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ABSTRACT

Nine subjects listened to speech and music in a hearing aid, either through a vented earmold or a closed earmold. The complex frequency responses of the two systems were made equal by means of digital filtering. The subjects rated the perceived sound quality of the systems on seven perceptual scales and a scale for total impression. The results of the ratings indicate that there is no difference in perceived sound quality between vented and closed earmolds that are equalized in frequency response, provided that the perceived loudness is the same in both cases.

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INTRODUCTION

A hearing aid is usually connected to the ear with an earmold. The earmold is not only used to lead the sound into the ear, it also prevents the sound from coming out again. Otherwise feedback howl may be created. Furthermore, the earmold stabilizes the placement of the aid. However, occlusion of the ear canal by an earmold has certain drawbacks. It gives a feeling of pressure in one's ear, and the own voice appears unnatural. Moreover, internally created sounds, such as swallowing or crunching, are unintentionally amplified (Courtois, 1988).

A vent in the earmold often improves the situation. It reduces the amplitude of the low frequencies, both for sounds coming from outside as well as for bone-conducted sound. The amount of the reduction depends on the size of the vent. It also lets the low-frequency sounds pass the hearing aid and reach the eardrum directly. Therefore vented earmolds are frequently used when only little low-frequency amplification is needed.

It is not easy to design a vent that is suitable for the individual person. It should be more convenient to use flexible electrical filters in the aid. Such filters will probably be available in the future. Therefore, it is interesting to investigate whether a hearing impaired person is able to hear any difference in sound quality if the hearing aid is electrically changed to give the same complex frequency response (amplitude and phase) with and without a vented earmold.

Theoretically, the transmitted signals should be identical in both cases, unless there is some kind of energy source in the ear itself. If so, aids with equal frequency responses, but with different acoustic impedances, may give different time responses due to different reflections in the ear and ear canal. Findings of otoacoustic emissions (Kemp, 1978) give some evidence of internal sources. Therefore, it may be theoretically possible to perceive different sound quality of systems that load the ear with different acoustic impedances, but still have equal complex frequency responses.

To investigate this matter one vented (open) and one unvented (closed) earmold was made for each of nine subjects. The frequency response of a certain hearing aid was measured for both earmolds, and the complex frequency responses were then made approximately equal by inverse filtering. The perceived sound quality of these two systems was judged by the subjects listening to speech and music. The use of sound quality judgments draws upon the experience from sound quality ratings of high fidelity loudspeakers and other reproduction systems (Gabrielsson and Lindström, 1985; Gabrielsson, Schenkman, and Hagerman, 1988; Gabrielsson, Hagerman, Bech-Kristensen, and Lundberg, in press).

I. THEORY

A. Measurement of frequency response

Simplified models are often needed when analyzing the performance of a system. One common model assumes the system to be characterized by linear and time-invariant relations.

Let the input-output relationship of a system be indicated symbolically by

$$U(t) = L[u(t)] \quad (1)$$

Let the response to two different inputs $u_1(t)$ and $u_2(t)$ be $U_1(t)$ and $U_2(t)$, and c_1 and c_2 denote two constants. A system is linear if the response to $c_1u_1(t) + c_2u_2(t)$ is $c_1U_1(t) + c_2U_2(t)$ for all values of u_1, u_2, c_1, and c_2 (DeRusso et al., 1965). This definition can be expressed symbolically:

$$L[c_1u_1(t)+c_2u_2(t)] = c_1L[u_1(t)]+c_2L[u_2(t)] \quad (2)$$

Equation (2) is also known as the *superposition principle*.

A system is time-invariant if the relationship between the input and output is independent of time. If the response to u(t) is U(t), then the response to $u(t-t_0)$ is $U(t-t_0)$ (DeRusso et al., 1965).

One example of an approximately linear, time-invariant system is a hearing aid used under normal operating conditions.

