Transducers, Earmolds and Sound Quality Considerations

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ABSTRACT The physical limitations to hearing aid performance have now been largely removed, and recent speech discrimination research provides excellent information on how to maximize the aided speech discrimination score for a given individual. Much less information is available on how to maximize the overall utility of the hearing aid for a given individual as he goes about his daily life. This is a multidimensional problem, and arguments for multidimensional research are offered.

INTRODUCTION

This chapter presents an argument for a shift in emphasis in hearing aid research. The argument is presented as follows:

I. Due to recent developments in subminiature transducers and electronics, the limitations to the physical performance of hearing aids have been largely removed.

II. The problems introduced by the acoustic coupling—especially the earmold—are now sufficiently well understood that the true frequency response of the hearing aid, as perceived by the user, can be individually tailored for the user in a highly predictable manner.

III. The excellent speech discrimination research of the last decade has provided sufficient information so that it is now possible to choose, on an a priori basis, the frequency response of the hearing aid that will come close to maximizing the given individual's aided speech discrimination score. Close enough, in particular, so that further improvements can be obtained only at the expense of a very large additional effort.

IV. In contrast, much less research has been undertaken to determine what is required in order to maximize the utility of a hearing aid for the user as he goes about his daily life. A high return on research investment might be expected if multidimensional questions such as the following were addressed: What hearing aid characteristics are required to simultaneously maximize speech discrimination *and* sound quality? (At the moment it is not clear what the best compromise between those two goals might be, or even if a compromise is necessary.)

I. PROGRESS IN TRANSDUCERS

A. The Best, Fifty Years Ago

To put today's efforts in perspective, let us first consider the successful hearing aid of nearly fifty years ago. Figure 1 shows the insertion gain, measured on a KEMAR manikin, of a 1934 Radioear model hearing aid loaned to me by Sam Lybarger, its designer. Although the advertising copy claimed (undoubtedly correctly) that this was "the most effective hearing aid acoustical research had produced," the transducer limitations of fifty years ago were severe. This carbon-transmitter-plus-carbon-amplifier hearing aid produces a peak insertion gain of 50 dB but a high-frequency-average-gain (1.0, 1.6 and 2.5 kHz) of only 31 dB. It has a total harmonic distortion of approximately 30% and, as the

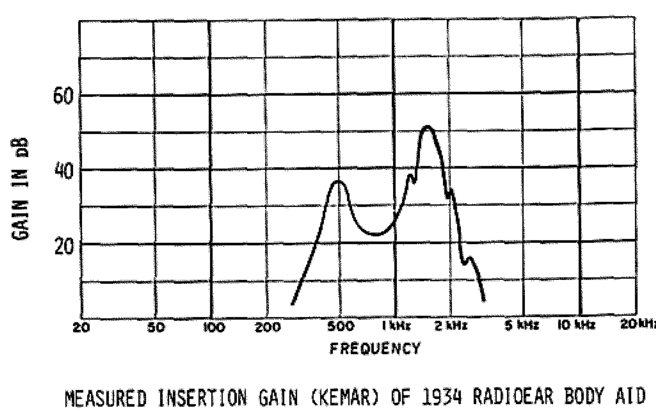

Figure 1 *Measured insertion gain (KEMAR) of 1934 Radioear model B-20 body aid.*

tape recorded demonstration (played for the conference participants) confirms, has a totally unacceptable sound quality by today's standards. Yet is was a highly successful hearing aid, and provided substantial benefit to many users.

The interesting question for our present purpose is; how could a hearing aid with a 30 dB peak in the frequency response and 30% total harmonic distortion be highly successful, especially considering that the aided speech discrimination provided the user of that hearing aid was probably poorer than would be provided by the *least suitable* hearing aid one could obtain for a user today? The answer is simple: Without a hearing aid, most of those users couldn't *hear* the speech. Speech *audibility* and not speech discrimination was the first problem to be solved, and hearing aids of fifty years ago solved that problem. (Moreover, 30% total harmonic distortion isn't all *that* bad: That's not an unusual figure for the telephone each of us uses daily.)

B. Today's Transducers

Recent developments in subminiature microphones and earphones have been summarized at length elsewhere (Killion, 1980), and a shorter review will be given here.

