are consistent in suggesting that data from existing self-assessment inventories do not have high inherent reliability for individual subjects. For example, 95 percent critical differences for subscales of the PHAB range from 25 percent to 38 percent (38). This result is not very surprising, given the myriad uncontrolled experiences that might affect responses on any given day. Nevertheless, the practical implication is that when data are evaluated on an individual basis, self-assessment inventories may be sensitive only to relatively large differences between conditions. Thus, to gain sensitivity sufficient to detect smaller differences between hearing aids with different technologies, field evaluations should be conducted using groups of subjects.

Because the data from self-assessment inventories is necessarily subjective, the possible influence of extraneous factors such as memory, personality, education, age, health, and mood should be a matter of concern. If these factors significantly influence the responses given to inventory items about hearing aid benefit, experimental control must be exercised over the influential variables when composing matched groups of subjects for field evaluations. While it seems plausible that at least some nonauditory variables could affect inventory data, relatively little research interest has been directed at this problem to date, despite the widespread interest in, and use of, self-assessment inventories.

In a study relevant to this issue, Gatehouse (41) reported that age has a significant effect on the amount of self-assessed hearing disability: older individuals routinely report less disability than younger individuals with the same audiograms. Based on this result, it would not be surprising to discover that older individuals typically report less hearing aid benefit than younger persons. If so, field evaluations made by groups with different ages may not be comparable. In the same study, Gatehouse also noted a strong relationship between personality and self-assessed hearing disability and a weaker relationship between IQ and self-assessed hearing disability. His data suggest clearly that it would be important to control for these variables if valid comparisons are to be made across groups assessing different hearing aid technologies.

Cox and Rivera (38) noted a significant relationship between an individual's willingness to make negative self-appraisals and the negativeness of his/her responses to items that query the loudness discomfort associated with amplified environmental sounds. This result is interesting because the loudness discomfort occasioned by hearing aid use is a variable that many technologically advanced hearing aids attempt to minimize. Clearly, field evaluations comparing these devices will need to control variables that influence rated discomfort.

These studies indicate that certain nonauditory variables can be expected to have significant influences on data derived from field evaluation research as well as from clinical uses of this technique. More research is indicated to determine which variables are important, how they may parsimoniously be quantified, and the extent and direction of their influence on self-assessment data.

Experience with hearing aids appears to be another factor that can affect responses to self-report inventories. Cox and Alexander (22) reported that self-assessed hearing aid benefit increased during the postfitting adjustment period in a manner similar to the improvement in laboratory-assessed benefit. In addition to the effect of benefit maturation on inventory scores, subjects who were previously experienced hearing aid users reported significantly more benefit than the group of previously naive subjects. This result might be attributed to a self-selection process, whereby only those individuals who consider themselves to be receiving adequate benefit continue wearing hearing aids long enough to become experienced users. This self-selection effect would operate whenever previously successful hearing aid users are employed as subjects. It is probably also reasonable to assume that previous experience with traditional linear hearing aids would have an effect on inventory responses evaluating an instrument that processes sound in a different way.

The recent upsurge of interest in inventories to quantify hearing aid benefit suggests that field evaluations of new technology in hearing aids will probably be employed increasingly in the near future, perhaps because of the lack of a generally accepted approach to laboratory evaluation and/or lingering doubts about the validity of any such evaluation. Laboratory measurements of performance with hearing aids are valuable only if they are predictive of performance in daily life. However, it is not simple to devise laboratory measures that are demonstrably predictive of daily life experiences. For example, Cox and Alexander (22) were able to establish a significant relationship between laboratory measurements of hearing aid benefit in two simulated environments and subscales of the PHAB assessing the same two environments. However, in a third and especially troublesome environment, the "cocktail party," no relationship was found between laboratory measurements and field assessments. Field evaluations will continue to be a necessary adjunct to laboratory testing until both types of measurements are sufficiently refined that a clear relationship can be established between the two types of data.

SUMMARY

The application of new technological developments has brought sophisticated sound processing of various types within the grasp of professionals who fit and evaluate hearing aids on hearing-impaired listeners. These advances bring with them the challenge of developing techniques that will promote appropriate choices among available device features and valid evaluation of their benefits. Full exploitation of the capabilities of the new generation of hearing aids will call for substantial changes in fitting and evaluation protocols. We can anticipate a need for a more thorough evaluation of the auditory processing capabilities of the hearing aid candidate, both in terms of loudness perception and in auditory resolution. Furthermore, verification of an appropriate fitting will require a more extensive REAR-based measurement protocol, assessing a variety of input conditions.

One of the most intriguing features of the new types of hearing aids is their ability to adapt their performance to changing input conditions. The effects of these adaptations on speech intelligibility should be determined. Because of the complex and somewhat unpredictable nature of new amplification devices, evaluation of their effects and comparisons of different strategies calls for the use of intelligibility tests employing speech material, competing stimuli, and environmental influences that are as natural as possible. It seems unlikely that the traditional approach of measuring the intelligibility of monosyllabic words in a noise-free, sound-treated audiometric test room will yield data that can elicit important distinctions among systems. In addition, before valid conclusions can be drawn about the benefit accruing to a particular amplification system, the potential for maturation of benefit should be considered.

Field evaluations using self-report inventories are an attractive option for appraisal of innovative hearing aids when the validity of laboratory tests is in question. The generalizability of self-report data would be increased if standardized inventories were used in field evaluations. A few inventories have been developed that quantify performance with hearing aids in several subscales, each relating to a different type of input condition. These could be useful in evaluating instruments that adapt their performance on the basis of input. However, enthusiasm for field evaluations should be tempered by data that have shown a number of variables to affect self-assessed hearing aid benefit, including age, aspects of personality and adjustment, and previous experience with hearing aids. Furthermore, the test-retest reliability of self-report data is generally poorer than that of objective data obtained in a laboratory setting.

Because the applicability and effectiveness of hearing aids employing new technological features are still uncertain, a diversified approach to performance evaluation, employing a combination of laboratory and field strategies, seems advisable. Ultimately, the data will indicate which processing approaches are successful and for whom they are appropriate.

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