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Fitting a Wide Range Compression Hearing Instrument Using Real Ear Threshold Data: A New Strategy[1]

In the search for a fitting strategy that could encompass the optimal setting of many programmable parameters for a digital signal processing (DSP) hearing instrument, a number of existing fitting methods were critically examined. This paper outlines various aspects of this examination which resulted in the development of a new fitting method that was eventually adopted for use with the SENSO digital hearing instrument.

Fitting Rationale

Since the desired development of a hearing instrument was a self-adjusting type with no user operated volume control, the first idea which emerged was to adopt an existing fitting method for self-regulating hearing instruments. Self-adjusting instruments with analog amplifier circuitry have been known for several years. These are often categorized as wide dynamic range compression (WDRC) or non-linear hearing instruments, and several methods intended for the fitting of these instruments have been developed.

A common rationale for the fitting of WDRC hearing instruments is known as *loudness mapping*, the objective of which is to restore normal loudness relationships among environmental sounds (Cox 1995). According to this rationale, the hearing instrument amplifier characteristic should be adjusted in such a way that the normal dynamic range of sounds is transformed into the narrower dynamic range of the hearing-impaired listener. This should be accomplished without altering the loudness relationships between sounds. Initially, this appears to be a plausible and straight-forward rationale; however, some impediments were brought into focus during the search for a fitting strategy for a digital instrument.

Individual Loudness Estimation

The loudness mapping approach presupposes, in principle, that the individual, as well as the average normal, loudness perception, is known for all sounds in our acoustic environment. While average loudness perception of normal hearing listeners has been modeled in considerable detail, it is generally acknowledged that individual loudness perception for hearing impaired people cannot be very well predicted from the corresponding individual audiometric threshold data. This conclusion has lead to the introduction of additional measures such as categorical loudness estimation in the fitting procedures (IHAFF 1994).

However, experience has shown that the introduction of supra-threshold measures in the fitting routine does not guarantee a satisfactory fitting, per se, and that a subsequent fine tuning was usually required (Kiessling 1996). A number of factors, such as stimulus uncertainties and methodological differences, can be readily identified to explain why there is a lack of predictability that consequently thwarts using previously proposed methods of supra-threshold loudness scaling methods.

Stimulus Uncertainties

Acoustic inaccuracies may account for significant lack of predictability. Of special importance is the uncertainty regarding the actual sound pressure level presented at the eardrum of an individual person during audiometry or during loudness scaling experiments. Fig. 1 illustrates the magnitude of this inaccuracy. For this study, a set of audiometric earphones was placed over the ears of several subjects and the sound pressures produced were recorded at their eardrums. As can be seen from the figure, the range of variation of sound pressure levels

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was in excess of 20 dB at the high and low frequencies. This range of variation also describes the uncertainty of which sound pressure the subjects had been listening to. Evidently, this uncertainty depends somewhat on the type of transducer used (Shaw 1966). But with all transducers, including free field presentation (Shaw 1976) and insert phones (Wilber et al. 1988) a substantial range of variation in the order of 20 dB remains. This uncertainty is particularly evident in the important frequency band from 2000 - 4000 Hz.

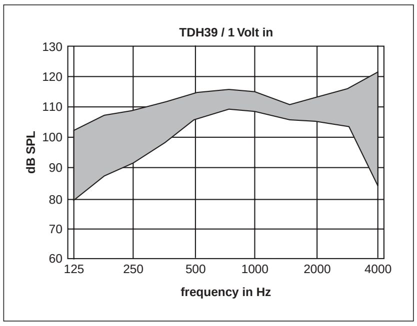

Fig. 1: Range of sound pressures produced by an audiometric earphone mounted in a circumaural cushion on ears of different persons. A constant earphone voltage of 1 Volt has been used (Adapted from Rankovic et al. 1992).

A related but relatively independent problem concerns the sound pressure produced at the eardrum by a particular hearing instrument. Imagine that, without changing its settings, a hearing instrument is placed successively on different ears. It then may not produce the same SPL in all ears. The range of the SPL observed in different ears will be a measure of the variation of what SPL will be produced in an individual ear. Fig. 2 illustrates this problem. As can be seen from the figure, the range of sound pressure levels presented by the hearing instrument exceeds 20 dB at several frequencies. This variation makes it impossible to predict precisely the in-situ response of a hearing instrument.