Today's subminiature hearing aid microphones can be obtained in a wide variety of frequency responses including a nearly flat response from 20 Hz to 20 kHz, have a noise level comparable to that of an unimpaired human ear, and have a distortion level well below the limits of audibility. Indeed, the flat-frequency-response versions of these same subminiature microphones are being widely used in the broadcast and recording industry.

Hearing aid earphones are now available with bandwidths extending from 20 Hz to 17 kHz, undistorted output power handling capabilities ten times that required to reproduce a full symphony orchestra as heard in a front row seat, and distortion at or below audible limits over most of their useful operating range.

Not surprisingly, therefore, it has been possible to construct experimental high-fidelity hearing aids whose sound quality equals that of expensive high fidelity systems, as judged by both "golden ear" professionals and "man on the street" listening panels (Killion, 1979). The frequency responses of five of the sound systems used in those listening tests are shown in Figure 2. The experimental Over-The-Ear aids had an 8 kHz bandwidth and the In-The-Ear aids had a 16 kHz bandwidth. Whatever signal processing might be required for a complete hearing aid, it is clear that the transducers are no longer the limiting factor.

II. ACOUSTIC COUPLING

A. Bandwidth

The acoustic coupling controls the bandwidth of both the microphone and earphone responses. In the case of the microphone, the same basic microphone element can exhibit a frequency response which is nearly flat

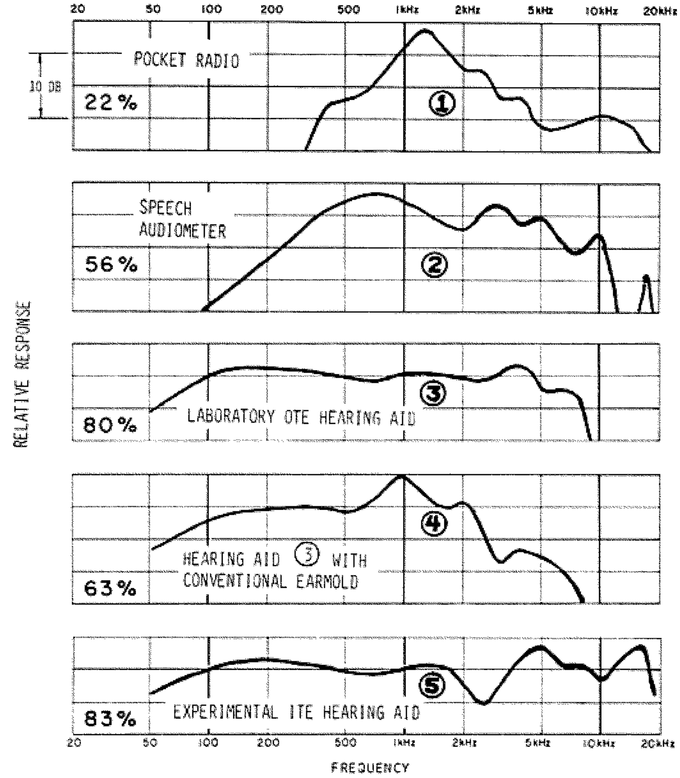

Figure 2 *Frequency response of five sound reproduction systems, as measured with 1/3-octave bands of noise and an equalized KEMAR manikin. (From Killion, 1980).*

from 20 Hz to 12 kHz or a response with a sharp peak at 2000 Hz followed by a steep high frequency rolloff above that frequency, depending only on the choice of coupling tube. Similarly, with the appropriate earmold coupling, the most recent subminiature earphone is capable of a 16 kHz bandwidth, even in an Over-The-Ear hearing aid. Yet with a different earmold, that same earphone provides a bandwidth of only 3 kHz or less.

