OCCLUSION EFFECTS

Part I

HEARING AID USERS EXPERIENCES OF THE OCCLUSION EFFECT COMPARED TO THE REAL EAR SOUND LEVEL

How do you experience the difference?

Dept. of Acoustic Technology
Technical University of Denmark
Report No 71, 1997
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Part I

HEARING AID USERS EXPERIENCES OF THE OCCLUSION EFFECT COMPARED TO THE REAL EAR SOUND LEVEL

by

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Dept. of Acoustic Technology
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PREFACE

This report is submitted as a part of a Ph.D.-project. I thank my supervisors senior engineer Peter Lundh at Oticon AS and senior lecturer Torben Poulsen at the Department of Acoustic Technology, Technical University of Denmark, for good guidance and for reviewing the manuscript.

I would also like to thank Grete Boisen and Jørgen Nielsen at the hearing clinic at Bispebjerg hospital for help to get in contact with appropriate subjects for the survey. Thanks to Inger Nielsen from the hearing clinic at Bispebjerg hospital, who assisted at the laboratory measurements.

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Lyngby and Hellerup, Sept. 1997

Mie Østergaard Hansen
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ABREVIATIONS AND SYMBOLS

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<tr>
<td>AC</td>
<td>Air conduction</td>
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<tr>
<td>BC</td>
<td>Bone conduction</td>
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<td>BTE</td>
<td>Behind The Ear</td>
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<tr>
<td>CIC</td>
<td>Completely In the Canal</td>
</tr>
<tr>
<td>dB</td>
<td>decibel</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transformation</td>
</tr>
<tr>
<td>ITE</td>
<td>In The Ear</td>
</tr>
<tr>
<td>ITEC</td>
<td>In The Ear Canal</td>
</tr>
<tr>
<td>$f_s$</td>
<td>Sampling frequency</td>
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<tr>
<td>HA</td>
<td>Hearing aid</td>
</tr>
<tr>
<td>HL</td>
<td>Hearing Loss</td>
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<tr>
<td>Hz</td>
<td>Herz</td>
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<tr>
<td>MCL</td>
<td>Most Comfortable Level</td>
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<tr>
<td>$p$</td>
<td>Probability</td>
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<tr>
<td>POGO</td>
<td>Prescription of Gain and Output</td>
</tr>
<tr>
<td>PTA</td>
<td>Pure Tone Average</td>
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<tr>
<td>OEHAoff</td>
<td>Objective occlusion effect with the hearing aid turned off</td>
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<tr>
<td>OEHAon</td>
<td>Objective occlusion effect with the hearing aid turned on</td>
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<td>SPL</td>
<td>Sound Pressure Level</td>
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$\rho$ statistic correlation coefficient

$\alpha$ statistic significance level
1 INTRODUCTION

The report is introduced by a review of the background and previous investigations. The purpose of the survey is explained and a guide line how to read this report is given.

1.1 BACKGROUND

Many people use earmoulds every day either with a hearing aid or as hearing protection. This report focuses on the hearing aid user, but almost all the problems experienced by the users can be applied to for example earplugs for hearing protectors.

Talking to hearing aid users or audiologist one get the impression that some people find it rather unpleasant to wear earmoulds. Irritations occur as acoustically, mechanically or biologically related whereas the change in the perception of own voice is the most discussed disturbance, [Hickok et al., 1993]. These effects are all an effect of the occluded ear canal and will therefore be referred to as occlusion effects. The acoustic occlusion effect can in fact be measured as a difference in sound pressure.

The most common way to deal with occlusion problems today is by drilling a ventilation canal (vent) through the earmould. The problem is that if the vent shall be large enough to prevent acoustical related irritations then the hearing starts to howl. Another way, which has come within the last few years, is to make a deep inserted earmould. It is not all hearing aid users who can be fitted or like this kind of earmoulds, [Jones&Bongiovanni, 1996].

The occlusion effect have been investigated by several authors but they mostly refer to experimental situations where for example only normal hearing person were tested.

At the time when the present investigation started, there were publicised a survey from Bisphjerg Hospital in Denmark, [Biering-Sørensen et al., 1994], which tried to compare hearing aid users irritations and the measured difference in sound pressure in the ear canal. It was not possible to conclude for sure that there is such a relation and this was one reason to set the present investigation. If an appropriate technical solution should be found it is necessary to know whether or not there is some kind of relation between the users problems and earmould design and hearing aid fitting. This background led to two purposes of the investigation.

1.2 PURPOSE

The investigation has two purposes:

a) - to look at the problems that the hearing aid user experience in the daily life and to derive the most dominating user problems according to occlusion of the ear canal.

b) - to find the most significant relations between the users problems and objective measurable factors, such as perceptive hearing loss, vent size and real ear measurements.

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The data shall be achieved by a user survey including a questionnaire and an experimental set up established in Oticon's audiological clinic.

1.3 DEFINITION OF THE TERM "OCCLUSION EFFECT"

The original audiological understanding of the term 'occlusion effect' was original related to bone conduction threshold measurements. Since then, the term has been used in several ways to describe changes created by earmoulds. There seems to be some confusion about what the term 'occlusion effect' exactly refers to, it is therefore reasonable to define how the term will be used in this report.

<table>
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<th>Occlusion</th>
<th>- occlusion of the ear canal</th>
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<td>Occlusion effect in general</td>
<td>- objectively measurable and subjectively perceived changes between occluded and open ear canal.</td>
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<tr>
<td>Objective occlusion effect</td>
<td>- objectively measurable changes between occluded ear and open ear performances. If nothing else is commented it refers to the difference in real ear sound pressure between occluded and open ear.</td>
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<tr>
<td>Subjective occlusion effect</td>
<td>- occlusion effect detected by a psycho-acoustic measurement method, i.e. audiometry.</td>
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<tr>
<td>Experienced occlusion effect</td>
<td>- individually experienced annoyances caused by acoustical, mechanical or biological changes between occluded and open ear canal.</td>
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The objective occlusion effect on body sounds, such as speech, occurs because the sound radiated from the ear canal walls will be reflected instead of just travel out of the ear. Hereby the sound pressure in the ear canal is increased. Sound conducted in the body has most energy at low frequencies and the occlusion effect is often referred to as the increase in sound pressure at low frequencies.

The objective occlusion effect varies between subjects even with the same kind of earmould and venting. An example of the values of objective occlusion can be taken from Wimmer (1986). The paper refers to an experiment performed by Lundh at Oticon. The occlusion effect was measured on 4 subjects who were fitted with a tight earmould. Measurements were made while the subjects read aloud. The average occlusion effect is shown in Figure 2.5.
1.4 PREVIOUS INVESTIGATIONS

Objective occlusion effect has been demonstrated many times and the effect of leakage or venting has been illustrated for example by Revit (1992) and May & Dillon (1992). A short summary of each of the most important references are given in appendix A.

The largest investigation reported in the literature involved 130 subjects [MacKenzie et al., 1989]. The subjects were divided into a group of 106 and a group of 24 persons. The subjects had hearing losses between 30-60 dB HL taken as an average at 0.5, 1, 2 and 4 kHz. The small group participated in a laboratory experiment with the purpose of finding the gain limit where feedback occurs. The large group was fitted for their first time with hearing aids. Each subject had to try out an unvented, a 0.8 mm vented and a 2 mm vented earmould attached to a BTE aid. After wearing each earmould for 2 weeks, the moulds were evaluated. Fewer than 20% of the subjects were in general uncomfortable wearing earmoulds. Nearly 40% felt blocked up with the unvented earmould, 23% felt blocked up with the 0.8 mm vent and 14% felt blocked up with the 2 mm vent. About 40% complained about moist and itch no matter what size of vent they were fitted with. The results indicated that there is a relation between the size of the vent and the sensation of occlusion.
The relation between venting and sensed occlusion has also been demonstrated in a smaller investigation made by Kuk (1991). Nine hearing aid users with symmetrical sensorineural hearing loss participated. They tried a vented and an unvented earmould and they were asked to judge the quality of their own voice. The overall preference was the vented earmould. The investigation also showed that there is no difference in word recognition as long as the insertion gain is the same for the vented and unvented earmould.

Sensation of occlusion and the relation to vent size and objective occlusion was investigated in a laboratory experiment at National Acoustic Laboratory in Australia [May & Dillon, 1992, (oral paper)]. This experiment can be considered as a sort of a worst case because only normal hearing persons participated. Each of 10 subjects was fitted with several differently designed earmoulds. The occlusion effect was measured as the change in real ear sound pressure level between the open and the occluded ear canal while the subjects were speaking. The results shows that the objective occlusion effect varies up to 20 dB between subjects but there was a clear trend that larger vent sizes give less occlusion. A correlation of 0.63 between the objective occlusion effect and the rating of perception of own voice was found. Most persons rated a tight earmould as unacceptable and a skeleton earmould like the open ear condition.

A survey made at Bispebjerg hospital in Denmark, [Biering-Sørensen et al.,1994] attempts to reflect the perception of occlusion in the daily life of a hearing aid user. The purpose with the survey was to find a relationship between an objective measure of occlusion and the individual sensation of own voice. Fortyfive persons were selected among the clients at the hospital. They were divided into a group with sensorineural hearing losses and a group with conductive hearing losses. It was assumed that the group with conductive losses would not experience change of own voice. The acoustic occlusion effect was measured as the change in bone-conduction threshold between open and occluded ear. The subjects individual earmould were used and the contra-lateral ear was masked. The individual sensation of occlusion was determined by the mean of a questionnaire two months after fitting the subjects hearing aid.

The responses on the questionnaire told that 18% of the conductive group and 24% in the sensorineural group sensed occlusion in general. More noticed a change in own voice; 57% in the sensorineural group and 27% in the conductive group. The survey was designed upon the theory that conductive hearing impaired people will not experience change of own voice and according to the authors, the survey result was unexpected. An explanation could be that the subjects had not fully understood that the change in own voice is only the change created by occluding the ear canal and not the change created by amplification. The authors themselves recommend to do further studies with conductive hearing loss.

Sensation of change in own voice was compared with the acoustic occlusion effect and the air-bone-gap. It was not possible to state a significant difference in the acoustic occlusion effect between subject who sensed a change in own voice and subjects who did not.

This result conflicts with the conclusions drawn from the investigation made by MacKenzie et al. (1989), Kuk (1991) and May & Dillon (1992). There might be several explanations. Firstly, as mentioned before, the subjects had to answer the question correctly. Secondly, Biering-Sørensen et al. only consider the air-bone-gap and not the hearing loss in their analyses even though the subjects range from 10-90 dB HL at 250 Hz. It is likely to believe
that a person with a loss of 10 dB HL will be able to sense a change in own voice whereas a person with 90 dB HL will not, because hearing aid amplified sound mask the occlusion effect. Thirdly, the acoustic occlusion was measured indirectly by using a threshold test. Hereby a subjective measurement error may be introduced. Also it is uncertain how well the bone conduction threshold shifts reflects the actual change in sound pressure level when a person speaks.

Until now the focus has been on own voice and other acoustic related occlusion effects. But there is in fact several non-acoustic occlusion effects. These are described by Hickok et al. (1993) and can be experienced as headaches, itch, moist, tension, pain, tearing eyes, running noses and feelings of being 'plugged up'. Some of these effects are explained by the fact that cranial and facial nerves runs close to the wall of the ear canal. If the nerves are very sensitive the contact between the earmould and the ear canal wall might be able to stimulate the nerves.

Itch and moist is mostly reported by hearing aid user. Madsen et al. (1991) conclude in a survey of 76 persons that the use of an earmould does increase the amount of persons who are annoyed by itchy ear canals. Itch were often followed by dryness and flush. The itch could be caused by an increase in bacteriums and among people who clean their ear canals mechanically, i.e. with a cotton bud, the prevalence of itch was greater than for people who does not clean their ears. The survey could not find a significant relation between itch and vent size.

Summarize the literature it can be concluded that occlusion effect created with own voice and in the form of itch and moist is a problem to some hearing aid users. The occlusion effect of own voice seems to be less annoying with greater vents but the degree of occlusion effect can be very different from person to person. The personal experience of occlusion might be directly related to the degree of objective occlusion as concluded by May & Dillon (1992) or it might not be possible to find a significant relationship when hearing impaired people are involved as indicated by Biering-Sørensen et al. (1994).