If a sinusoidal signal

$$s(t) = A \sin(2\pi ft)$$

is applied to a linear time-invariant system, the output signal of the system is also a sinusoidal. The frequencies of the input and the output signals are the same, but the amplitudes and the phases could be different. The transmission is characterized by two parameters: amplitude and phase response. We need to know the amplitude and the phase response for all frequencies to characterize the system for any type of input signal. The response could be written as a complex function

$$H(f) = |H(f)|\exp(j\varphi(f))$$

the frequency response of the system. $|H(f)|$ is the amplitude response, and $\varphi(f)$ is the phase response.

There are two different methods to measure the frequency response (Olofsson, 1975). Either H(f) can be measured with a sinusoidal signal for each frequency of interest, or with a broadband signal composed of all the frequencies of interest. In the latter case the frequency response is given by the Fourier transform of the response signal divided by the Fourier transform of the input signal (Rabiner and Gold, 1975).

B. Compensation of frequency response

Let Ho(f) be the frequency response of the hearing aid with the open earmold and Hc(f) the frequency response of the hearing aid with the closed earmold.

Let A(f) be a filter with frequency response given by

$$A(f) = Ho(f)/Hc(f) \tag{3}$$

If we pass a signal through this filter prior to feeding it into the hearing aid with the closed earmold, the total frequency response is given by

$$H(f) = A(f)Hc(f) \tag{4}$$

If (3) is substituted in (4) we obtain

$$H(f) = (Ho(f)/Hc(f))Hc(f) = Ho(f) \tag{5}$$

The frequency responses of the two systems, that is, with open and closed earmold, are then identical.

It was decided to compensate only one of the responses and to leave the other one unaltered. Thus, we have simulated the frequency response of one of the earmolds.

Thus, the stimuli were presented unfiltered through the open earmold and filtered through the closed. An earlier (unpublished) study showed that using filters in the opposite way, that is, to make sound coming through the open mold sound like that coming through the closed mold, caused distortion due to the need for high amplification of the low frequencies. Therefore, it was not possible to conduct an experiment that was balanced in this respect.

II. METHODS

A. Measuring system

Both the measurement and the compensation of frequency responses were made using a general purpose signal processor, TAMP (Technical Audiological Measuring Processor). The main part of TAMP is a TMS32010 signal processor specially made for signal processing purposes (Texas Instruments, 1988). Other parts are D/A and A/D converters and digitally controlled amplifiers, attenuators, and filters. The system is controlled by a host computer.

For compensation of frequency response TAMP was programmed as a digital filter. In principle the frequency response of a digital filter can have any shape. In practice this is not true due to certain technical limitations of TAMP. Especially for frequencies below 500Hz it is hard to obtain the desired response.

The frequency response of the open and the closed mold was measured, using a broadband input signal, with a Rastronics probe microphone (PM-10L) connected to a TAMP system. Due to the low frequency emphasis of the probe, the microphone signal was compensated in a preamplifier to get a more flat response.

B. Stimuli and listening conditions

Four programs were used as stimuli for the sound quality judgments:

1) Female voice reading a fairy-tale in an anechoic chamber.

2) Male voice reading a text in an office room with a background of other voices.

3) Jazz music, excerpt from "Ole Miss" by W.C. Handy, performed by the Peoria Jazz Band in an auditorium. Gramophone record: OPUS 3, 79-00, Testskiva 1: Perspektiv.

4) Female solo voice, the folk chorale "Fröjda Dig, Du Kristi brud," performed by Marianne Mellnäs in Oscar Church in Stockholm. Gramophone record: Proprius PROP 7762.

Each program lasted for about 1 minute and was as homogeneous as possible within itself with regard to sound level, presence of musical instruments/voices, and musical coherence. They were earlier used in Gabrielsson et al. (1988). All programs were monophonically recorded and played back on a tape recorder, Revox B77, 19 cm/sec.