B. Response Shaping

The construction of the earmold plays a significant role in determining the delivered frequency response of

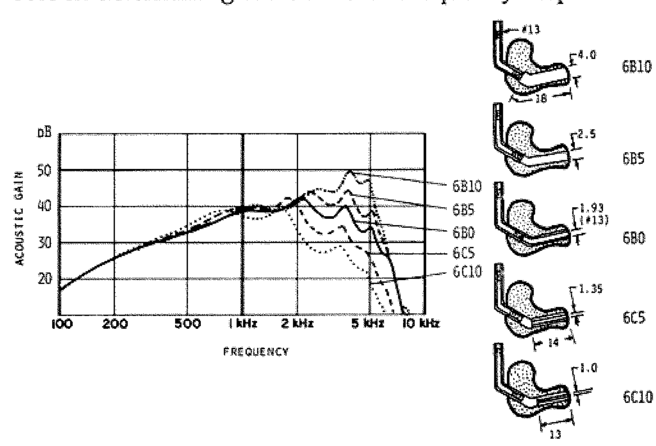

Figure 3 *Use of "horn" and "reverse horn" earmold construction to control high-frequency emphasis. (From Killion, 1981).*

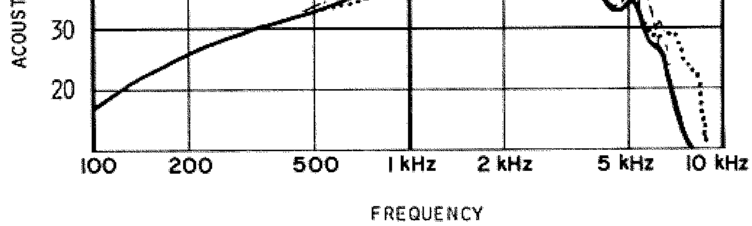

Figure 4 *Use of earmold construction to selectively emphasize different frequency regions. (From Killion, 1981).*

any hearing aid. For Over-The-Ear hearing aids, a series of recently developed earmolds (Killion, 1981) allows highly predictable modification of the mid- and high-frequency output of the hearing aid, much as venting has been used for decades to modify the low-frequency output. Figure 3 shows the use of "horn" and "reverse horn" earmold constructions to control the high frequency output of a hearing aid. Figure 4 illustrates the frequency response tailoring that eases the task of providing selective amplifications for individual hearing-loss configurations. These issues are discussed at greater length in Libby's chapter.

III. MAXIMIZING UTILITY

A. Speech Discrimination Research

The apparent motivation for the majority of past hearing aid research has been the assumption that the most important problem to be solved was that a hearing aid did not provide adequate speech intelligibility for most users. Although this assumption was undoubtedly correct for the technology of the 1930's and 40's, it is probably no longer true. Nonetheless, the majority of hearing aid research has used, and continues to use, the aided speech discrimination score as the prime measure of the utility of the hearing aid for the user. This has been particularly unfortunate since the two major conclusions of the single most important piece of hearing aid research—the Harvard Report—are now known to be wrong: It is *not* true that frequencies above 4000 Hz are unimportant to speech intelligibility for most hearing aid users, and it is also *not* true that individual selective amplification (tailoring the frequency response of the hearing aid to partially compensate for the frequency dependence of the user's hearing loss) "is fallacious."

Fortunately, in the last decade we have seen excellent fundamental research. The research studies of Villchur (1973), Pascoe (1975), Skinner (1976), and Lippman (1978)) all took the real-ear or insertion-gain response of the hearing aid into account, and we now know that extending the bandwidth of the hearing aid beyond the traditional 500 to 4000 Hz limits represents a significant improvement for many (but not all) users, and that indi-

too often forgotten fact that speech cues ha
audible to be usable, and Lippman's (19
appears to indicate that making the speech cu
is *all* that has to be done (i.e., no further signa
ing is necessary beyond that required to make
sounds audible).

B. The Real Question

It is sad but true that in several decades of f
hearing aid research, the most important
question—"What are the factors most import
hearing aid user?"—has received very little fu
effect, the most important research ques
answered without data before the research eve
The effect of that decision has been to fur
research dollars into research where virtually
measure of utility has been the aided speech d
tion score.