1.4 HOW TO READ THIS REPORT

This report addresses readers who has interest in audiology and hearing aid design. It is assumed that the reader has a basic knowledge about hearing loss and hearing aid fitting otherwise it will be difficult to understand the complexity of the problems completely.

A quick way of getting an idea of the aspects in this report is to read the main summary and the short summaries of each main chapter. The report is structured into three layers of chapters in order to make it easy to find a particular aspect by looking it up in the table of contents. Figure and table references are written with bold script in the main text. The table and figure numbers refers to the main chapter number. References to the literature are written in [...] or the authors name is mentioned followed by the year in brackets. Abreviations are explained only once in the text and can be found in the list of abbreviations. At relevant points the main text refers to appendices.
2 THEORY

Readers who have knowledge about hearing aids and earmoulds can skip section 2.1. It gives a short introduction to hearings aids, earmoulds and hearing aid fitting. Section 2.2 is a summary of the most important surveys regarding individually experienced occlusion effects.

2.1 HEARING AIDS AND EARMOULD

2.1.1 Hearing aids

The basic idea in a hearing aid is to compensate the hearing loss by amplifying external sounds. A very simple hearing aid consists of a microphone that picks up airborne sounds. The signal is split into for example a low- and a high-frequency band. The amplifier gain in each channel is adjusted according to the hearing loss. The absolute level can be set with a volume control which is either automatic or manual. The hearing aid has also a fixed gain amplifier that is either placed before or after the adjustable amplifier. The sound is transmitted into the ear canal via a telephone (loudspeaker). The most simple construction is a linear amplifier, which means that the signal is amplified with for example 10 dB regardless of the input level. However this is not acceptable since very loud input levels would create uncomfortable high output levels, therefore a limiter is applied. The limiter can either control the input or the output level.

A linear hearing aid consist today of a linear amplifier and a limiter. The volume control is controlled manually. A non-linear hearing aid is more advanced. The volume control adjusts automatically according to the input (or output) level. It is also possible to get hearing aids with several programs. The amplifier is set differently according to the listening situation, for example traffic noise and quiet conversation.

There are three traditional hearing aid configurations; Behind-The-Ear (BTE), In-The-Ear (ITE) and In-The-Ear-Canal (ITEC). Recently a new type of hearing aid has come out; Completely-In-the-Canal (CIC). A properly fitted CIC that reaches into the bony part of the ear canal, can reduce the occlusion effect dramatically, [Killion et al., 1988]. However, not everybody is candidate for a CIC aid. Very small ear canals or ear canals with bulges are not suitable for a deep fitted earmould, [Oticon, 1997]. Elderly people have in general a thinner skin layer in the ear canal than younger people. A thin skin can make a deep fitted earmould painful. Also older people might have difficulties handling the small CIC aids, [Giller, 1993]. The conclusion is that occlusion still is a problem for many people.

The visible difference between a BTE, ITE and a ITEC aid is the size and the microphone position. A BTE aid consists of a physical separate device that is connected to an earmould via a tube. The microphone is placed on top of the pinna. In an ITE and ITEC aid all parts are placed inside the earmould shell, and the microphone is located in concha. The CIC aid also compromise all parts in the shell. An CIC aid is even smaller than an ITE and ITEC and the microphone is moved into the ear canal. The four types are illustrated in Figure 2.1.
2.1.2 Earmoulds

The earmould is made of an impression of the hearing aid user's outer ear. A conventional earmould normally reaches 1/3 into the ear canal. There are three basic types of earmoulds; standard, skeleton and non-occluding, see Figure 2.2. The standard earmould design is the most used. In ITE and ITEC aids the outer part of the earmould is cut off so it does not fill up concha. The skeleton looks like the standard but a part of the earmould material is removed in concha. The non-occluding mould prevent occlusion of the ear canal, but if the hearing loss is too large this mould is unusable because of acoustic feedback.

![Image of various earmould types]

Figure 2.2 - A standard, skeleton and non-occluding earmould. (Microsonic, 1994)

In an open ear or with a non-occluding earmould the sound transmitted into the ear canal via the ear canal walls will travel out of the ear canal. A tight fitted mould reflects some of the sound and a sound pressure is build up in the occluded ear canal.

In order to reduce this occlusion effect and relief the air pressure in the ear canal, the earmould is often modified with a ventilation canal, usually called a vent. A vent reduce the reflection at low frequencies and the occlusion effect reduces. The three most simple vents are shown in Figure 2.3. The dimensions of the vent is decided during the fitting procedure.
The parallel vent is the most common. It works like an acoustic lowpass filter where the cut-off frequency and filter gain are decided upon the length and diameter of the vent. A diagonal vent is often used in very small ear canals since there is no room for a parallel vent in the tip of the earmould. The external vent is an alternative that can be used to minimise the chance for acoustic feedback between the vent outlet and the microphone.

Figure 2.3 - Basic designs of vents. (Microsonic, 1994)

2.1.3 Fitting a hearing aid
Fitting a hearing aid includes electrical gain setting and acoustical modification of the earmould. It is not a simple task to find the best frequency response for the specific person. Because the optimal fitting depends not only on the hearing loss but also on the sound environment. Here will only be looked at the basic gain setting and vent design.

The most simple choice of gain setting is based on the hearing threshold for airborne sound and the associated insertion gain. The insertion gain is found by measuring the sound pressure level in the open ear canal and subtract that from the level measured with the hearing aid in place. The test signal is provided by a loudspeaker. Several rules can be used to set the gain of the hearing aid. In Denmark the most used rules are the ½ gain rule, Prescription of Gain and Output, POGO II and National Acoustic Laboratory, NAL.

The ½ gain rule is simple. It prescribes the insertion gain to half the hearing loss. For example if the hearing loss is 30 dB at 500 Hz, then the measured insertion gain shall be 15 dB at 500 Hz.

POGO II reduces the low frequency gain compared to the ½ gain rule: insertion gain = \( \frac{1}{2} \times (\text{HL at 250 Hz}) - 10 \text{ dB}, \frac{1}{4} \times (\text{HL at 500 Hz}) - 5 \text{ dB} \) and at higher frequencies the insertion gain is \( \frac{1}{2} \) the hearing loss.

NAL is a bit more complicated and will not be used in the present survey.

The sensation of occlusion can be tested with a so called occlusion meter or just by asking the patient how he/she perceives own voice. If the occlusion effect seems unacceptable, the vent is enlarged. In practice the vent size is not enlarged unlimited because there is a risk of acoustic feedback and it is often seen that the vent is made too small to prevent occlusion.
3 TEST PARAMETERS

This chapter discusses several aspects which have to be considered in the design of the questionnaire and laboratory experiment. The decision of what kind of sample group to use depends especially on parameters regarding audiological factors and the hearing aid fitting. The sample size is a compromise of the theoretical optimum and practical elaboration. The design of a questionnaire and real ear measurements techniques are also discussed. Pilot studies showed that the best measures for real ear occlusion was obtained with continuos speech.

3.1 AUDIOLOGICAL ASPECTS

This section comprises some considerations about the subjects hearing abilities.

3.1.1 Hearing threshold, air conduction

Hearing aids are normally fitted on the basis of the hearing threshold which implies that the experience of acoustic occlusion effect depends on the difference between the insertion gain, which is set on the basis of the hearing loss, and the objective acoustic occlusion. When the needed insertion gain equals or exceed the objective occlusion effect, the sensation of occlusion might be negligible because the hearing aid amplified sound is perceived as well or better than the amplified body conducted sound.

The maximum obtainable occlusion effect is approximately 25 dB at 250 Hz, according to Lundh (1986). The limiting hearing loss (air conduction) for not sensing occlusion is therefore 50 dB HL (half gain rule) or 70 dB HL (POGO II). This hypothesis is only valid if the difference between the hearing threshold of air conduction and bone conduction, the air-bone gap, AC-BC, is ignored.

3.1.2 Hearing threshold, bone conduction

In clinical occlusion tests the bone conduction is tested with a bone conductor (vibrator) placed on the mastoid behind pinna or on the forehead. If no occlusion is sensed, it indicates that the patient has a conductive hearing loss. An AC-BC < 10 dB and a significant air conduction loss indicates that the patient has a disorder in the inner ear. Whereas a BC = 0 dB or an AC-BC ≥ 15 dB indicates a dysfunction in the middle ear. The bone-conducted signal reaches the inner ear by three pathways [Dirks, 1994]:

1. Vibrations stimulate the cochlear which creates movement of the fluid and thereby stimulates the haircells.
2. Relativ movements of the middle ear bones stimulate the cochlear and hence the haircells.
3. Vibrations of the bone create sound radiation in the ear canal which stimulates the ear drum and the sound reaches the middle ear by the normal pathway.

The objective occlusion of own voice is created by the increased sound pressure in the ear canal. If the middle ear has a dysfunction and the inner ear is normal, the sensation of occlusion might be absent because the bone conducted signal at pathway 1 is not influenced by the closed ear canal. This leads to the assumption that patients with a pure conductive
loss might not experience occlusion. In situations with disorders in the inner ear and normal functioning middle ear, the perceived sound will be influenced by the acoustical conditions in the ear canal.

If this hypothesis should be investigated it demands a sample of pure conductive losses and a sample of sensorineural losses where all patients have nearly the same air conduction threshold and are wearing the same vent sizes. It requires a sample size too large for this survey. Most hearing impaired have a sensorineural or mixed loss, and only few people have a pure conductive loss, where the bone conduction threshold equals zero. The present survey shall find some general trends and therefore will the sample only include sensorineural losses. Sensorineural hearing impaired patients are in practice found by looking at their audiograms and check that AC-BC ≤ 10 dB.

3.1.3 Tubal dysfunction
The function of the Eustachian tube is to equalize the pressure in the middle ear space to the atmospheric pressure, [Katz, 1994]. Tubal dysfunction can occur with sensorineural hearing loss. In order to avoid bias in the sample it must be required that the subjects have a normal functioning Eustachian tube.

3.1.4 Abnormal function of the tympanic membrane
The acoustic impedance at the eardrum (tympanic membrane) is (among other functions) controlled by the stiffness of the tympanic membrane. In an acoustic matter the eardrum and middle ear impedance is influenced by the acoustic impedance of the ear canal. If the eardrum does not function normally the impedance of the eardrum will depend upon the abnormality. Abnormal function of the eardrum and the middle ear occurs for conductive losses and can be detected with a tympanometer that measures the impedance of the eardrum and middle ear. The present survey shall not include an analysis of the influence of abnormal eardrum and middle ear but the survey shall only be concerned about the occlusion effect in ears with normal eardrum and middle ear.

3.1.5 Tinnitus
Permanent tinnitus is a constantly ringing or buzzing audible sound. The most prevalent tinnitus is created in the inner ear. Occlusion of the ear canal might increase the loudness of tinnitus because occlusion of the ear canal reduce the masking effect of external sounds and the tinnitus becomes more distinct. Another possibility is that the loudness of the tinnitus itself increases, [Hickok et al, 1993a]. Therefore, it is expected that the sense of occlusion is different for persons with and without tinnitus.

From a practical point of view, it is very difficult objectively to sort out subjects with tinnitus. The only way is to ask them directly. It is expected though that the sample automatically will include some subjects with tinnitus and some without.
3.2 HEARING AIDS

3.2.1 Distortion
A hearing aid user might complain about own voice. But it does not mean that the change in own voice absolutely has to be caused by occlusion. It can also be caused by distortion in the hearing aid and it is therefore important to be able to distinguish between changes in own voice caused by the earmould and changes caused by electrical distortion in the hearing instrument.

3.2.2 Vent dimensions
The relation between optimum vent size and hearing loss is a complex matter because avoiding occlusion at low frequencies (250-500 Hz) requires a big vent diameter and avoiding feedback at higher frequencies (3,000-4,000 Hz) requires a small vent diameter. It must be expected that the vent size reflects the objective occlusion effect somehow.

3.2.3 Binaural / monaural fitting
There is no exact rule to decide whether a person should be monaurally and binaurally fitted, only a guideline can be given. In theory all symmetrical hearing losses should be treated binaurally but this is not the case in practice.

A patient who is binaurally fitted might experience a more tense feeling of different occlusion effects, especially acoustic effects and the feeling of being in a barrel, than a patient who is monaurally fitted. The acoustic occlusion might be more profound because the absolute sound pressure level is greater when two ears are blocked instead of only one and according to the theory of binaural loudness summation, the binaural loudness becomes larger than monaural when the overall level increases [Tobias, 1972]. In the present survey both binaural and monaural fittings will be included.