The programs were digitally processed using TAMP. The compensation filters A(f) for the closed mold systems were realized as digital filters. The processed signal was fed to the electrical input on a Phonak Varionet CD hearing aid to minimize external acoustical influence. For the same reason the hearing aid microphone was not connected during the experiment. The subjects listened monaurally, using their preferred ear, with individually fitted earmolds (one vented, one unvented). The same impression was used for both molds to make them as similar as possible. The vent in the open mold was widened as much as possible without deforming its outside shape. The other ear was left open.

Figure 1 shows an example of the difference in frequency response between open and closed molds.

The gain control of the hearing aid was set to give a comfortable listening level judged by the experimenters. It was then fixed through the whole experiment.

The experiments were conducted in a sound insulated room normally used for audiological purposes.

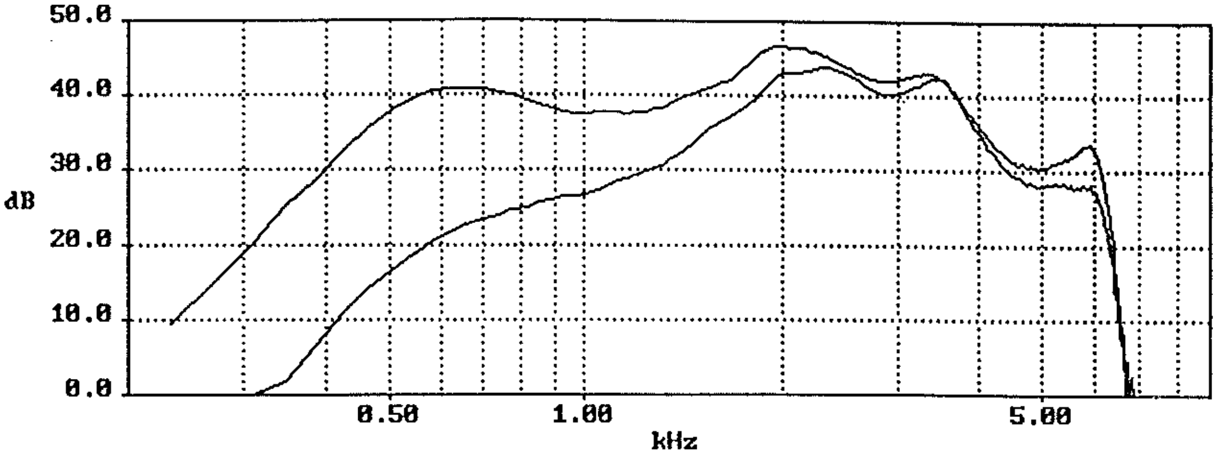


Figure 1. Frequency response with a closed earmold (upper curve) and with an open earmold (lower curve).

C. Subjects

Nine subjects (5 males, 4 females) participated in the experiment. None of them had any ear pathology, neither had they been exposed to dangerous levels of noise for long periods. All of them were tested for normal hearing (20 dB HL, 125-8 000 Hz, ISO 389), normal tympanograms and elicitable ipsilateral stapedius muscle reflexes. They had no previous experience of hearing aids. All subjects were paid.

D. Response variables

The perceived sound quality was rated on eight scales. Seven of these refer to perceptual dimensions: fullness (Swedish: fyllighet), loudness (ljudstyrka), brightness (ljushet), softness/gentleness (mjukhet), nearness (närhet), spaciousness (öppenhet), and clarity (tydlighet). The eighth scale was an overall evaluation, "total impression" (Sw. totalintryck).