Now that really good answers to the questi
to maximize the aided speech discrimination s
it is appropriate to ask again what the real q
The real question, of course, is; "How can we
the utility of the hearing aid for the user?"
several of the presentations at this conference
this question is now being vigorously addresse
dition of looking *only* at the aided speech disc
score has been so firmly entrenched in au
research that some over-compensation may be

It is easy to forget that the main reason m
need a hearing aid is because they can't *he*
without a hearing aid, not because they ca
stand speech. Most of them, in fact, do qu
understanding speech without a hearing aid, p
is loud enough. The user with a precipitous
hearing loss is an obvious exception, althoug
nearly all research indicates the main problen
audibility. Once the high-frequency speech
amplified sufficiently to make them audible,
with ski slope losses report a great deal of
their daily life from hearing aid usage (Dodd
ford, 1968).

C. Four Counterexamples

Even if we agree that the single most impor
in the utility of a hearing aid is its ability to m
more intelligible, that fact does not imply tha
improvement in the aided speech discrimina
(over that obtainable with any intelligent h
selection) is the most important goal for h
research. With the hearing aids and selection p
available today, improved speech discrimina
has probably ceased to be the most importa
most users. I'd like to give four examples to
this point:

1. Sound Quality

Several investigations, from the Harvard Study to Pascoe's study, have indicated that:

a) most individuals with sloping hearing loss obtain maximum discrimination scores with high-frequency-emphasis selective amplification, and
b) the majority of the same individuals *prefer* a *flat* frequency response. Adjectives such as "harsh, unpleasant sounds" are often used to describe the amplification providing best speech discrimination.

What do you do when faced with such a tradeoff? If you have made an a priori decision that speech discrimination is the only important dimension, you give them "high frequency emphasis regardless," to quote the title of one paper recommending just that approach. If you think sound quality is more important, you may do just the opposite.

The thing that makes it hard to decide which viewpoint is correct is the ability of people to adapt. The old saying, "wear it awhile and you'll get used to it" is just as true today as it was back in the 1940's, when Silverman reported that hearing aid users could become accustomed to sounds which were uncomfortably loud. The many satisfied users of high-frequency-emphasis hearing aids provide examples of successful adaptation, while the many hearing aids in dresser drawers—some providing excellent speech discrimination—provide examples of unsuccessful adaptation.

How does one obtain information to resolve a conflict between two factors such as intelligibility and sound quality when adaptation plays such an important role? One approach has been to use surveys of user satisfaction. But these have shown that the vast majority of users are at least somewhat satisfied, and that the degree of satisfaction does not appear related in any observable way to how they obtained their hearing aid. More importantly, it only gives information on old designs and not new designs. Another way might be a long-term psychoacoustic experiment using the method of adjustment. The user would be given a hearing aid with a knob or multiposition switch which controlled some electroacoustic characteristic in such a way as to provide a tradeoff between speech discrimination and some other dimension. The user would be asked to try different settings over a period of weeks until he found the best compromise.

2. Volume Control Settings

Interestingly enough, we already have data from just such experiments, where the knob was the volume control. These data form the basis of my second example, illustrated in Figure 5. If we take the available data on the relationship of word and sentence intelligibility to presentation level, the Dunn and White (1940) data on amplitude peaks in conversational speech, and Martin's (1973) data on the gain employed in typical conversational settings by users with sensorineural hearing loss, we can obtain an estimate of the tradeoff between speech discrimination and annoyance: The tradeoff shown here is an estimate of the one which must be

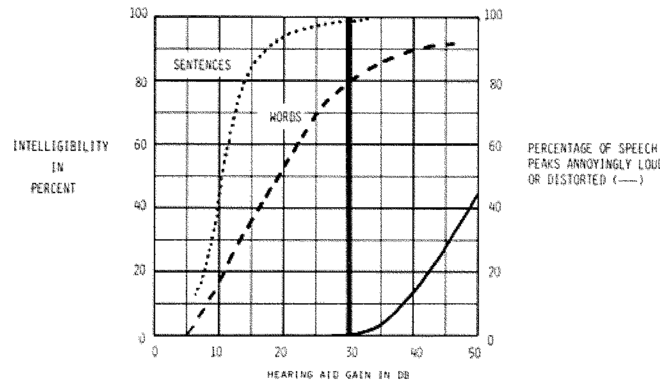

Figure 5 *Estimated relationship between hearing aid gain, speech intelligibility, and annoyance for user with 60 dB sensorineural hearing loss in conversational setting.*

made by someone who has a 60 dB sensorineural hearing loss when he uses a conventional hearing aid of the type available to Martin's subjects. The heavy vertical line shows the gain typically chosen under those conditions, a gain sufficient only to bring conversational speech to a 20 dB sensation level—well below the 30–40 dB required to maximize the speech discrimination score for monosyllabic words. The point I want to make is that it appears that most subjects do not *voluntarily* choose to maximize speech discrimination at the sacrifice of comfort and/or sound quality!