3.2.4 Hearing aid amplification
Correct fitting of the hearing aid is important to assure a good sound quality. The hearing aid amplification is set according to some fitting rules, see section 2.1.3.

If the hearing aid amplification is large enough, the occluded sound will be masked effectively by the hearing aid amplified sound. Consequently, occlusion will not be experienced. It is therefore important to check the hearing aid amplification and how well it corresponds to the predicted fitting according to hearing loss.

3.2.5 Hearing aid configuration
The choice of hearing instrument type is not only based on the hearing loss but does often depend on the patient comfort and demands to cosmetic outlook. Examples on fitting ranges are given in Table 3.1. Despite that BTE aids can be used for very mild hearing losses, it is likely to believe that mild losses normally are treated with ITE or ITEC aids.
Table 3.1 - Fitting limits for some Oticon hearing instruments. Data taken from the technical data sheets.

If no restrictions are set on hearing aid configuration it must expected that both BTE, ITE and ITEC aids will be represented.

3.3 EXPERIENCE

The human body adapts well to some anatomical changes and likewise it could be believed that hearing aid users will adapt to the occlusion effect. More experienced users might get use to the occlusion effect whereas new users probably will react on any changes in sound quality. MacKenzie et al. (1989) reported that in their survey 21% of the subjects felt general uncomfortable wearing an earmould when they first got it. After 6 weeks only 10% felt uncomfortable. If the hypothesis about adaptation is true, it will affect the survey which therefore should include experienced as well as inexperienced users.

3.4 SAMPLE

The investigation of the user problem should involve a representative group off all hearing instrument users. As the number of users is large it is necessary to perform the investigation only on a sample of users. This introduces systematically errors which have to be considered. Firstly an error is introduced if the sample does not represent the population in an acceptable way and secondly an error will be introduced by the fact that not everybody is expected to answer all questions in a questionnaire.

3.4.1 Detection of occlusion

One of the purposes of this survey is to detect the problems that the users might experience due to occlusion. This will be carried out by means of a questionnaire. In order to detect whether there is a problem with occlusion or not this question could be posed:

Do you have a feeling of occlusion? YES___ NO____

The possibility for answering yes on this question can roughly be estimated from the survey results made by Biering-Sørensen, Pedersen and Parving (Biering-Sørensen, 1994).
One group of patients had hearing losses of 10-50 dB HL at 250 Hz. It was expected that the patients all had hearing aids with maximal vent sizes of 0.8 mm which is too small to relieve occlusion. Theoretically these patients should experience occlusion. The results showed that 57% experienced occlusion. Roughly speaking, the probability of answering yes is 55% provided that the patient actually does experience occlusion.

Another group of patients had a hearing loss of 20-90 dB HL at 250 Hz with an average of 58 dB HL. These patients were classified as conductive hearing impaired and were therefore assumed not to experience occlusion. However, 27% said they had occlusion. Based on this it can be estimated that there is a probability of 25% to answer yes even though the patient does not sense any occlusion effect of own voice.

In this survey it is assumed that all subjects have some objective measurable occlusion effect. The degree of occlusion cannot be predicted because the survey is designed to make use of the subjects own hearing aids and thereby the individual vent size which are unknown before selecting the subjects. The experience of occlusion is believed to depend on the degree of objective occlusion and the degree of hearing loss (see next sections for details). As the degree of objective occlusion is unknown it is not possible to estimate how many of the subjects who might experience occlusion. In this situation the best statistical estimate is to say that the probability of experience occlusion is 50% [UNI-C, 1993]. If 50% is expected to experience then 55% of these 50% will answer ‘yes’ they do experience occlusion. These estimations are illustrated in Figure 3.6.

![Figure 3.6](image)

*Figure 3.6 - Probability of answering yes or no to the experience of occlusion. Probabilities are estimated based upon the results from Biering-Sorensen et al. (1994).*

The sample size needed to achieve significant results on a yes/no question can be simply estimated by looking at the 95% confidence interval for a binomial distribution, [UNI-C, 1993]:

---

Oclusion effects. Part I.
\[ n > \frac{1.96^2 P(1-P)}{dP^2} \]

where;
\( n \) = sample size
\( P \) = probability for answering yes
\( dP \) = uncertainty in the answer

According to Figure 3.6 the probability for answering yes is 27.5% + 12.5% = 39% = \( P \). If \( dP = 20\% \) then \( n = 92 \). If a smaller sample size is desirable then the uncertainty must be greater. If \( dP = 25\% \) then \( n = 15 \).

### 3.4.2 Relation between experienced and objective occlusion

The other purpose of the investigation is to determine relations between the feeling of occlusion and hearing aid type, hearing loss, vent size etc. Due to the expectation that most of these parameters have influence on the objective occlusion, the main interest is to find the relation between the feeling of occlusion and the objective occlusion.

The subjective sense of occlusion is expected to depend on the vent, the fitting and the hearing loss, whereas the objective occlusion is a function of the vent size, see chapter 2. The individual experience of occlusion is affected by the objective occlusion. If the hearing loss is profound at low frequencies, the hearing aid gain might be high and influence the experience of occlusion. The point is that it must expected that the individual experience of occlusion is influenced by the individual objective occlusion effect and hearing loss.

If the objective occlusion effect is plotted against the hearing loss a figure like the one in Figure 3.7. must be expected to occur. When the hearing loss gives a target gain that equals the objective occlusion, the sound of the occlusion and the amplified sound might be perceived with equal loudness and a simple guess is that there will be 50% chance to experience the occlusion effect. In Figure 3.7 the target gain according to POGO II at 250 Hz is the line with the slope of 1:2. A larger slope means that the objective occlusion effect exceeds the target gain and more annoyance must be expected. Consequently a smaller slope indicates that the target gain dominates the objective occlusion effects and less annoyance should be expected.

When the experience annoyance is fixed, the objective occlusion effect should be correlated with the hearing loss (or target gain). If the variance of hearing loss and objective occlusion is the same for each line, then the normalized regression line due to the variance has a slope equal to the correlation coefficient between objective occlusion and hearing loss.

This approximation can only be used if the observations are normally distributed. It is reasonable to assume that both the measured objective occlusion effect and hearing loss fulfill that requirement.
The required sample size at a significance level = 5%, confidence interval = 95%, can be found by the mean of a two tailed t-test. The method of estimation the required sample size is briefly described here. A more detailed description is for example given in Hirsch and Riegelman (1992).

If the hearing loss and objective occlusion effect are independent i.e. not correlated then $\rho = 0$. The other possibility is that they are correlated and then $\rho <> 0$. The difference between the estimated correlation coefficient and the hypothesis is used to calculated a test value:

$$\text{test value} = \frac{\rho - \rho_0}{SE}$$

where;
$\rho =$ estimated correlation coefficient
$\rho_0 = 0$

and

$$SE = \text{standard error} = \sqrt{\frac{1 - \rho^2}{n-2}}$$

where;
$n =$ sample size

The calculated test value is compared with a two tailed t-distribution for significance level 5%. If the test value is larger than the t-value the hypothesis $H_0$ is rejected, meaning that
experienced and objective occlusion effect are not significant independent. This test leads to the following sample sizes:

\[
\begin{align*}
\rho &= 0.75, \quad \text{sample size} = 8 \\
\rho &= 0.50, \quad \text{sample size} = 16 \\
\rho &= 0.25, \quad \text{sample size} = 62
\end{align*}
\]

The sample size is considered to be a homogeneous group, i.e. the calculated numbers indicate the sample size for each sub-sample.

### 3.4.3 Sample size from a practical view

The sample size must be limited because of practical reasons such as time and money. The survey is time consuming because proper candidates must be found and asked to participate. Assuming that 50% are willing to participate, then it is necessary to actually find twice the sample size. The clinical measurements will take a couple of hours and this means that no more than 3 persons can be tested per day.

The survey holds many parameters and an ideal survey would include a subgroup for each parameter. Just considering the three parameters; pressure relief vent / non-occluding vent, perceptive/conductive hearing impairment and binaural/monaural fitting. Each subgroup should contain only one of each parameter which makes 8 subgroups. According to the considerations about sample size 15 persons are needed in order to get significant answers on the questionnaire with an uncertainty of 25%.

With 15 persons in each group, the sample size counts 120 persons, which is too many.

Another aspect is that the sample criteria should be kept simple, so that it is more easy to find proper candidates in all subgroups. It was therefore decided to divide the subjects into three groups according to their hearing loss. If the 3 groups shows correlation between experienced and objective occlusion effect with correlation coefficients of 0.75, 0.50 and 0.25, then 79 persons are needed.

It was intended that the test of the subjects should have taken place at a hospital clinic as a part of the daily routine. But this was not possible and the tests were moved to Oticon's own clinic. The consequence was that fewer persons could be tested and the sample size was limited by the practical circumstances. The theoretical considerations of sample size could not be expected to be fulfilled.

### 3.4.4 Sample composition

The objective occlusion occurs at low frequencies and therefore the sample is divided into groups according to the hearing loss at 250 Hz. The upper limit is set to 60 dB HL as it is assumed that persons with more profound hearing losses cannot experience occlusion, see section 3.1.1.

The objective occlusion is expected to be a function of vent size and the vent size can be related to the hearing aid configuration. The hearing aid configuration will therefore be another restriction for the subgroups.
The survey includes a questionnaire and therefore it must be demanded that the candidates have no problems with reading or writing and that they are sound minded. An attempt to assure this is to restrict the age range to 15-80 years.

The criteria for candidacy are:

**General criteria:**
- Age: 15-80
- Sound minded, shall be physically able to read and write without problems
- Normal tympanic membrane
- No inflammation in the ear canal or in the middle ear
- AC-BC ≤ 10 dB at all frequencies
- Difference between hearing loss on left and right ear ≤ 20 dB HL

**Specific criteria:**
The subjects shall be included in one of the following groups.

**Group 1:** Audiogram, air-conduction, 250 Hz: 0-25 dB HL for the hearing aid ear. Preferably fitted with ITEC-aids.

**Group 2:** Audiogram, air-conduction, 250 Hz: 30-40 dB HL for the hearing aid ear. Preferably fitted with ITEC- or ITE-aids.

**Group 3:** Audiogram, air-conduction, 250 Hz: 45-60 dB HL for the hearing aid ear. Preferably fitted with ITE- or BTE-aids.

### 3.5 QUESTIONNAIRE
The importance of the design of the questionnaire should not be underrated. The most important issues are discussed here. The final design of the questionnaire is given in appendix D.

#### 3.5.1 Pre-questionnaire test
A minor survey was made on 4 subjects. The purpose was partly to see if the problems described in former surveys for example by Hickok et al, (1993) and Kuk, (1991) could be reproduced and partly to get an idea of how people would describe the experienced annoyances. The results indicates what people in general might experience and how they will describe their experiences.

**Method**
The experiment can be considered as a worst case situation involving four employees at Oticon, who were assumed to have normal hearing. Individual tight fitted earmoulds were made for all subjects. One subject had an earmould made of real earmould material (subject 4), the three others had earmoulds made of the impression material. The subjects wore the earmoulds according to a schedule lasting 5 days, see appendix B.
The subjects were asked to wear the ear moulds while walking, eating something crispy, eating something not crispy, drinking, turning the head, scratching the face, scratching the head, talking with another person and while speaking in the phone with an earmould in the other ear. The subjects described all their observations in a dairy.

**Results**

All subjects experienced a change in the perception of own voice, which they described as a louder voice, a darker voice, a resounding voice or a voice in a barrel. Three of the four subjects had a general feeling of being inside a barrel.

Everyone either heard or felt heavy jolts while walking. Some described it as low frequency bumps or like hitting two metal pipes against each other. Loud sounds were also heard while drinking and chewing and could be described as a ringing inside the head. The subjects found the noises from breathing, chewing, drinking, walking and coughing annoying while listening to other people. All subjects also found that their own breathing was audible, but normally they did not take any notice of it. Only one subject noticed a change in breathing.

The change between one or two ear moulds gave different reactions. One subject found that one ear mould was more comfortable than two ear moulds and another subject had the opposite opinion due to a feeling of no balance between right and left side of the head.