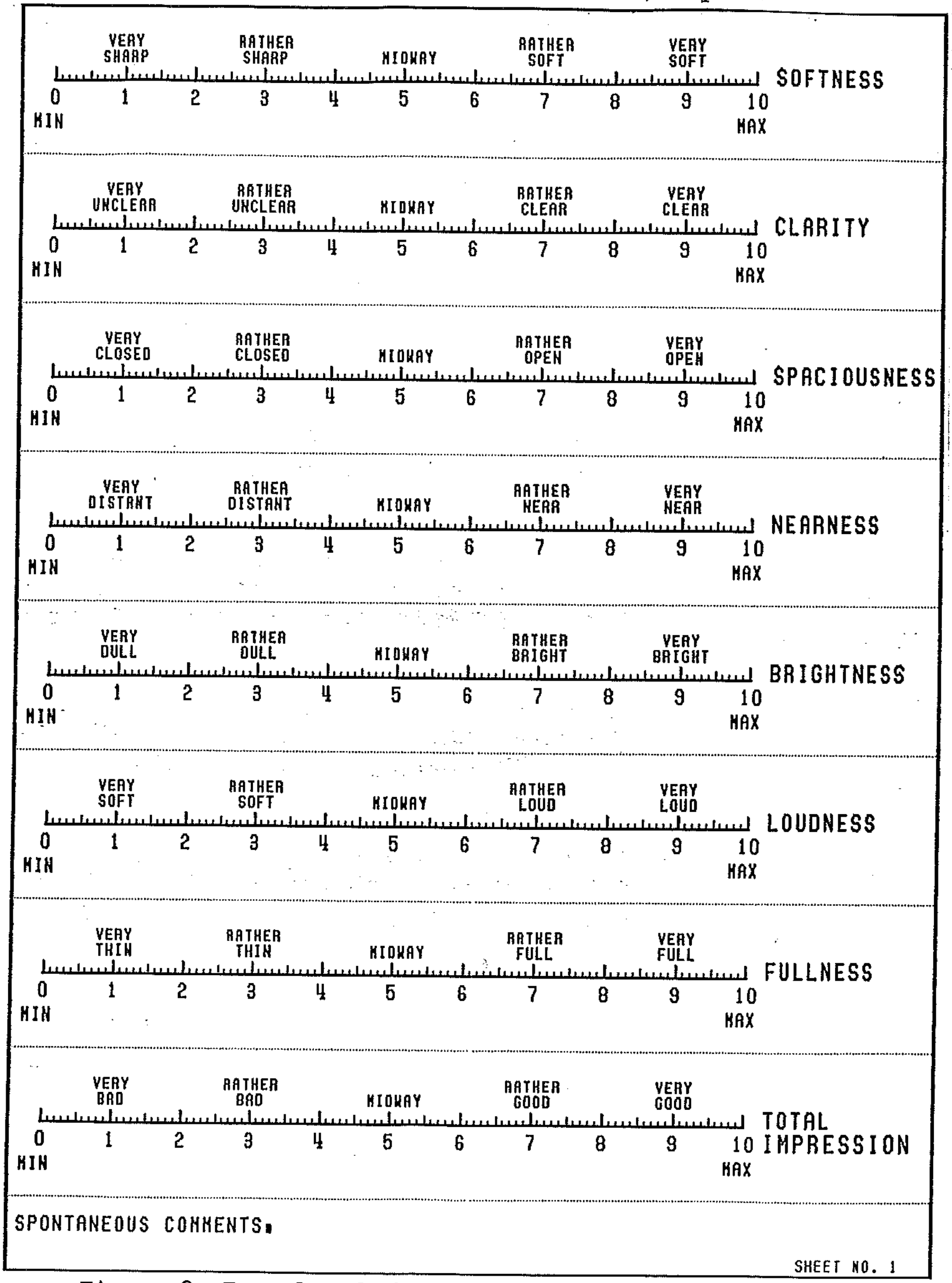
Each scale was graded from 10 (maximum) to 0 (minimum), and with special definitions for 9, 7, 5, 3, and 1 as seen in Fig. 2. Decimals were included, since most subjects in earlier investigations used decimals in their ratings. Further explanation of the scales was given in the instructions (see Appendix).

E. Design and procedure

Each subject took part in three sessions, two for preparation and one for the actual experiment.

In the first session, screening audiogram and tympanogram with stapedius reflex test were conducted. An impression was made for the two molds. The subject was told that he/she was going to listen to sound through a hearing aid, fitted to the ear with a mold, and rate the sound quality. The fact that two types of molds would be used was not told.