Evidently, it is possible to minimize this problem by introducing in-situ measurements. However, with the SENSO hearing instrument, which operates according to a complex compression algorithm that differentiates between speech and noise stimuli, traditional in-situ measurements cannot be interpreted in a way relevant to audiology. Yet, by introducing a sound generator in the hearing instrument, the hearing threshold can be determined using the same transducer for recording the hearing threshold and for the sound reproduction. By doing so, a potential error in presentation level can be counterbalanced and the source of the problem bypassed.

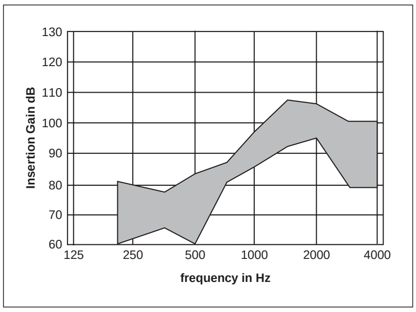

Fig. 2: Range of insertion gains produced by a hearing aid when fitted to the one ear of 17 different subjects (Adapted from Olsson 1985).

The total acoustic uncertainty encountered when fitting a hearing instrument from an audiological measurement can be estimated from the data presented in figs. 1 and 2. Since there is no pronounced correlation between the earphone response and the hearing instrument response, the degree of uncertainty at each frequency may be expected to exceed the greatest amounts of variation shown in the two figures. Thus, if a fitting rule for fitting a hearing instrument prescribes a specified number of dB above the hearing threshold, the range of variation might very well exceed 25 dB in the critical frequency range from 2000 - 4000 Hz. With a deviation of this magnitude, even a theoretically correct fitting rule may yield a fitting which is far from optimal.

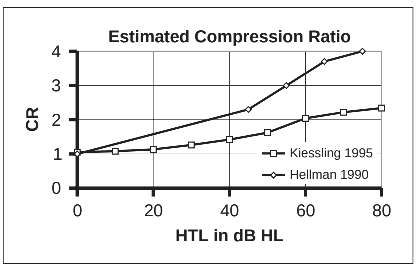

Fig. 3: Compression ratio vs. hearing threshold level obtained from two studies (Kiessling 1995, Hellman and Meiselman 1990).

Methodological Differences

Hellman and Meiselman (1990) measured the slope of the loudness function for normal-hearing and hearing-impaired listeners by using a magnitude estimation method. For hearing-impaired listeners, they found that the slope increased with the hearing impairment as can be seen in fig. 3. The corresponding *compression ratio* (CR) can be estimated from the slope of the loudness function, bearing in mind that a normal slope of 0.6 corresponds to CR=1 and that slope is proportional to CR. In fig. 3, a comparison has been made for the CR calculated from Hellman and Meiselman (diamonds) with the compression ratio obtained by Kiessling (1995) by a different method: categorical loudness scaling (squares). It appears that the CRs obtained from the magnitude estimation experiment differ substantially from the CRs obtained in the categorical loudness scaling experiment. The difference appears to be due to a methodological difference. Since we have no indication which informs us that one of the studies is more correct than the other, the value of restoring an exact loudness function may be questioned.

The results of loudness scaling experiments vary considerably among laboratories/experimenters. (Pascoe 1988, Bentler and Pavlovic 1989) A fundamental uncertainty with regard to the precision of the fitting process is introduced because a fitting rule cannot counterbalance the methodological bias of individual test sites.

Whether hearing instrument fittings based on loudness scaling have validity is another factor that must be considered. It has been observed that subjects can reproduce their responses with a small test-retest variation (i.e., a test-retest variance which is small compared to the group variance). This has been taken as an indication of the necessity of using loudness scaling compared to audiogram-based methods, but strictly speaking, it only shows that the individual criterion used by each subject does not change over time. The vague nature of the individual loudness categorization has the effect that the category assigned to a certain stimulus depends drastically upon the range over which the preceding stimuli were presented (Pascoe 1988).

Problems in Specifying Input-Output (I/O) Curves

In hearing instrument fitting based on loudness mapping, the target I/O-curve of the hearing instrument must, in each frequency band, be determined from the corresponding loudness function. Therefore, an I/O curve representing perceived loudness as a function of the stimulus level can be mapped. Ideally, there is a close relationship between the shape of the loudness function and the input-output characteristic of the hearing instrument for a given type of stimuli such as narrow band stationary sounds. When sounds with a complex frequency spectrum are considered, the contribution of the various frequency bands to the total loudness is likely to vary from person to person due to individual variations in loudness summation (Launer 1995). With time-varying sound (e.g. speech), the perceived loudness also depends upon the dynamic properties of the compression circuit. Thus, if the principle of loudness mapping is correct, then the target I/O-curve would be different for hearing instruments that have a fast and slow acting compression. Thus, it is likely that a single I/O in each band cannot be correct for both narrow band and broad band sounds nor for slow and fast acting compressors. This raises the question of whether it is feasible at all to prescribe I/O-curves, as the fitting targets are supposed to be valid for all hearing instruments and for all input sounds.