The literature study and the pre-questionnaire investigation lead to the following list:

* **Acoustical related occlusion effects**
  - Own voice sounds different
  - Localising own voice is difficult
  - Breathing is more audible
  - Heart beat is audible
  - Movements of the head is audible
  - Chewing is very noisy
  - Walking creates loud sounds

* **Mechanical related occlusion effects**
  - Pain caused by the earmould
  - A feeling of pressure in the ear canal

* **Biological related occlusion effects**
  - Moist, itch and warmth
  - Eczema
  - Heart beat rate changes
  - Breathing rhythm changes
  - Headache
  - Running nose and tears in the eyes
  - Cough and hoarseness
Psychological related occlusion effects
- It feels like being in a barrel

3.5.2 Model of 'no response'
For a large sample size of 60 it might be necessary to actually find twice as many candidates because not all wish to participate. It is helpful to consider why some candidates do not respond. A general model of reasons for no response is shown in Figure 3.8.

Obviously it is a condition that people are qualified to answer a questionnaire. But not all are willing to fill in the questionnaire and therefore it is important to motivate people to answer. Motivation can be done by informing in an easy and understandable way which may create some interest about the item. It is important to design the questionnaire with a nice manageable layout, easy understandable questions and not to make it too long. On the top of that a small gift for participating in a contest is motivating. In this special case the motivation of people will also be done at the hearing clinic by performing some audiological test and personal conversation about the questionnaire.

A person who are able and by first impression are willing to answer but still will not, might have a reason related to the experience of occlusion. New users might be so much annoyed that they decide not to wear the hearing instrument and therefore they do not think it is relevant to answer the questionnaire. This is a very important aspect, if the annoyance is caused by occlusion. This situation can partly be avoided by making it clear that it is important to answer anyway. On the other hand these people might think it is important to answer because they want to complain about their troubles and would like to have something done. This last hypothesis can be used also for more experienced users who are annoyed by occlusion.

The amount of 'no'-responses could be reduced by sending a reminder to people who have not replied within a certain time. Due to the fact that it is difficult to predict the reason for no respond, an examination of reasons should be performed. The examination could be performed by a personal contact to a sample of the 'no'-respondents and ask them why they have not answered the questionnaire.
Figure 3.8 - Model of response and no response.

It turned out that the number of objectors is approximately equal to the number of respondents.

3.5.3 Design
The design of the questionnaire is important to the respondent but also for the ease of data analysis. The questionnaire shall not only include questions about occlusion but also provide useful information about the respondent in order to evaluate the answers. There is two kind of information in this questionnaire:
- background (age, sex, hearing aid fitting etc.)
- actual behavior and experience (use of hearing aid, experience of occlusion etc.)

The order of the questions can be discussed. The point is to motivate the respondents as much as possible. If all the background questions are put first, the respondent might find it easy to answer and do not pay proper attention to the rest of the questions. On the other hand, a couple of easy questions is a good way to start the questionnaire because the respondent will feel capable to answer.

The present questionnaire begins with questions about monoaural/binaural use of hearing aids. Questions about tinnitus etc. finish the questionnaire.
The questions in between are concerned about different kind of experiences with occlusion. Questions in the different categories have been mixed randomly in order to force the respondent to concentrate on the single question. It would give a better overview if the questions were sorted into categories but it could also have the effect to create less concentration.

It is only possible to keep the respondent motivated in a certain amount of time. It is therefore extremely important to design a questionnaire which is as short as possible with easy understandable questions. The time consumption restricts the possibility of posing questions for test-retest check. Therefore only a few questions were posed twice using different words.

3.5.4 Construction of questions and answers

The most difficult task is to formulate the questions. The two most important things to remember is that the questions must be easy for the respondent group to understand the first time they read them and that the questions must not be leading towards a certain answer.

One thing is the formulation of the question itself another is the design of the answer. There are 3 main categories: open answer, list of answers and scales, [UNI-C, 1993]:

Open answer

The respondent answers with his/hers own formulation

List of answers

The respondent shall choose one answer within a given list of possible answers. Example: apple, banana, nectarine.

Scales

The respondent shall choose one answer on a scale of answers.

Nominal scales

None of the answers are related and one answer excludes the rest. Example: yes / no

Ordinale scales

The answers can be ranked. Example: good, better, best

Metric scales

The answer can be ranked and there is a certain distance between each answer. A metric scale can be discreet or continuos.
Examples: 1,2,3 or 0-10, >10.

Open answers provide the possibility of more detailed answers and the respondent are not lead into a certain direction of answers. Open answers demands that the respond is capable of formulate an answer and it is difficult, if not impossible, to perform statistical analysis of the answers.

Lists is an easy way for the respondent to give an answer. It have the disadvantages that the respondent might not think of other answers even though the list includes a category called 'other'. The lists must focus on the important answers in order not to be too long.
Scales are a good design for statistical analysis. The nominal and ordinal scales can be used with non-parametric methods. A discrete metric scale can be analysed with non-parametric methods and a continuous metric scale with parametric methods. The scale can be more or less easy to use for the respondent depending on the design of the question.

Scales includes two special categories. The neutral category which is for the respondents who cannot make a decision. The disadvantage is that it is tempting to choose this category and respondents that actual do have an opinion do not show that. 'Don't know' is another special answer. It can help some respondents to go on with the questionnaire if they do not know what to answer and no one is forced to give an answer on which they are not sure. But again it is easy to answer: 'I don't know', even though I actually do know, so in this way some information might be lost.

All 3 main categories of answers are used in the present questionnaire.

3.5.5 Test
The final draft of the questionnaire was tested by 8 hearing aid users. They were asked to fill out the questionnaire at home and to comment if the questions were difficult to understand immediately and to comment the answer categories. Their comments were used to make a final revision of the questionnaire.

3.6 STIMULI USED IN THE MEASUREMENTS
The literature talks about occlusion effects measured with a bone conductor, own voice or body sounds. In order to evaluate these stimuli, a pilot study was set up. The pilot study had 2 aims: to try out the measurement procedure and to find the best stimulus.

3.6.1 Vowels
The Rastronics 2000 provides a feature to measure the occlusion effect with simple sounds such as vowels. The equipment is easy to use and the measurement only takes a few seconds. Unfortunately the pilot study showed that it is not a reliable method for measuring the occlusion effect at all frequencies.

The probe microphone is positioned in the ear canal and the subjects is asked to vocalize, for example an /ee/. The signal is picked up by a reference microphone placed on an ear hanger. The level is displayed on a screen and so is the recording. The recording is started manually by pushing a button and it lasts for a couple of seconds. The hearing aid is then inserted and the subjects is asked to make the same sound again. When the reference level is judged to be the same as before the recording is started. The two recordings are subtracted and the difference is a measure of the occlusion effect.

These measurements were done twice for each subject. The occlusion effect was measured with the hearing aid turned off. In fact some of the subjects had normal hearing and a custom made earmould was used instead. This method was tested on 7 subjects.
There are two major problems with this method. Firstly, the reference level is not precisely the same in the two measurements because the recording is started manually by pushing a button when the supervisor judge that the timing is good. Secondly, it can be difficult to repeat exactly the same vowel twice. It is especially difficult because the occlusion effect makes the vowel sound different to the test person even if it is the same sound. Some subjects had great difficulties reproducing the same pitch as illustrated in Figure 3.9 where the best and the worst repetition of the vowel /eee/ are shown.

![Figure 3.9](image)

**Figure 3.9** - Occlusion effect, /eee/. Closed earmould. Two subjects. Upper: the best repetition (FPTP). Lower: the worst repetition (FP06).

It would be a possibility to make a correction such that the pitch in the open ear spectrum fits the fundamental in the occluded ear spectrum. But the higher formants can still be located at different frequencies.

**Figure 3.9**, right, also illustrates the problem with the reference level. The shape of the two spectra are the same but the occlusion effect deviate 15 dB.

If vowels shall be used as stimuli it will be necessary to record the reference signal and to train the subjects in repeating the same sound. Only the /eee/ was measured in the pilot study but for the main investigation it would be necessary to use different sounds because

Occlusion effects. Part I.
the occlusion effect might depend on the sound that is made. The conclusion of the pilot study is that the Rastronics 2000 can be used only to indicate if there is an occlusion effect or not.

3.6.2 Continuous speech
Complains about occlusion are often related to the situation where the hearing aid user is talking. Speech should therefore be an appropriate stimulus.

The occlusion effect caused by speech was measured with a signal processor system. The ear canal response was recorded by a probe microphone and the reference signal by a microphone placed in front of the speaker. Both signals were recorded via a signal processor card onto a hard disk and further data analysis were done by the programs 'Hypersignal' and 'Matlab'. Recordings of 1 minute continuous speech were made from 4 subjects. A Danish text was very carefully chosen. It did only contain neutral words and words that are commonly known. Repeated measurements turned out to be very consistent and therefore continuous speech is appropriate for a user survey.

3.6.3 Chewing
The occlusion effect is not only related to speech, but also to walking, chewing, swallowing, coughing etc. Chewing something crunchy might even be worse than speaking. Curtois et al. (1988) reports that swallowing one mouthful of water can create 25 dB occlusion effect at 125 Hz with closed mould. Chewing gum can cause an occlusion effect on 30 dB at 125 Hz and stamping the feet can increase the sound pressure by 10 dB at 125-2,000 Hz.

The occlusion effect created by chewing was in the pilot study measured with the same equipment as used for continuous speech. One subject performed the test. The subject was asked to chew a piece of crispbread. It turned out that the chewing created very high peaks which complicated the measurements. The results were also very difficult to reproduce. It is very important to concentrate on chewing the same way twice. The occlusion effect varied up to 10 dB depending on contra-lateral or ipsi-lateral chewing. Furthermore a hard chewing creates 10 dB more occlusion effect than a soft chewing.

![Chewing crispbread](Figure 3.10 - Occlusion effect. Chewing crispbread. 1 subject. Linear frequency axis.)
It was decided upon these measurements that a chewing test would be too inconsistent for the purpose of the user investigation.

3.6.4 Bone vibrator

The disadvantages of the three former methods is that it is difficult to control the level of the stimuli. This can be avoided by using a bone vibrator. Unfortunately it turns out, that bone vibrator measurements cause other difficulties. The bone vibrator technique was tested in the pilot study on 2 subjects. A bone vibrator type B-71 was connected to the signal processor station. A probe microphone was used to measure the sound pressure level in the ear canal. The measurements were carried out by means of the program 'Sysid'. This program measures the transfer function from input to output. A chirp signal was chosen as test signal. It was found that the measurements were difficult to reproduce.

Revit (1992) states that the bone vibrator and the own voice technique gives nearly the same occlusion effects, but from measurements reported by Lundh (1986) it can be derived that own voice create 5-10 dB less occlusion effect than a bone vibrator, see Figure 3.11. This is another reason for not using the bone conductor technique. A vibrator excites the skull whereas own voice excites primarily the soft cartilage in the ear canal and therefore bone conduction is probably not a good estimate for the occlusion effect generated by own voice.

![Mean occlusion effect by bone conductor and own voice](image)

**Figure 3.11** - Occlusion effect, average for 8 ears. Own voice and bone conductor. From [Lundh, 1986].
4 TEST METHOD

The procedures of handling candidates and the questionnaire are outlined. The clinical measurements and the technical set up are described. Appendix C and D inform more detailed about methods and technical equipment.

4.1 MANAGEMENT OF CANDIDATES

The candidates were found in corporation with the audiological clinic at Bispebjerg hospital. This particular clinic was chosen partly because many ITEC aids are dispensed from this clinic and partly because of convenience as it is located near Oticon's clinic.

Two associates at Bispebjerg hospital searched for candidates among the patients at the clinic. The search was based on the sample criteria, see section 3.4.4. Only patients that had visited the clinic within the last 6 months were included in the search. The hospital mailed the candidates a letter asking them to participate in the user survey. If the candidates liked to participate, they contacted Oticon. The candidates were asked to permit that their clinical record could be seen by the supervisor (the author of this report) and an assistant. If the supervisor judged that the candidate fulfilled the requirements in a clinical manner, then a questionnaire was send to the candidate.

The candidates answered the questionnaire at home and approximately 3 weeks later they attended in a test at Oticon's clinic. The subjects were paid by Oticon and they got a refund for transportation expenses.

4.2 GENERAL MEASUREMENT PROCEDURE

The occlusion measurements took place in Oticon's clinic. A visit took 1½-2 hours and followed this procedure:

Step 1: Audiogram

The audiogram measured at Bispebjerg was evaluated before the subject arrived. If the subject claimed to now have more hearing troubles than before the visit at Bispebjerg, a new audigram was made at Oticon. This procedure saved time.