The second session started with fitting the two earmolds without letting the subject see the molds. The frequency response of the hearing aid with earmold placed in the ear was measured for both earmolds. It was recorded with a probe microphone placed in the ear canal between the mold and the skin. The tip of the probe was placed 5 mm in front of the earmold. Each measurement was repeated after removing and putting back the probe microphone and the hearing aid with the mold. The two measurements were compared to investigate their reliability. The measured amplitudes were not allowed to differ more



VERY SHARP | RATHER SHARP | MIDWAY | RATHER SOFT | VERY SOFT
0 1 2 3 4 5 6 7 8 9 10 SOFTNESS
MIN MAX

VERY UNCLEAR | RATHER UNCLEAR | MIDWAY | RATHER CLEAR | VERY CLEAR
0 1 2 3 4 5 6 7 8 9 10 CLARITY
MIN MAX

VERY CLOSED | RATHER CLOSED | MIDWAY | RATHER OPEN | VERY OPEN
0 1 2 3 4 5 6 7 8 9 10 SPACIOUSNESS
MIN MAX

VERY DISTANT | RATHER DISTANT | MIDWAY | RATHER NEAR | VERY NEAR
0 1 2 3 4 5 6 7 8 9 10 NEARNESS
MIN MAX

VERY DULL | RATHER DULL | MIDWAY | RATHER BRIGHT | VERY BRIGHT
0 1 2 3 4 5 6 7 8 9 10 BRIGHTNESS
MIN MAX

VERY SOFT | RATHER SOFT | MIDWAY | RATHER LOUD | VERY LOUD
0 1 2 3 4 5 6 7 8 9 10 LOUDNESS
MIN MAX

VERY THIN | RATHER THIN | MIDWAY | RATHER FULL | VERY FULL
0 1 2 3 4 5 6 7 8 9 10 FULLNESS
MIN MAX

VERY BAD | RATHER BAD | MIDWAY | RATHER GOOD | VERY GOOD
0 1 2 3 4 5 6 7 8 9 10 TOTAL IMPRESSION
MIN MAX

SPONTANEOUS COMMENTS:

SHEET NO. 1

Figure 2. Example of the response form (translated to English).

than ±3 dB in the frequency range 300 - 6000 Hz. The actual difference was within ±2 dB for all subjects, and for most of them within ±1 dB.

Before the third session the digital filter, used for the unvented mold, was created in the host computer. The filtered frequency response differed less than ±3 dB from what was intended. An example of the theoretical filter and the actually used filter is shown in Figure 3.

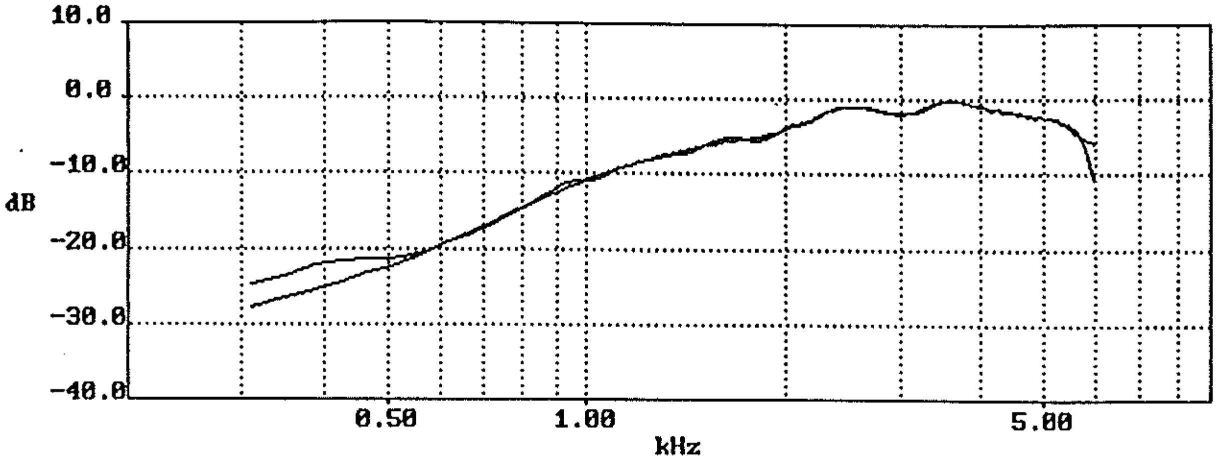


Figure 3. Example of theoretical and actually used filter frequency response.