3. Binaural Aids

I'd like to give a third example. For years the fact that binaural hearing aid users were willing to pay an extra few hundred dollars for the second aid was considered an enigma, because it was difficult to demonstrate any significant improvement in speech discrimination with the addition of the second hearing aid. Moreover, user surveys revealed that the binaural aids appeared most useful in quiet surroundings—conversational situations at home, listening to music, etc.,—where speech discrimination should not have been a problem anyway (Dirks and Carhart, 1962).

I think the reason for the enigma was that everyone was asking the wrong questions. Because of the assumption that anything that was truly useful to a hearing aid user must somehow reflect in an improved discrimination score, no one asked how important sound quality and/or the sense of auditory space was to users. Indeed, at least one researcher specifically dismissed user reports that speech "sounded better" or was "more natural" with binaural aids, on the basis of his armchair conclusions that such reports were of questionable validity and that the user was in no position to judge what he needed anyway.

Almost as an afterthought in a recent fidelity-rating experiment (Killion, 1979), a comparison between a monaural and binaural condition was included: A comparison recording obtained by simply shorting out one of KEMAR's microphones for the monaural condition. The results were even more dramatic than those reported by Fletcher in 1942. Two subject groups gave ratings in the Bad-to-Extremely-Bad fidelity region and all three subject groups rated the monaural condition lower than any of sixteen other sound systems. The *only* sound system which was given a lower rating than the monaural condition was a $5.00 pocket radio whose amplifier was driven into heavy overload distortion!

The conclusion appears obvious: If the hearing aid user has good binaural hearing, it may well be that the main reason he chooses binaural hearing aids is simply that sound quality is more important to him than we usually assume. There are other possible reasons (binaural squelch, head shadow, loudness summation), of course, but I know of no other dimension where, on a 0-to-100 percent rating scale, binaural hearing is worth 70–80 percentage points!

4. Compression Aids

As a fourth and final example, consider the research on compression hearing aids. Anecdotal evidence indicates that once a user learns how to function with a compression hearing aid, he wouldn't consider any other kind. Yet the careful studies of Barfod (1978) and of Lippman (1978) have shown no advantage for compression amplification over carefully chosen linear amplification. The problem is that the prime measure of utility in Barfod's and Lippman's studies was speech discrimination for constant-presentation-level word lists. In effect, the stimuli were precompressed by the talker monitoring the VU meter when the lists were originally recorded (Villchur, 1978). Perhaps the major utility of compression involves nothing more than convenience: Compression amplification may alleviate the annoyance of having to readjust the volume control every few minutes. For someone who has trouble manipulating the volume control in the first place, that could well be a major factor.

It may be that Skinner's (1976) study—which involved only *linear* amplification—will prove fundamental to the implementation of *compression* amplification, because it so clearly underlined the dilemma presented to the user of linear amplifications: The frequency response that gave Skinner's subjects their best low-level discrimination also cut their useful dynamic range nearly in half!

D. Ranking the Factors

Table I provides one estimate of the rank ordering in importance of five factors that help determine the utility of a hearing aid for a user. The prime importance of the first factor, that the hearing aid improve the audibility of quiet sounds, is self evident. Fortunately, this problem has been solved almost from the beginning: Even the hearing aids of the 1930's made the speech sounds audible for the user.