Step 2: Questionnaire and MCL

The supervisor talked with the subjects about the questionnaire and tried to help filling out blanks. At this point the subject was told to adjust the hearing aid(s) to a comfortable level. This level was defined as the most comfortable level, MCL, and the corresponding gain setting was used in subsequent measurements.

Step 3: Otoscopy

The supervisor looked in the subject's ear with an otoscope. If ear canal was plugged up with ear wax, the subject was sent to a doctor to get a rinse.

Step 4: Insertion gain measurement
- see section 4.3

Occlusion effects. Part I.
Step 5: Insertion loss measurement (Insertion gain with hearing aid turned off)
- see section 4.3

Step 6: Occlusion effect measurement
- see section 4.4

Step 7: Tympanometri
- see section 4.5

Step 8: Hearing aid distortion
- see section 4.5

Step 9: Physical measures of the vent
- see section 4.5

The supervisor had this procedure in writing and had to follow it carefully. The supervisor was instructed to check amplifier settings and file names.

The test procedure was a result of improvements from several pilot sessions.

4.3 INSERTION GAIN AND INSERTION LOSS

Insertion gain and insertion loss was measured with the same method.

4.3.1 Set up

The subject was placed approximately 0.5 m from a loudspeaker with a 45° angle of incidence. A 1.1 mm tube to a probe microphone was placed in the ear closest to the loudspeaker. The tube was inserted in a depth corresponding to the length of the subjects own earmould + 3 mm. The tube was inserted between the earmould and the earcanal wall. A little bit of impression material was used to seal the leakage between the earcanal wall and the earmould.

A Rastronics 2000 generated a sweep of 60 dB SPL warble tones. A warble tone is a pure tone which is frequency modulated with another tone. A reference microphone was attached to the ear hanger on the probe microphone. The reference microphone ensured that there was the selected sound pressure level right below the earlobe. The measurements took place in a sound proofed booth.

4.3.2 Calibration

The Rastronics 2000 was calibrated as described in the instrument reference guide, for details, see appendix C. The calibration was checked several times during the investigation period.
4.3.3 Procedure
The insertion gain was found by measuring the response for the open ear and the response with the hearing aid in place. The hearing aid volume control was set to MCL position. The insertion gain at MCL is the aided response minus the open ear response.

The insertion loss was measured the same way but with the hearing aid turned off. Insertion loss is the difference in sound pressure level between hearing aid occluded ear response and the open ear response.

4.4 OCCLUSION EFFECT

4.4.1 Set up
The occlusion effect of own voice was measured with the set up illustrated in Figure 4.1. The subject was seated in a sound proofed booth facing a microphone. The reference microphone was a directional microphone Beyer Dynamic type MC 73. Because of reflections in the box, it was decided to use a directional microphone. The tube (diameter = 1.1 mm) of the probe microphone was positioned in the ear canal of the subject. Each microphone signal was lead through an amplifier, that could be varied in 1 dB steps. The probe microphone output signals were low-pass filtered and stored via a signal processor on a hard disk using the program 'Hypersignal'. The supervisor could listen to the subject via a third microphone and a loudspeaker.

![Diagram of the set up](image)

**Figure 4.1** Set up used for measurement of occlusion by own voice.

4.4.2 Calibration
The sound pressure level in dB SPL was found by comparing the recorded signal with a calibrator signal of known sound pressure level. The calibrator signal was provided with a pistonphone and recorded with a 1'' microphone. The probe microphone does not have a flat frequency response like a 1'' microphone. The recorded signal was therefore corrected.
with a filter shaped as the inverse of the probe microphone plus the probe tube frequency characteristic. More details are described in appendix C.

4.4.3 Procedure
The subject was sitting in a chair in the booth. When he/she had found a comfortable reading position, the reference microphone was positioned. The probe microphone was positioned and the door closed. The recording started when the subject reached a certain passage in the text. The same text was read for all measurements.

The amplifiers were preset to a certain gain for each recording. The needed gain was found in the pilot study. If the input level was too large anyway, the gain was decreased and the amplifier settings were noted.

This procedure was repeated three times; once for the open ear, once with the hearing aid turned off and once with the hearing aid set to the gain corresponding to MCL (see section 4.2). The occlusion effect could then be calculated as the occluded ear response minus the open ear response for both the hearing aid turned off (OEHAoff) and the hearing aid turned on (OEHAon). The probe was inserted between the earmould and the ear canal wall and the leakage created by the probe tube was sealed with impression material.

4.5 OTHER MEASUREMENTS
The distortion in the hearing aid with the MCL gain setting was measured with a Interacoustic Hearing Aid Analyzer MS 40.

Tympanometry was performed with a standardised method using Interacoustic Impedance Audiometer AZ 26.

The length, inner and outer diameter of the vent was measured manually with a slide gauge.
5 CONDITION OF DATA

The condition of data are presented in this chapter. The data have been analysed by means of the programs "Excel", "Matlab" and "Statgraphics". The methods of data processing, the handling of missing values and the retest validity are described.

5.1 DATA TREATMENT

5.1.1 Subject related data
Subject related data includes features such as age, sex, hearing aid type, earmould dimensions etc. These data were all hand written on the control sheet and later typed manually into an EXCEL data sheet. The data are given in appendix E.

5.1.2 Questionnaire
The responses in the questionnaire were also manually typed into an EXCEL data sheet according to defined codes for each answer. An EXCEL procedure automatically controlled that each input corresponded to a legal value. When an error message turned up it was interpreted whether the error was caused by a mistake in the manual key input or by a illegal response. Missing values were also detected.

5.1.3 Insertion gain and insertion loss data
Signals measured with Rastronics 2000 were stored on floppy disk. The stored audiogram, target curve (POGO II), insertion gain and insertion loss were copied to EXCEL data sheets. As the audiogram was manually entered into Rastronics 2000, this audiogram was checked by entering the audiogram once again into the EXCEL sheet. If a mistake was discovered, the target curve had to be corrected. The insertion gain measurements were checked by comparing it with the target curve. This was also done in the test session.

5.1.4 Occlusion effect data
The data from the occlusion measurements were stored in binary files on the PC containing the signal processor card. The program "Hypersignal" can perform FFT and spectrum analysis on time domain files, but Matlab provides a faster routine. Another reason for using Matlab was that further data analyses would be easier. The speech data files were created with a sample frequency, \( f_s = 20.833 \) Hz, but it was judged that the spectra did not hold relevant information above 5 kHz. In order to make the analysis faster the signals were down sampled to half of the original \( f_s \). The power spectra of the signals were found by the Welch method (see appendix H) using a 512 point FFT and 50% overlapping Hanning windows, (Matlab file: multisp.m). The new sampling frequency is 10.417Hz and a single Hanning window contains therefore 512/10.417 = 49,2ms.

5.2 PRIME DATA

5.2.1 Candidacy fulfilment
The candidates were selected according to their hearing loss record but even then it was not ensured that everybody fulfilled the requirements of candidacy.
The visit at Oticon started with a relaxed talk and during this talk the session leader had a chance to judge whether the candidate was suited to participate. Fortunately no subjects were excluded at this stage. None of the candidates was excluded because of problems with reading or writing.

It was required that the subjects had normal eardrum and middle ear which was checked by tympanometry. A normal tympanogram will show a volume between 0.3 - 1.6 ml, (Katz, 1994). Subjects no. 12 and 32 had abnormal tympanograms and care should therefore be taken regarding data from these subjects. Subjects no. 12 had a tendency to exostosis and no. 32 once had inflammation of the middle ear. Tympanometry was not made on four subjects, but according to the hospital reference, the tympanograms were normal.

5.2.2 Sample statistic

The characteristic parameters for the sample are given in Table 5.1. It is seen that group 1 and 3 hold fewer subjects than planned and that group 3 is female dominated. The mean age in each group is the same. In practice the subjects were mainly chosen on basis of their audiogram, why a distribution of BTE, ITE and ITEC aids must be expected in all three groups. The values for the vent diameter is the average diameter of the inner and outer vent opening in the ear mould. It seems that group 1 has the largest vents but the difference in vent diameter between groups are not significant.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Group 1</th>
<th>Group 2</th>
<th>Group 3</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of subjects</td>
<td>16</td>
<td>21</td>
<td>11</td>
<td>48</td>
</tr>
<tr>
<td>Male subjects</td>
<td>12</td>
<td>10</td>
<td>2</td>
<td>24</td>
</tr>
<tr>
<td>Female subjects</td>
<td>4</td>
<td>11</td>
<td>9</td>
<td>24</td>
</tr>
<tr>
<td>Youngest</td>
<td>25</td>
<td>27</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Oldest</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Mean age</td>
<td>64</td>
<td>63</td>
<td>64</td>
<td>64</td>
</tr>
<tr>
<td>Mean HL at 250 Hz</td>
<td>15</td>
<td>34</td>
<td>53</td>
<td>34</td>
</tr>
<tr>
<td>Mean HL at 250, 500 Hz</td>
<td>18</td>
<td>36</td>
<td>51</td>
<td>35</td>
</tr>
<tr>
<td>ITEC</td>
<td>8</td>
<td>15</td>
<td>3</td>
<td>26</td>
</tr>
<tr>
<td>ITE</td>
<td>5</td>
<td>3</td>
<td>5</td>
<td>13</td>
</tr>
<tr>
<td>BTE</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>Monaurally fitted</td>
<td>8</td>
<td>10</td>
<td>3</td>
<td>21</td>
</tr>
<tr>
<td>Binaurally fitted</td>
<td>8</td>
<td>11</td>
<td>8</td>
<td>27</td>
</tr>
<tr>
<td>Average vent diameter</td>
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<td>2.31</td>
<td>1.58</td>
<td>2</td>
</tr>
<tr>
<td>Smallest vent diameter</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Largest vent diameter</td>
<td>5.47</td>
<td>5.1</td>
<td>4.5</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 5.1 - Sample statistic. Group 1: mild, group 2: moderate, group 3: moderate-severe hearing loss.

The questionnaire responses were evaluated based on 48 subjects whereas the occlusion effect with the hearing aid turned off (OEHAoff) was analysed on 42 subjects and the
occlusion effect with the hearing aid turned on (OEHAn) on 41 subjects. It can be concluded that all, except two, met all the requirements for participating.

5.2.3 Audiograms
The subjects ranged from mild to moderate-severe hearing impaired. The maximum and minimum hearing loss at each frequency and the average hearing loss are shown in Figure 5.1.

![Audiogram graphs showing hearing thresholds for different groups and all subjects.](image)

**Figure 5.1** - Audiograms. Solid line: average with sample standard deviations. Dashed lines: Minimum and maximum hearing loss at the single frequency.

5.2.4 Reliability of questionnaire responses
Fortyeight subjects answered the questionnaire. The goodness of the responses is always discussible as some people might find it difficult to answer the posed questions. In order to detect whether or not the respondents had given consistent answers a cross-check was made. The answers on the following questions were compared (the questionnaire is found in appendix D):
If more than 3 of the cross checks showed disagreements, the respondent was considered unreliable. It turned out that only subject no. b20 had more than 3 disagreements and therefore this subject should be watched carefully in the following analyses. Among the other respondents, 9 subjects showed no disagreements, 18 showed 1 disagreement, 15 showed 2 and 5 showed 3 disagreements.

Not all subjects had responded to all questions and the missing answers equal 2.5% of the total number of possible answers.

The question about own voice included a description of the sound either in words or with prescribed words. The meaning ws to get an idea of how people perceived the sound and to be able to exclude the subjects who does experience a change in own voice but not because of occlusion. If a subject only wrote that own voice was louder with the hearing aid on, the change in own voice is probably caused by the hearing aid amplification and not by occlusion. In this way, subject number b71, c60, c70, d31 and e91 were excluded in analyses regarding own voice. Subject c60 wrote for example that own voice sounds lighter, clearer and louder.

5.2.5 Occlusion effects

Out of the 48 respondents of the questionnaire, 42 subjects carried through the whole test in Oticon's clinic. The validity of the occlusion effect measurements are difficult to evaluate. Therefore subjects should only be excluded if the data clearly shows an error in the measurements. Even though the test procedure was strictly followed there is always a chance to make human mistakes, i.e. wrong pre-amp setting or applying a wrong filename for a measurement.