A New Fitting Strategy

The variation in loudness perception among sensorineural hearing-impaired listeners with a similar audiogram is, therefore, only one out of a series of uncertainties which present challenges to the fitting rationale. An adjustment of the hearing instrument response according to the individual loudness judgments of stationary narrow band signals presented to the ear by an audiometer transducer may not be the most appropriate basis for determining the optimum hearing aid parameter settings. A criterion for the accuracy of a fitting procedure could ideally be the percentage of users who do not demand any further adjustment of the hearing instrument when fitted according to the target or prescriptive procedure even if suitable alternatives were available to the user. Such data are apparently unavailable.

To achieve an accurate fitting, a better estimate of what was presented to the ear during the audiometric test was needed, as well as how these stimuli were related to the sound delivered by the hearing instrument in an everyday sound environment. Utilization of digital technology to improve the fitting and to minimize fitting time was also considered. Consequently, a fitting method was developed in which:

1. The 'in-situ' hearing threshold was measured in three frequency ranges (low, mid, and high). This was done by programming audiometer functions into the signal processor of the hearing instrument, which could then be utilized for the threshold determination through the individual earmold by presenting a multi-tone complex filtered by the filters of the hearing instrument. In this way, the acoustics of the individual earmold and the influence of the residual volume of the ear canal would automatically be counterbalanced.

2. By using the Pascoe (1988) loudness data and a model for the loudness growth of sensorineural hearing-impaired listeners, target I/O curves were estimated at each frequency band. Although this estimation was likely to be imprecise and did not include individual variation in loudness perception, we felt that this factor was more than compensated for by the elimination of acoustic uncertainties. Thus, it is expected that this approach would provide a starting point for further adjustments which was equally as good as that obtained by performing a time-consuming loudness estimation procedure.

3. Finally, a series of effective fine tuning options incorporated in the signal processor were available for a subsequent fine tuning. These included a fully automatic feedback managing system and possibilities for displaying and adjusting the estimated UCL values.

Evaluation

Several evaluation studies have been carried out at independent clinics, and are in the process of being published in peer reviewed journals at this time. These studies consistently show that the majority (55% - 85%) of those being fitted according to the in situ fitting strategy express immediate satisfaction with the sound reproduction. The average time spent for a complete fitting of two hearing aids, including threshold measurements in both ears, amounted to 7-15 minutes. Typically, the additional fine tuning necessary for the remaining users had a similar duration. After the users had worn their hearing aids for a period of time, they typically returned for further fine tuning according to their individual needs.

References

Bentler RA & Pavlovic CV: Comparison of discomfort levels obtained with pure tones and multi-tone complexes. J Acoust Soc Am 1989; 86:126-32.

Cox RM: Using loudness data for hearing aid selection: The IHAFF approach. Hear Jour 1995; 48 (2): 10,39-44.

Hellman RP and Meiselman CH: Loudness relations for individuals and groups in normal and impaired hearing. J Acoust Soc Am 1990; 88: 2596-2606.

IHAFF Group: Technology leads to new fitting strategies. Hear Instrum 1994; 12:15.

Kiessling J: Scaling methods for the selection, fitting and evaluation of hearing aids. Proceedings of the Oldenburg Symposium 1995, World Scientific, Singapore: 297-306.

Launer S: Loudness perception in listeners with sensorineural hearing impairment. (Dissertation), Oldenburg University, Germany, 1995.

Olsson U: Hearing aid measurements on occluded-ear simulator compared to simulated in-situ and in-situ measurements. Report TA 111,Technical Audiology, Stockholm, Karolinska Institute, 1985.

Pascoe DP: Clinical measurements of the auditory dynamic range and their relation to formulas for hearing aid gain. In J Hartvig Jensen's (ed) Proc. 13th Danavox Symposium, 1988; 129-151.

Rankovic CM, Freyman RL & Zurek PM: Potential benefits of adaptive frequency-gain characteristics for speech reception in noise. J Acoust Soc Am 1992; 91: 354-362.

Shaw EA: Earcanal pressure generated by circumaural and supra-aural earphones. J Acoust Soc Am 1966; 39: 471-79.

Shaw EA: Transformation of sound pressure level from the free field to the eardrum in the horizontal plane. J Acoust Soc Am 1976; 56:1848-61.

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