The second factor, that the hearing aid be cosmetically and psychologically acceptable, is partly a counseling and reeducational problem (Brooks; 1979, 1981) but rarely an electroacoustic problem. The limitation of the purely electroacoustic solution to the hearing aid problem was dramatized some time ago by the estimates

TABLE I

Estimated Rank Ordering of Five Factors in Hearing Aid Acceptance

1. IMPROVES SPEECH AUDIBILITY
2. COSMETICALLY AND PSYCHOL. ACCEPTABLE
3. COMFORTABLE TO THE EAR
4. GOOD SOUND QUALITY
5. MAXIMIZES SPEECH DISCRIMINATION

that some 500,000 Medresco bodyworn aids were lying in dresser drawers (mostly because, it was concluded, they were simply too bulky) even though their electroacoustic characteristics had been designed to maximize the aided speech discrimination score in keeping with the findings of the Medresco study (Radley et al., 1947). Whether this was a direct failure of speech discrimination research per se (in providing the wrong electroacoustic guidelines), or an indirect failure of speech-discrimination-only research (in failing to ask the important questions) is perhaps irrelevant. Along the same lines, however, the fact that three-fourths of hearing aids dispensed in the USA in the late 1950's were headworn aids (Lybarger, 1966) at a time when the electroacoustic performance of headworn aids was substantially inferior to that of the better bodyworn aids, also supports the importance of factor #2.

The importance of the third factor, that a hearing aid must be comfortable or it won't be worn on a regular basis, almost goes without saying. Anyone who has tried wearing a hearing aid with an ill-fitted earmold, for example, knows from personal experience that it almost can't be done. Similarly, a hearing aid whose output routinely exceeds the user's loudness discomfort level causes so much difficulty that Briskey (1976) once suggested that finding the appropriate saturation output for a hearing aid comprised 70% of the successful fitting.

The relative ordering of "good sound quality" and "maximizes speech discrimination score" in Table I are a result of the writer's self-evident bias. The point to be made, however, is that it is just as easy to study the effect of electroacoustic characteristics on sound quality as it is on speech discrimination scores—separately or jointly—but yet after decades of research there is *virtually no available evidence to settle the question as to which is more important to the typical user.* Even if there were only a 20% probability that sound quality was more important than a further improvement in speech discrimination, one could argue that 20% of the research fundings should go toward maximizing aided sound quality. (One could even argue that *all* funding should go in that direction for a few years as a compensatory measure!)

IV. WHICH TRADEOFFS ARE NEEDED?

Fortunately, there are increasing indications that it may be possible to provide excellent speech intelligibility *and* excellent sound quality simultaneously. With today's hearing aid technology, the traditional tradeoff between aided speech intelligibility and aided sound quality may no longer be required. The following evidence supports this hypothesis.

A. High Frequency Emphasis Vs. Sound Quality

Lawton and Cafarelli (1978) studied the effect of modifying one of the British standard hearing aids by substituting a wideband microphone and earphone for the conventional transducers used in its original design. The average speech discrimination score in noise of their 28 subjects improved 3.9% with the wider bandwidth experimental version (an improvement that was statistically, if not practically, significant). A small (1.7%) additional improvement was obtained when a well-damped "horn" earmold was substituted for the conventional earmold. More importantly, 24 out of the 28 subjects *preferred* the sound quality with the well-damped earmold.

The frequency response of Lawton and Cafarelli's wideband aid with the two earmolds is shown in Figure 6. Note especially that the well-damped "horn" earmold actually provides increased high-frequency boost for the user. Here, at least, was a case where increasing the high frequency emphasis did *not* cause rejection of the hearing aid because of a "harsh tinny sound."

Indeed, it may be that the common complaint of a harsh, tinny sound relates more to peaks in the frequency response and/or high-frequency overload distortion than it does to the presence of high-frequency emphasis per se. Research data to answer this question are virtually nonexistent, even though the importance of the question was clearly recognized in the 1940's.

Further evidence that substantial high-frequency emphasis is not necessarily incompatible with good sound quality was provided recently in a taped demonstration recorded by Villchur (and played for the conference participants). When the same high-frequency emphasis used by Lippman (1978) to maximize the speech discrimination score for one subject was applied to conversational speech and then electronically processed to simulate that subject's deafness (as described by Villchur, 1977), the result was most unpleasant; so much so that it would probably not be acceptable to a user. Without compression, the amount of high-frequency emphasis required by that subject meant that the more intense peaks in conversational speech became uncomfortably loud. When the high-frequency-emphasis compression amplification that gave Lippman's subject the same (but no better) speech discrimination score was applied, however, the result was quite acceptable.