It is possible to get an indication of the validity of the occlusion measurements by comparing the low-frequency occlusion measured with the hearing aid turned off and on. If the phase of the occluded ear canal sound pressure is 180 deg. out of phase with the aided ear canal sound pressure then it is possible that the aided ear canal sound pressure will be 6 dB lower than the occluded ear canal sound pressure. Therefore there is a reason to be suspicious, if the occlusion effect with the hearing aid turned on (OEhaon) is more than 6 dV lower than with the hearing aid turned off (OEhaoff). In analyses considering OEhaon subject no. 15 is excluded.

5.2.6 Missing values

Statistical data analysis is done be the means of the program "Statgraphics". The program handles missing values either pairwise or listwise. Listwise all data for the specific case are
excluded, pairwise the single case is excluded. For example if the mean age of 8 children should be found but one child does not know his age, then mean age is calculated as the sum of the 7 ages divided by 7 and not by 8. In this study pairwise exclusion is used unless other is stated.

5.3 RETEST VALIDITY OF OCCLUSION MEASUREMENTS

The reliability of the reference and the probe microphone measurements is calculated based on six subjects (b71, c60, c70, d60, e01, e91). Due to the measurement time only six retests were made. The retests were made by repeating the open ear and the closed ear measurements. The hearing aid and the probe were taken out and inserted again between each measurement as well as new impression material was put on to avoid leakage caused by the probe.

For each subject the difference between the first and second measurement was calculated and the average difference for the six subjects is shown in Figure 5.2. In order to eliminate the influence of different way of speaking, the real ear curves was normalised to the 1/3 octave smoothed reference speech spectrum for the open ear.

The average difference of the probe measurements is close to zero as would be expected. The curves are not smooth and reflections from the earmould is clearly seen at high frequencies. The standard deviation for the open ear is less than 2 dB and generally less than 4 dB below 2.000 Hz for the occluded ear except at single frequencies. These results agree well with findings of differences in insertion gain made by Hawkins (Hawkins, 1987). Six audiologist made insertion gain measurements on the same subjects and the average difference was 4.1 dB (500 Hz) and 2.2 dB (1.000 Hz).

It is expected that the reliability of the occluded ear measurement is poorer than the open ear measurements due to placement of the probe, the insertion length of the probe and the leakage between probe and earmould. The increase in the open ear retest at frequencies above 3 kHz is difficult to interpret. The retest is calculated as the first open ear measurement minus the second one. Between the first and second measurement a closed ear measurement was made and after removing the earmould the probe was inserted again in the open ear.
5.4 RETEST VALIDITY OF INSERTION GAIN MEASUREMENTS

The retest validity is also acceptable for the insertion gain measurements. Retests were made on five subjects (c60, c70, d61,e01,e91) and showed that the difference between two measurements were less than 5 dB at low frequencies. The average difference curve lies around 0 dB. The difference curves show that the insertion gain measurements hold many fluctuations which are caused by reflections (mostly at high frequencies) and by the adjustments of the speaker level. The output from the loudspeaker was adjusted according to the level measured by the reference microphone placed on the ear and especially at low frequencies and high output levels the loudspeaker tended to distort the output signal.
6 RESULTS

The results achieved in the investigation are presented here. The results are sorted into sections about data from the questionnaire, data from the reference microphone and data from the probemicrophone. Here in chapter 6 the data are analysed against several parameters, such as hearing loss and tinnitus.

The questionnaire shows that most people experience that their own voice changes, when they use their hearing aid. Annoyance from own voice is seen in relation to tinnitus, hearing loss etc. It is shown that the subjects in general soften their own voice when the ear is occluded and this is related to hearing loss and experienced annoyance. The experienced annoyances does in a certain way reflects the objective occlusion. A significant difference in the behaviour of subjects with tinnitus and subjects without tinnitus is found. The data are analysed by the mean of several statistical test methods. These methods and other statistical parameters are described in appendix H.

This chapter is split into three main subsections. Section 6.1 concerns the responses on the questionnaire, section 6.2 looks at the measured signals from the reference microphone and in section 6.3 the objective occlusion effect is analysed.

6.1 EXPERIENCED CHANGES

The title of this section is 'experienced changes' and not occlusion. The reason is that even though the questionnaire was designed to get responses on changes caused by occlusion, it is not sure that the experienced changes actually are caused by occlusion. For example if a person states that own voice sounds louder, it can be caused by occlusion or by the hearing aid amplification. However, in the way the questionnaire was designed, the probability is high that the experienced changed are caused by occlusion.

6.1.1 Overall responses to the questionnaire

The questionnaire was designed with the purpose to examine the problems that occlusion of the ear canal can create for the hearing user in the daily life. It is expected that some people have problems of acoustical, biological and mechanical origin and that the change of own voice is what most people experience. The questionnaire is reprinted in appendix D.

The questionnaire is rather comprehensive. Therefore, to begin with, the percentages of subjects who can detect an effect are found. In Figure 6.1 the responses for each yes/no question are drawn for each of the three subject groups. The annoyance rating will later be analysed separately.

The number of subjects who do experience a change was calculated based on yes/no questions. A yes/no question is either a regular yes/no question or a list of answers, see example below. If a case is crossed, it counts for an yes-answer and if it is not crossed, it counts for a no-answer.
Example:
I can hear:

(yes)  X  Own breathing
(no)  My heartbeat
(no)  My blood circulation
(yes)  X  A sound when I turn my head

It had not been possible to avoid not responded questions in all questionnaires why the percentages must be calculated on the actual number of responses for the particular question:

\[ Experienced \ changes = 100 \cdot \frac{\sum S_y}{N} \%
\]

where,

\[ S_y = \text{number of yes-answers} \]
\[ N = \text{number of responses on that particular question} \]

**Figure 6.1** - Percentages of the subjects who can detect a difference between using their hearing aid or not.

+ = group 1, • = group 2 and ○ = group 3.
Figure 6.1 can be used to describe the importance of different effects. Change in own voice and chewing is clearly dominant. About 66-100 % experience these effects. Less dominant effects, but still experienced by more than 40 %, are the sound of own footsteps, sound of breath, itch, moist and ventilation of the ear canal. 12 subjects mentioned in the questionnaire that their hearing aids sometimes suddenly turn off even though the batteries are still powerful. This is probably caused by condensed water.

In general the biological effects are not so profound as the acoustic related effects. Among the acoustic effects, change in own voice is dominant and sound generated by body actions. The feeling of being shut in is felt by 14-30 %.

The three lines follow the same pattern which tells that the three group behave alike. However, it is possible that the data might have been twisted if the sample group is not homogeneous. The sample group will be analysed in chapter 6.1.4. But to begin with, all subjects are considered as one single group.

Instead of looking at every single question, the questions are sorted into the same categories of changes as the questionnaire was based on. All these questions are 'yes/no' scaled.

- 'Own voice' (question: 7)
- 'Body in action', such as drinking, walking etc. Own voice is NOT included (question: 9, 4, 19, 22, 25)
- 'Body in rest', such as heart beats, breathing etc. i.e. no body movements (question: 8, 21)
- 'Mechanical' changes such as pressure created by the earmould (question: 10, 12, 15, 17 20, 23)
- 'Biological' changes such as itch, ear wax production etc. (question: 11, 18)
- 'Psychological' feeling of being in a barrel (question: 24)

The experience of a changed voice is not necessarily caused by occlusion. The subjects were asked to describe the changes in own words and by crossing out some prescribed descriptions. If the subject marks in the questionnaire that own voice only sounds louder, there is a chance that the change in own voice is not caused by occlusion but entirely by hearing aid amplified sound. In attempt to assure that it is in fact an occlusion effect and subject number b71, c60, c70, d31 and e91 were excluded in analyses regarding own voice. Subject c60 wrote for example that own voice sounds lighter, clearer and louder.

The case of hearing own footsteps is similar. A louder sound can be created by the amplification of the hearing aid alone and the answer is only included if they have stated that the sound of footsteps seems to come from the inside of body or head.

The barchart in Figure 6.2 shows that all types of changes do occur and that the change in own voice and sounds created by body activity are most common. A change in own voice is experienced by 73% of the hearing aid users so this problem should not be ignored.
The questionnaire gives some indications of how the change in own voice is experienced. Most subjects explained their own voice to sound louder, which is expected due to hearing aid amplification and/or occlusion. Just as many stated that it sounds like an echoing voice, and again quite many find that their voice sounds deeper and hollow, like speaking in a barrel. Some subjects described with their own words, that the change in own voice sounds like speaking into a telephone, into a microphone, in a large room, in a tube, weaker, resounding or more rough. Some of the subjects cannot recognise their own voice. This shows very well that people experience the change in own voice in many ways.

The following section will concern the biological, mechanical and acoustical changes respectively.

6.1.2 Mechanical and biological effects
The biological and mechanical effects of occluding the ear could have a relation to the degree of objective occlusion e.g. the vent size. But the questionnaire does not give a convincing answer. In Figure 6.3 are shown a linear regression between the score for the experienced biological effects and the average vent size. Obviously there is no correlation. The two most common biological annoyances are moist and itch. Neither of these two show a significant correlation with the vent size.
Nearly half of the subjects claimed that they felt too little ventilation of the ear canal. A larger vent creates more ventilation but a one way analysis of variance shows that the subjects with largest vents feel a need for more ventilation as illustrated in Figure 6.4. It must therefore be concluded that the vents in the earmoulds are not large enough to provide the wanted ventilation of the ear canal.

Subjects who have moisty ear canals feel that their ear canal is ventilated to little as shown in Figure 6.5. Some people have by nature more tendency to sweat than others and with the tight connection between moist and ventilation this human difference might explain why subjects with large vents feel need for more ventilation and some subjects with small vents do not.
6.1.3 Score for acoustical and mechanical annoyances

The annoyance is measured on a 4 point scale as this example shows:

**Example:**

**Question. 7c**

Do you experience the change in your own voice as:

- Not annoying (1)
- Slightly annoying (2)
- Annoying (3)
- Very annoying (4)

The numbers in the brackets are the score. If a person does not experience a change, the score is 0.

The annoyance scores for the categories mentioned in 6.1.1 is the sum of the scores for the respective answers. Due to missing values, the scores are averaged with the number of responses.

\[
Average\ score = \frac{\sum S_i}{N}
\]

where;

- \( S_i \) = annoyance score for answer to question number i
- \( N \) = number of responses on that particular question

Four categories are used:

- Average of experienced acoustic annoyance (question: 7c, 19b, 22a, 25a)
- Average of experienced mechanical annoyance (question: 15a, 20a)
- Chewing (question: 22a)
- Walking (question: 19a)
The answers are measured on a discrete ordinal scale and they are therefore not normally distributed. An approximation to a normal distribution would require a larger sample size than in this survey. Test for normal distributions show this. The consequence is that non-parametric statistical methods must be used.

The correlation between the annoyance score of each question is calculated by the Kendall rank method. The results are tabulated in Table 6.1.

<table>
<thead>
<tr>
<th></th>
<th>Voice 7c</th>
<th>Walk 19b</th>
<th>Chew 22a</th>
<th>Drink 25a</th>
<th>Mould 15a</th>
<th>Mould 20a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice 7c</td>
<td>1,00</td>
<td>0,37</td>
<td>0,27</td>
<td>0,10</td>
<td>0,06</td>
<td>-0,14</td>
</tr>
<tr>
<td></td>
<td>1,00</td>
<td>0,01</td>
<td>0,06</td>
<td>0,53</td>
<td>0,70</td>
<td>0,37</td>
</tr>
<tr>
<td>Walk 19b</td>
<td>1,00</td>
<td>0,08</td>
<td>-0,07</td>
<td>0,04</td>
<td>-0,05</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1,00</td>
<td>0,54</td>
<td>0,61</td>
<td>0,78</td>
<td>0,70</td>
<td></td>
</tr>
<tr>
<td>Chew 22a</td>
<td>1,00</td>
<td>0,37</td>
<td>-0,08</td>
<td>0,08</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1,00</td>
<td>0,01</td>
<td>0,56</td>
<td>0,54</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drink 25a</td>
<td>1,00</td>
<td>-0,12</td>
<td>0,42</td>
<td>-0,10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mould 15a</td>
<td>1,00</td>
<td>0,57</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mould 20a</td>
<td>1,00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.1 - Correlation between different annoyance scores. Upper number: Kendalls Rank correlation coefficient. Lower number: significance level. The light greyed fields are the significant correlations with a confidence interval of 95%. The matrix is symmetrical around the diagonal.