At the beginning of the third session the subject was instructed how to judge the perceived sound quality using the eight rating scales (Appendix). Several practice trials were given, until the subject felt comfortable about the procedure. The main experiment included three ratings of all eight stimuli combinations (4 programs x 2 systems), a total of 24 ratings. These were divided into six blocks. Within each block the mold was constant but the four programs appeared in a randomized order.

Half of the subjects started with the open mold (first block), the other half with the closed mold. Within each subject the order of the molds was counterbalanced. The order of the eight rating scales on the response form was different for each subject but always the same within each subject. A short break was made after two thirds of the ratings.

F. Data treatment

The subjects' ratings were subjected to analysis of variance, separately for each scale. This was done both for each subject (sources of variance: molds and programs; fixed model) and over all subjects (sources: molds, programs, and subjects; mixed model). For general principles concerning analysis of variance and related questions, see Winer (1971) or Kirk (1982). For application in listening tests, see Gabrielsson (1979).

III. RESULTS

The perceived sound quality of sound-reproducing systems is affected by the loudness level (Gabrielsson and Sjögren, 1979; Gabrielsson and Lindström, 1985; Gabrielsson et al., in press). Therefore, ratings of the sound quality should as a rule be made at the same (perceived) loudness for the systems tested.

However, for four subjects there was a significant difference in the rated loudness between the two systems. The sound was perceived louder with the open mold than with the closed. Further investigation showed that for these subjects there had in fact been a small difference in sound pressure level (<3 dB) between the two systems, due to certain technical reasons. The nine subjects were therefore divided into two groups. Group I consisted of five subjects for whom there was no difference in loudness between the systems, and Group II of the above-mentioned four subjects, for whom there was a difference in loudness.

A. Reliability of ratings

The intra-individual reliability of the ratings is indicated by the "within cell mean square" (MSw) in the individual analysis of variance. The MSw value is the estimated average variance of the three ratings made for each stimulus in each scale. The smaller this variance, the better is the reliability.

The mean values across subjects for the MSw index for each scale and group are shown in Table 1.

Table 1. Mean values for the MSw index.

Scale	Group I	Group II
Loudness	0.96	0.91
Clarity	1.11	1.47
Fullness	1.04	1.27
Spaciousness	1.10	0.98
Brightness	0.37	0.71
Softness	1.30	1.19
Nearness	0.94	1.23
Total impr.	1.16	1.26

In both groups MSw is lowest for the brightness scale. For all scales the MSw values are of the same size or somewhat lower than in other experiments with normal hearing subjects

(Gabrielsson et al., 1988; Gabrielsson et al., in press).

The <u>inter-individual reliability</u> (the agreement between the subjects) was estimated by the $\underline{r}_b$ index (Winer, 1971, p. 283; Gabrielsson, 1979). Its maximum value is 1.00. The values of the index are shown for both groups in Table 2.

<u>Table 2</u>. The $\underline{r}_b$ index for groups I and II.

Scale	Group I	Group II
Loudness	0.87	0.92
Clarity	0.88	0.88
Fullness	0.58	0.80
Spaciousness	0.78	0.88
Brightness	0.79	0.86
Softness	0.76	0.40
Nearness	0.72	0.89
Total impr.	0.78	0.90

The inter-rater reliability is generally high; the only exception is for softness in Group II. For most scales the $\underline{r}_b$ value is higher for group II than for group I. This is probably due to the fact that the difference in loudness between the systems that occurred in Group II, also introduced differences in other scales (cf. below), thus increasing the amount of systematic variance in relation to the error variance.