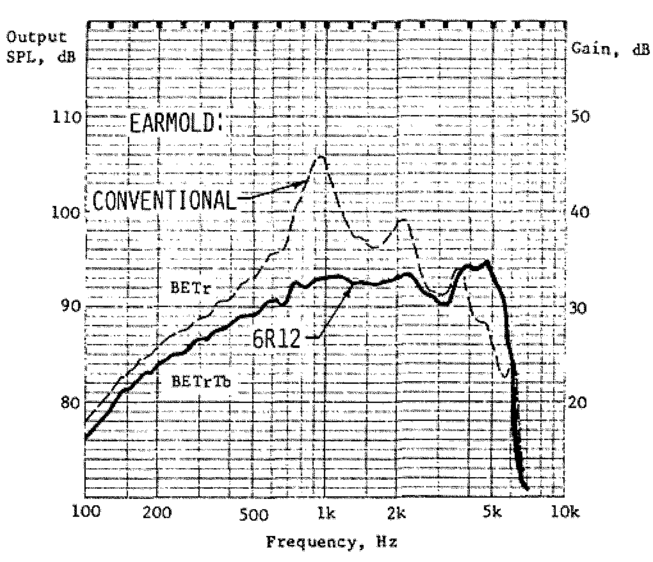

Figure 6 *Frequency response of experimental wideband hearing aid used in Lawton and Cafarelli study, measured into* 2-cm^3 *(HA-1) coupler with two earmolds. (From Lawton and Cafarelli, 1978).*

Finally, the dilemma presented by Skinner's (1976) results (that the best frequency response for a low-level speech cut her subject's dynamic range in half) might be avoided by the use of level-dependent selective amplification such as described by Goldberg in 1960, and used by Villchur (1973) in his two-channel compressor experiments. Indeed, Villchur's subjects universally preferred the sound quality of the signal processing that provided best speech discrimination!

All of these considerations point to the conclusion that the high-frequency emphasis typically required to maximize speech intelligibility may be entirely compatible with good sound quality *if* the right signal processing is used.

B. Low Frequency Response Vs. Sound Quality

Several studies in the last decade (Pascoe, 1975; Skinner and Karstead, 1979; Beck et al., 1980; Sung et al., 1980) have found that extending the low frequency cutoff of the hearing aid down to 250 or even 150 Hz can produce an improvement in speech discrimination scores compared to the traditional 500 Hz cutoff.

Skinner and Karstead (1979) found that once the frequency response of a master hearing aid was optimized with essentially unlimited bandwidth, a reduction in either the high frequency or the low frequency cutoff resulted in a reduction in speech discrimination scores. Their results are summarized in Figure 7, from Skinner et al. (1981).

It is significant that in each of the above studies, the experimental hearing aids had extended high-frequency response and substantial high frequency emphasis. Stated differently, none of the hearing aids had low frequency *emphasis*, only extended low frequency response (as opposed to a sharp cutoff below, e.g., 500 Hz). The experimental comparisons were thus made between retaining (de-emphasized) mid- and low-frequency speech cues and disposing of them entirely.

The effect of extended low frequency response on sound quality ratings has been studied most extensively by Punch and colleagues recently (Punch and Beck, 1980; Punch et al., 1980). In both studies, the low-frequency cutoff of the hearing aid bore a consistent and significant relationship to sound quality judgments: The lower the cutoff frequency, the higher the sound quality

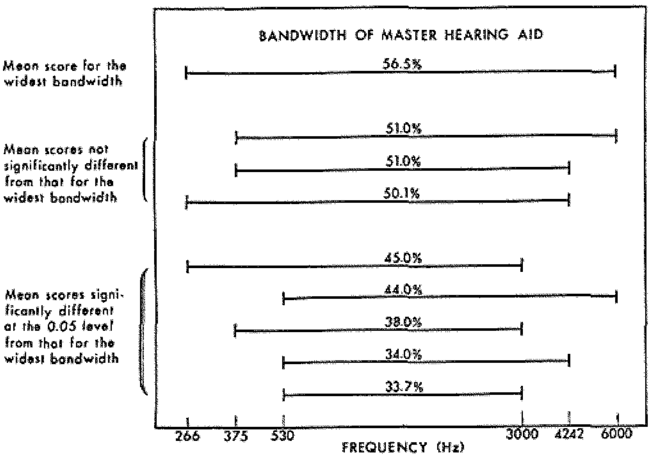

Figure 7 *Mean speech discrimination scores obtained for various bandwidths of a master hearing aid with two hearing impaired subjects. (From Skinner et al., 1981).*

rating. Here, again, none of the hearing aids tested had low frequency *emphasis* but only an extended low frequency cutoff.