The correlation matrix shows that the annoyance caused by the earmould with closed mouth (15a) is strongly correlated with the speaking (20a) situation. The annoyance of change in own voice is significantly correlated with the annoyance when walking. It means that persons who are annoyed by own voice also will, with a certain probability, be annoyed by the sounds or jolts caused by footsteps. Annoyance caused by drinking and chewing is significant correlated, as must be expected, but it must be noted that only 4 persons experienced a change created by drinking. A correlation between own voice and chew and only be accepted with a significance level of 0.06, which is a bit less significant than usually required. It was expected to find a significant correlation between own voice and chewing because in both cases the sound is partly made by jaw movements. The weak correlation might be explained in the way of asking. The subjects was ask to tell how annoyed they were when they had to listen to others and eat at the same time. This is not quite the same situation as listening to own sounds made by chewing.

6.1.4 Subdivision of data

It is important that the sample is homogeneous. A homogeneous sample means that the sample group cannot be divided into two or more subgroups who behave differently. For example in this specific survey the parameter hearing loss is expected to show an influence on the experienced annoyance but it is not intended that tinnitus should split the sample into two groups.
The survey comprises many data and parameters and this section gives a view of all the parameters and the most important experienced annoyances as found in the latter section. The most important parameters is described in more details in the succeeding sections. In order to get a better view of the parameters in this survey a Kendall rank correlation analysis is performed on continuos and ordinal data. The correlation matrix is shown in Table 6.2.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Own voice,</td>
<td>1.00</td>
<td>0.27</td>
<td>0.37</td>
<td>-0.18</td>
<td>-0.10</td>
<td>-0.12</td>
<td>-0.13</td>
<td>-0.15</td>
<td>-0.08</td>
<td>-0.29</td>
<td>0.11</td>
</tr>
<tr>
<td>annoyance</td>
<td>1.00</td>
<td>0.06</td>
<td>0.01</td>
<td>0.22</td>
<td>0.46</td>
<td>0.38</td>
<td>0.30</td>
<td>0.31</td>
<td>0.56</td>
<td>0.05</td>
<td>0.42</td>
</tr>
<tr>
<td>2. Chewing,</td>
<td>1.00</td>
<td>0.08</td>
<td>0.05</td>
<td>-0.04</td>
<td>0.06</td>
<td>-0.31</td>
<td>0.04</td>
<td>0.09</td>
<td>0.00</td>
<td>0.04</td>
<td>0.00</td>
</tr>
<tr>
<td>annoyance</td>
<td>1.00</td>
<td>0.54</td>
<td>0.70</td>
<td>0.73</td>
<td>0.61</td>
<td>0.01</td>
<td>0.75</td>
<td>0.48</td>
<td>0.99</td>
<td>0.71</td>
<td></td>
</tr>
<tr>
<td>3. Walking,</td>
<td>1.00</td>
<td>0.32</td>
<td>0.38</td>
<td>0.11</td>
<td>0.74</td>
<td>0.02</td>
<td>0.24</td>
<td>0.80</td>
<td>0.98</td>
<td></td>
<td></td>
</tr>
<tr>
<td>annoyance</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. HL (250 Hz)</td>
<td>1.00</td>
<td>0.86</td>
<td>0.85</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.13</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>250,500 Hz)</td>
<td>0.00</td>
<td>0.69</td>
<td>0.46</td>
<td>0.35</td>
<td>0.30</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. HL (250,500 Hz)</td>
<td>1.00</td>
<td>-0.06</td>
<td>0.70</td>
<td>0.47</td>
<td>0.01</td>
<td>0.10</td>
<td>0.14</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. HL (2, 4 kHz)</td>
<td>1.00</td>
<td>0.07</td>
<td>0.14</td>
<td>0.04</td>
<td>-0.02</td>
<td>0.16</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Age</td>
<td>1.00</td>
<td>0.12</td>
<td>0.17</td>
<td>-0.02</td>
<td>0.16</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. First HA</td>
<td>1.00</td>
<td>0.37</td>
<td>0.31</td>
<td>0.14</td>
<td>0.85</td>
<td>0.15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. Use of new HA</td>
<td>1.00</td>
<td>0.31</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10. Use per week</td>
<td>1.00</td>
<td>0.01</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11. Vent diameter</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.2 - Correlation between different parameters and annoyance scores. Upper number: Kendalls Rank correlation coefficient. Lower number: significance level. The lightgreyed fields are the significant correlations with a confidence interval of 95%. The matrix is symmetrical around the diagonal.

Hearing loss

One of the hypotheses in this survey is that a greater low frequency hearing loss leads to less annoyance of own voice. However, the correlation analysis does not show a significant relation. There is two explanations, firstly the objective occlusion effect must also influence the experienced annoyance and secondly the sample might not be homogeneous.
**Vent size**

The objective occlusion effect is expected to depend on the vent size. Indirectly it must be expected that the annoyance should be somewhat correlated with the vent size. But this is not the case, as the hearing loss also is expected to have an influence. These considerations are discussed and analysed in more details later.

**Experience and use of hearing aids**

Another hypothesis is that a more experienced hearing user would be less annoyed than a less experienced user. According to the correlation results this is not true for own voice and chew but walking is significant related to the purchase of the first aid. Own voice is related to the time of use per week. The correlation coefficient is negative which means that longer use leads to less annoyance. However, the conclusion is not that simple as there can be various reasons why people do or do not use their hearing aid. This is discussed later. Talking about the first hearing aid and use, the correlation analysis tells that the longer time a person have used the newest hearing aid the weekly use become less. Again there can be several explanations of that which does not concern occlusion. The survey was not designed to look into this aspect and it will not be discussed into details. The purchase time of the first hearing aid is very significantly correlated to the low frequency hearing loss. There is no significant relation to the average hearing loss at 2 and 4 kHz. An explanation could be that most people with a hearing loss at high frequencies but normal hearing threshold at the speech frequencies do not feel the need of a hearing aid.

**Age**

The age seems only to influence the annoyance created by chewing, as the annoyance get less with age. It could be caused by the fact that elderly persons often eat more soft food, (because of artificial teeth), than younger people.

Four parameters, tinnitus, hearing aid fitting, hearing aid configuration and sex are measured on a nominal scale and the influence of each parameter is analysed with a Kruskal-Wallis test. This test is used to detect any significant differences between the data in each sample case, i.e. detect if there is a difference in annoyance between monaural and binaural fitting. Note, that a Kruskal-Wallis test is a non-parametric test and is here used even on the parametric data, such as vent size. This choice is made in order to get a more simple view of the data. It is statistical legal to use a non-parametric test on parametric data, but the test is not so strong as a parametric test would be. The results are shown in Table 6.3 and Table 6.4.
<table>
<thead>
<tr>
<th></th>
<th>Sex</th>
<th>Tinnitus</th>
<th>Tinnitus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Men</td>
<td>Women</td>
<td>Always</td>
</tr>
<tr>
<td>1. Own voice, annoyance</td>
<td>16,8</td>
<td>19,9</td>
<td>21,1</td>
</tr>
<tr>
<td></td>
<td>0,35</td>
<td></td>
<td>0,12</td>
</tr>
<tr>
<td>2. Chewing, annoyance</td>
<td>27,0</td>
<td>21,1</td>
<td>27,7</td>
</tr>
<tr>
<td></td>
<td>0,09</td>
<td></td>
<td>0,53</td>
</tr>
<tr>
<td>3. Walking, annoyance</td>
<td>20,3</td>
<td>25,8</td>
<td>27,7</td>
</tr>
<tr>
<td></td>
<td>0,14</td>
<td></td>
<td>0,30</td>
</tr>
<tr>
<td>4. HL (250 Hz)</td>
<td>16,1</td>
<td>24,9</td>
<td>19,9</td>
</tr>
<tr>
<td></td>
<td>0,02</td>
<td></td>
<td>0,06</td>
</tr>
<tr>
<td>5. HL (250, 500 Hz)</td>
<td>18,2</td>
<td>29,6</td>
<td>19,5</td>
</tr>
<tr>
<td></td>
<td>&lt;0,01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. HL (2, 4 kHz)</td>
<td>28,4</td>
<td>20,6</td>
<td>26,8</td>
</tr>
<tr>
<td></td>
<td>0,05</td>
<td></td>
<td>0,80</td>
</tr>
<tr>
<td>7. Age</td>
<td>19,1</td>
<td>29,9</td>
<td>22,5</td>
</tr>
<tr>
<td></td>
<td>0,01</td>
<td></td>
<td>0,68</td>
</tr>
<tr>
<td>8. First HA</td>
<td>21,2</td>
<td>25,8</td>
<td>21,8</td>
</tr>
<tr>
<td></td>
<td>0,22</td>
<td></td>
<td>0,65</td>
</tr>
<tr>
<td>9. Use of new HA</td>
<td>21,9</td>
<td>23,1</td>
<td>28,3</td>
</tr>
<tr>
<td></td>
<td>0,74</td>
<td></td>
<td>0,41</td>
</tr>
<tr>
<td>10. Use per week</td>
<td>22,8</td>
<td>21,3</td>
<td>16,8</td>
</tr>
<tr>
<td></td>
<td>0,65</td>
<td></td>
<td>0,25</td>
</tr>
<tr>
<td>11. Vent diameter</td>
<td>25,3</td>
<td>19,5</td>
<td>30,3</td>
</tr>
<tr>
<td></td>
<td>0,13</td>
<td></td>
<td>0,16</td>
</tr>
</tbody>
</table>

Table 6.3 - Comparison of parameters. Kruskal-Wallis test. Upper numbers: rank values. Lower number: significance level. The lightgreyd fields are the significance correlations with a confidence interval of 95%.

Oclusion effects. Part I.
Table 6.4 - Comparison of parameters. Kruskal-Wallis test. Upper numbers: rank values. Lower number: significance level. The lightgreyd fields are the significance correlations with a confidence interval of 95%.

**Men and women**

There is no significant difference in the annoyance experienced by men and women. However, the women have significant greater hearing loss than the men in this sample. It cannot be concluded that this is the case in general. It is more likely that the difference in hearing loss is arised because the women accidentally are significantly older then the men.

**Tinnitus**

Hickok et al. (1993) writes that people suffering from tinnitus might be more annoyed by occlusion than people who does not have tinnitus. In the present survey tinnitus is recorded as 'always', 'sometimes' and 'never'. The results in Table 6.3 show no significant difference
in the annoyance experienced by the three groups. However, the rank values, especially own voice rank, are nearly the same for persons with tinnitus always or sometimes and this rank value is clearly higher than the rank for persons without tinnitus. If the 'always' and 'sometimes' tinnitus groups are put into one single group, then it can be confirmed that persons with tinnitus are significantly more annoyed than persons who never have tinnitus. This difference is not influenced by a accident correlation between tinnitus and earmould leakage/vent. But the difference is probably influenced by the significant difference in hearing loss. Persons suffering with tinnitus have a greater hearing loss at 250 Hz than persons without tinnitus. However, the different hearing losses cannot explain why persons with tinnitus are more annoyed than persons without tinnitus. The results from the correlations analysis in Table 6.2 did not show a significant relation between hearing loss and annoyance score. So, why are tinnitus subjects more annoyed than non-tinnitus subjects? An explanation could be that the loudness of the tinnitus increases when the ear is occluded [Hickok et al., 1993a].

**Binaural/monaural fitting**

The pre-questionnaire study, see chapter 3, of occlusion showed that the experience of occluding the ear canal with an earmould is different for monaural and binaural fitting. One subject felt that monaural fitting was most comfortable due to occlusion. The results from the questionnaire survey do not show a significant difference between monaurally and binaurally fitted subjects but it seems that monaurally fitted subjects are a bit more annoyed than binaural fitted persons as the rank is higher. It can be explained by the fact that the monaurally fitted persons have more mild hearing losses at low frequencies.

**Hearing aid configuration**

The hearing aid configuration does not significantly effect the experienced annoyances. It corresponds well with the results that neither the vent size or the low frequency hearing loss. Other results given in Table 6.4 indicate that the hearing aid configuration depend on the high frequency hearing loss. The high frequency hearing loss is significantly greater for BTE fittings than for ITEC and ITE fittings. Also, there is significant difference in when the first hearing aid was purchased and the hearing aid configuration, such that the newest hearing aid users wear a ITEC aid.