B. Effects of earmolds

The mean ratings in the different scales for the two earmolds are shown in Figures 4 and 5. They are averaged across subjects and also across programs, since there were no significant interactions betweens molds and programs.

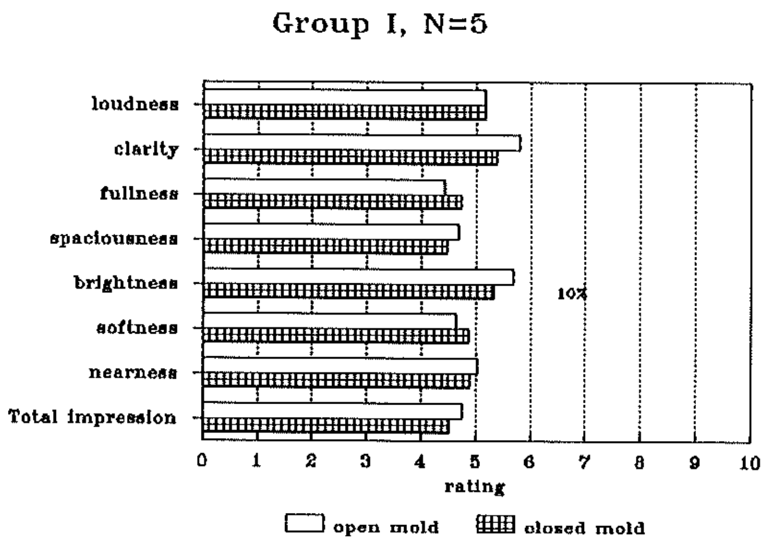


Figure 4. Mean ratings for open and closed earmolds, Group I. The percentage value indicates significance level.

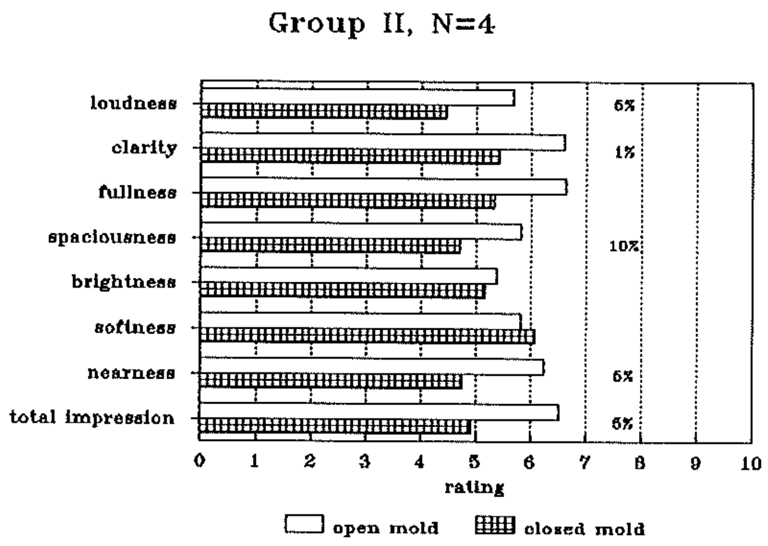


Figure 5. Mean ratings for open and closed earmolds, Group II. The percentage values indicate significance level.

For group I, there is no difference between the two molds in loudness, and there are only minor, non significant, differences in the other scales; however, there was a tendency that the open mold sounds brighter [$F(1,4) = 5.1$, $p < .10$].

For Group II, the reproduction with the open mold sounds louder than that with the closed mold [$F(1,3) = 25$, $p < .05$]. It is also rated higher in clarity [$F(1,3) = 86$, $p < .01$], in spaciousness [$F(1,3) = 6.5$, $p < .10$], in nearness [$F(1,3) = 21$, $p < .05$], and in total impression [$F(1,3) = 26$, $p < .05$]; furthermore, it is rated higher in fullness but the difference does not reach statistical significance.