The important observation for our present purposes is that the studies on extended low frequency response provide another indication that the traditional tradeoff between speech discrimination and sound quality may no longer be necessary.

C. Tonal Balance

When the bandwidth of a sound reproduction system must be restricted for economic or other reasons, research conducted in the 1940's indicated that the best tonal balance between high and low frequencies was obtained when the product of the high- and low-frequency cutoffs was about 640,000, i.e., when the same number of octaves were included above and below 800 Hz (Knowles, 1941; Hanson, 1944; Nixon, 1945). As summarized by Langford-Smith (1952), loss in speech intelligibility is quite small with a bandwidth restriction to 570 to 5000 Hz, but; "owing to the unnaturally high-pitched tone and obvious lack of balance, these frequency ranges are extended towards the bass for all communication purposes."

There is interesting market evidence from the hearing aid industry which indicates something like these same guidelines may apply to hearing aid sound quality. In 1968 when the first wideband subminiature microphones were introduced (Killion and Carlson, 1970) it became possible for the first time to produce headworn hearing aids with an extended low frequency response. A few manufacturers quickly offered these "improved" hearing aids, with nearly disastrous results. One possible explanation is that the subminiature hearing aid earphones available at the time allowed little in the way of true high-frequency emphasis and had a restricted bandwidth. This fact, coupled with the typical user's hearing loss characteristics, may well have produced a "boomy, muffled sound."

Similarly, when the first wideband subminiature earphone was introduced in 1971 (Carlson et al., 1976) it became possible to extend the high frequency response of headworn hearing aids from approximately 3 kHz to 6 kHz or beyond. Several manufacturers moved rapidly to make this increased bandwidth available, but the resulting hearing aids were not nearly as successful in the marketplace as expected. Part of the explanation may have been the fact that several additional response peaks due to tubing resonances became audible with the extended bandwidth. But it also seems likely that part of the reason for the lack of consumer acceptance was that many of these aids had a severe low-frequency cutoff below 1000 Hz, which may have produced a "shrill, harsh sound."

Whatever the final explanation, more and more dispensers are finding that simultaneously extending *both* the high-frequency and low-frequency response of the hearing aid can provide increased user acceptance compared to traditional hearing aids, especially when coupled with true high-frequency emphasis and a smooth insertion-gain response (Libby, 1981).

V. SUMMARY

We have reached the point where there are virtually no engineering limitations to hearing aid performance. Limitations in hearing aid performance in the future will be caused by a lack of solid evidence as to what to engineer.

It seems unlikely that we will discover the best overall solutions to the "hearing aid problem" as long as we persist in looking *only* at single-presentation-level speech discrimination scores. Maximizing the utility of a hearing aid for the user is a multidimensional problem and needs to be approached as such in research design. Fortunately, that appears to be the trend of the future. As mentioned above, several of the studies discussed in these proceedings are specifically addressed to the question of what hearing aid characteristics (clinical tests, etc.) correlate with the utility of the hearing aid for the user as he goes about his daily life.

Nonetheless, much remains to be done. It appears possible that many of the traditional tradeoffs between speech intelligibility and other hearing aid characteristics (sound quality, size, battery drain, etc.) are avoidable with appropriate design, but shamefully few design guidelines are available for the conscientious hearing aid engineer. Such guidelines can only be expected to come from research which explicitly sets out to simultaneously explore more than one dimension. As a first step, we need to identify areas of potential conflict between speech discrimination and sound quality, convenience, comfort, etc., and then attempt to determine which conflicts are unavoidable and which simply require a new approach.

Finally, it is a positive and not a negative statement to say that we have reached the point of rapidly diminishing returns for speech-discrimination-only research. That statement can be made only because of an exciting and fruitful decade of just such research.

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