The differences between the two molds for Group II can be attributed to the difference in loudness occurring for this group. Typically, a higher sound level also provides more clarity, fullness, spaciousness, nearness, and better total impression (Gabrielsson and Sjögren, 1979; Gabrielsson et al., in press).

IV. DISCUSSION

From this work there is no evidence that the perceived sound quality should differ between reproductions with open and closed earmolds. The differences that were found in some of the scales for Group II can be explained by the differences in sound level that existed for those subjects. Therefore, we do not believe that subjects perceive any difference between sound through an open or a closed mold as long as the complex frequency response and the sound level of the two systems are equal. This should hold also in the usual case with acoustic transmission where part of the signal reaches the eardrum through the vent. Hearing impaired people do sometimes report advantages with open mold fittings. However, this is probably due to the fact that less humidity is produced if a vented mold is used, and that the occlusion effect diminishes (Wimmer, 1986); the own voice sounds more natural.

Some investigations comparable to the present have been reported. Grover & Martin (1979) investigated subjective correlates of earmold occlusion. Subjective rating scales similar to ours and various degrees of venting were used. However, the different frequency responses were not compensated for, and the results for most scales differed between normal hearing and hearing impaired subjects. The most consistent result, obtained by both groups, was the difference in fullness and related scales between the closed and open mold. These results are probably due to the different frequency response curves only and not to the venting per se (cf. Gabrielsson et al., 1988).

Cox & Alexander (1983) tried to compare low-frequency cuts achieved acoustically by a vent with cuts achieved by electronic devices. In their abstract it is stated "use of a vented or open earmold significantly improved both quality and intelligibility even when it had essentially no effect on the hearing aid's low-frequency output". However, according to the figures shown, the response curves were in fact not equal. Futhermore, the acoustic load of the subject's ear was not taken into consideration, since the various modifications were recorded through a KEMAR manikin.

Technically, the frequency analysis and the digital filtering in our investigation worked very well. The amplitude deviations between the repeated measurements of the frequency responses for the two systems were within ±2 dB for all subjects. The filtered frequency response that was used differed less than ±3 dB from what was intended. Thus, TAMP can be used for laboratory design of master hearing aids with very well defined frequency response.

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APPENDIX

Instructions for ratings of sound quality

In this experiment you are going to listen to speech and music through an earmold in your preferred ear. Each program lasts for about one minute. Your task is to listen attentively and try to describe the sound quality by means of the scales that you can see on the response form. You shall mark your judgments on the response form while you are listening. All scales are graded from 10 (maximum) to 0 (minimum). You decide yourself on the accuracy that you consider necessary. You can use decimals if you like. The integers 9, 7, 5, 3, and 1 are defined on the response form. For instance, in the scale for clarity 10 means maxmimum (highest possible) clarity, 9 means very clear, 7 rather clear, 5 midway, 3 rather unclear, 1 very unclear, and 0 minimum (lowest possible) clarity. The other scales work in similar ways.

The scales may be further defined as follows:
Clarity. The reproduction sounds clear, distinct, and pure. The opposite is that the sound is diffuse, thick, blurred, and the like.

Fullness. The reproduction sounds full, in opposition to thin.

Brightness. The reproduction sounds bright, in opposition to dark and dull.

<u>Softness</u>. The reproduction sounds soft and gentle, in opposition to sharp, hard, keen, and shrill.

<u>Spaciousness</u>. The reproduction sounds open and spacious, in opposition to closed and shut up.

<u>Nearness</u>. The sound seems to be close to you, in opposition to at a distance.

<u>Loudness</u>. The sound is loud, in opposition to soft (faint).

<u>Total impression</u>. Give an overall judgment of how good you think the reproduction is.

There is a new response form for each case. First we are going to practice with some programs. Put a vertical line on that place on the scale that you think is the best to describe how the reproduction sounds.

Your judgments shall not be affected by what you think about the programs as such. The scales refer exclusively to <u>the quality of the reproduction</u>.