The analyses presented here leads to the conclusion that annoyance is in some degree related to the low-frequency hearing loss and tinnitus is the only parameter that significantly divides the sample into two groups. In the further analyses of data, the sample is therefore grouped into 'tinnitus' subjects and 'non-tinnitus' subjects.

**6.1.5 Use of hearing aid**

It is possible that some users experience occlusion to such a degree that they never or very seldom use their hearing aids and that binaurally fitted persons use only one hearing aid.

There can be many reasons why people do not use their hearing aid. Some binaurally fitted subjects explained that they often use only one aid because it is annoying to wear both aids. Others feel that they only need one aid.
The reason for not using the hearing aids seems to be caused by other factors than occlusion, especially for elderly people who tends to stay at home most of the time. However, one of the subjects actually said that she never uses her hearing aid because the sound her of own voice troubled her. A view of the general uses are printed in Table 6.5.

<table>
<thead>
<tr>
<th>Use per week</th>
<th>No. of persons</th>
<th>Situation of use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Never</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>&lt; 1 day</td>
<td>4</td>
<td>50% use HA in conversations and/or TV/radio</td>
</tr>
<tr>
<td>1-3 days</td>
<td>6</td>
<td>80% use HA for talkshows; 50% for conversation and TV/radio and large dinner parties.</td>
</tr>
<tr>
<td>4-6 days</td>
<td>6</td>
<td>All situations, mostly in conversation and TV/radio and less often at large dinner parties.</td>
</tr>
<tr>
<td>Every day</td>
<td>27</td>
<td>All situations, less often at large dinner parties.</td>
</tr>
</tbody>
</table>

Table 6.5 - Use per week and situations where the aid is used. 4 persons did not answer.

In agreement with these statements a statistical correlation analysis did not show any relations between the amount of hearing aid use and the experienced annoyance regarding to mechanical effects, biological effects or body sounds. But own voice seems to have some influence. The annoyance caused by own voice and the use per week is significant correlated as shown in Table 6.2. It indicates that the more annoyed the subjects are the less they use their hearing aid.

On an hourly basis there seems to be no relation between the use of hearing aid and annoyance by own voice for monaural fittings. Most of the binaurally fitted users are using both hearing aids most of the time. Out of a total of 26 persons, 5 used only one hearing aid more often than two, 3 used one or two for an equal amount of time and 18 used both hearing aids more than the one. Here it is assumed that if a subjects did not answer the question about how long time they used only one hearing aid, it was because they always used both hearing aids.

6.1.6 Experience of use and occlusion

The human body adapts well to some conditional changes. It is therefore of interest to see if hearing users adapt to the occlusion effect, e.g. if experienced users are more annoyed than inexperienced users.

In this survey experience is measured based on for how long time the subject have been using hearing aid as well as the weekly use (question: 4, 26 and 27). The experience is scored regarding to when the subjects got a hearing aid for the first time and how long the present hearing aid has been used. Kendalls correlation coefficient is tabled in Table 6.6 14for tinnitus and non-tinnitus subjects. Non-tinnitus subjects do not adapt to the occlusion effect. This is seen by small correlation coefficients.

Tinnitus subjects show a significant correlation between annoyance of own voice and experience of hearing aid use. It is important to say, that this does not necessarily mean that tinnitus subjects get used to the change in own voice. The explanation is rather that the subjects get more used to the combination of change in own voice and tinnitus sound.
6.1.7 Experienced annoyances versus hearing loss

It must be expected that mild hearing impaired people are more annoyed than more severe hearing impaired, see section 3.1.1 and 3.1., providing the objective occlusion effect is the same.

The results in the correlation matrix, Table 6.2, does not show a significant correlation between annoyance and hearing loss. However, when the subjects are divided into a group of tinnitus and non-tinnitus subjects, it is seen that there is a moderate relation for non-tinnitus subjects, see Figure 6.3.

![Linear regression between hearing loss and annoyance of own voice.](image)

**Figure 6.3** - Linear regression between hearing loss and annoyance of own voice. Left: non-tinnitus subjects, $\alpha = 0.01$, $\rho = 0.63$. Right: tinnitus subjects. $a >> 0.05$.

This is again an evidence that tinnitus plays an important role. These results indicate that the effect of tinnitus is stronger than the effect of hearing loss.
6.2 SPEECH LEVEL

The experienced changes caused by occlusion was analysed in the latter section. The data presentation will now concern the objective measurements and first the speech level is considered.

The speech level was measured with the reference microphone placed in front of the subject in order to detect changes in the voice due to occlusion of the ear. It is expected that one tends to speak softer when the ear canal is occluded.

6.2.1 Change in speech level

The changes are measured as the average sound pressure ($200 < f < 2,000$ Hz) of the difference spectra between occluded ear and open ear. The spectra are smoothed with a running 1/3 octave band filter. The level of the average sound pressure is calculated by:

$$L_{\text{average}} = 10 \log \left( \frac{\sum (\Delta P_i)^2}{N} \right); \quad \Delta P_i = \left( P_{\text{occ}}, P_{\text{open},i} \right)_{\text{smoothed}}$$

where;

$P_{\text{occ},i}$ = sound power of occluded ear, frequency component number $i$

$P_{\text{open},i}$ = sound power of open ear, frequency component number $i$

$N$ = total number of frequency components (200 - 2,000 Hz)

If the speech level is the same with open and occluded ear, $L_{\text{average}} = 0$. The frequency histograms are given in Figure 6.4. A chi-square test accepts the data as normally distributed. The speech level difference spectra for each subject is given in appendix F2. A one-sample test for normal distribution according to subjects shows that the mean is not equal to zero, see Table 6.7.

![Figure 6.4 - Frequency histograms for the sample of the difference in speech level.](image-url)
<table>
<thead>
<tr>
<th>Difference spectrum</th>
<th>Hypothesis, H0</th>
<th>Sign. level</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAoff - open ear</td>
<td>$\mu = 0$ dB</td>
<td>$\alpha &lt;&lt; 0.05$</td>
<td>H0 is rejected</td>
</tr>
<tr>
<td>HAoff - open ear</td>
<td>$\mu = -2$ dB</td>
<td>$\alpha = 0.35$</td>
<td>H0 is accepted</td>
</tr>
<tr>
<td>HAon - open ear</td>
<td>$\mu = 0$ dB</td>
<td>$\alpha &lt;&lt; 0.05$</td>
<td>H0 is rejected</td>
</tr>
<tr>
<td>HAon - open ear</td>
<td>$\mu = -3$ dB</td>
<td>$\alpha = 0.99$</td>
<td>H0 is accepted</td>
</tr>
</tbody>
</table>

Table 6.7 - One-sample statistical analysis of the difference in speech level.

These results are of course based on data achieved in a test situation, but the author believes that the data still reflect the real situation pretty well. The subjects did not have any training, therefore they ought to react spontaneous to the test conditions. The situation where the subjects change between open ear and hearing aid turned on is in the daily life a known situation, and the subject will therefore react as usual. Most subjects changed their voice so much that the supervisors could easily hear the difference.

6.2.2 Speech level and experienced annoyance
The change in speech level is affected by the perceived loudness of own voice. Therefore it is likely to believe that there is a relation between the change in speech level and experienced annoyance from own voice.

In this situation there is again a distinct difference in the behaviour of non-tinnitus and tinnitus subjects. Tinnitus subjects do not statistically soften their voice in relation to the experienced annoyance, but non-tinnitus subjects do. In addition it must be mentioned that non-tinnitus and tinnitus subjects change their voices in the same way, which is confirmed by a two-sample analysis.

Non-tinnitus subjects change of speech level and experienced annoyance of own voice is highly correlated. The test is made for the change in speech level when the hearing aid is turned on to the desired MCL. It is interesting to observe that the more softening in voice corresponds to less annoyance, see Figure 6.5.
When the speech level is softer, the objective occlusion effect will be smaller. It leads to the thought that the subjects speak softer because they try to compensate for the objective occlusion effect. If they succeed they feel less annoyed. The hearing loss will of course have an influence. Speech level change is significant negative correlated with the low-frequency hearing loss. It means that a milder hearing loss corresponds to a more soft speech level. So, the better a person can hear, the larger chance is there to detect a change in own voice and therefore this person will soften own voice in order to reduce the experienced occlusion effect and be less annoyed.

On the other hand, the subject might soften own voice because own voice is easier to hear due to hearing aid amplification and/or occlusion. If this is the case, then the subject should talk louder when not using the hearing aid in order to hear own voice better, and when the hearing aid is used, the subject can speak nearly at normal level. However, many subjects do not only soften own voice but they also cut of the endings of words, which makes it more difficult to understand, what they are saying.

This issue will not be addressed more in this report, but it shall be pointed out, that if the hearing aid user speaks more normal with the hearing aid on and at the same time get less annoyed by occlusion, then it is good. If the hearing aid user on the other hand soften own voice in order to compensate for the occlusion effect and also speaks less clear, then it adds an aspect to the problem with occlusion and the hearing aid fitting.
6.3 OBJECTIVE OCCLUSION EFFECT

This section analyses the objective measurements. The objective occlusion effects are compared to the hearing loss and the experienced occlusion annoyances from own voice.

6.3.1 Occlusion effects

The difference in closed ear and open ear sound pressure level is called the occlusion effect. When the hearing aid is turned off (OEHAs), the level difference is caused by occlusion but when the hearing aid is turned on (OEHAon), the level difference is caused partly by occlusion and partly by electrical amplification. In order to keep the terminology simple the term occlusion effect will be used anyway. The occlusion effect is calculated by:

\[ OE = 10 \log \left( \frac{P_{\text{occluded ear}}}{P_{\text{open ear}}} \right) \text{ dB} \]

where;
OE = occlusion effect
P = sound pressure
and,
OEHAs = OE with the hearing aid turned off
OEHAon = OE with the hearing aid turned on

The objective occlusion effect varies a lot from person to person with same vents but a general trend is found when the hearing aid is not turned on. An example of a typical curve of the occlusion effect is shown in Figure 6.6.

The curve for OEHAs increases from about 0 dB up to a maximum of 21 dB at 250 Hz. The occlusion effect is reduced at low frequencies because of the vent. If this person had a tight earmould without vent, the occlusion effect would probably have been 20 dB at 100 Hz too. A maximum occurs typically between 200-500 Hz when there is some kind of leakage in the earmould. In this example the occlusion effect decreases from 350 Hz to reach 0 dB at nearly 2 kHz. The occlusion effect decreases normally to 0 dB at 1-2 kHz.

The difference between occluded and open ear continues to decrease until about 3-4 kHz. There is a dip between 2-4 kHz because the open ear resonance disappears when the ear is occluded. At higher frequencies the curve rise again because the open ear response decreases and the probe microphone.

When people in general speaks about the occlusion effect, they mean the amplification of own voice at lower frequencies e.g. below 2 kHz. But the missing ear canal resonance is in fact also an effect created by occlusion of the ear. On the other hand it will not be correct to address the difference at even higher frequencies to the occlusion effect. The differences here are not caused only by occluding the ear canal but by reflections and probe placement.
The dotted line in Figure 6.6 shows the occlusion effect when the hearing is turned on. At frequencies below 1 kHz the response is exactly the same as when the hearing aid is turned off. It shows that the occlusion effect is larger than the hearing aid gain. The hearing aid amplification is dominant at higher frequencies.

6.3.2 Vent size versus objective occlusion

A non-vented and tight fitted earmould has a high acoustic impedance seen from the inside of the ear canal. This impedance can be reduced at low frequencies by drilling a vent into the earmould.

A very simple vent could have the form of a uniform tube. The transmission loss through a uniform tube is proportional with the reciprocal of the square of the vent radius, see appendix H:

\[
\text{Transmission loss [dB]} \propto \log \left( \frac{L[m]}{r^2[m^2]} \cdot 1m \right)
\]

where;
L = length of tube
r = radius of tube = \( \frac{1}{2} \) * diameter
1 m is only a mathematical help parameter in order to fit the units
A more detailed explanation is given in appendix H.

For the sake of convenience the reciprocal of the transmission loss (transmission gain) will be plotted against the occlusion effect, see Figure 6.7.

In practice, a vent is not a uniform tube, it is more hornshaped and it has most often a bend. The individual shape can vary and it is not possible to say exactly what kind of a horn shape the individual vent has. In attempt to keep this analysis as simple as possible, the transmission loss formula for a uniform tube will be used with the average of the inner and outer vent diameter. One has to keep in mind that the purpose here is not to estimate the
exact transmission loss, but it is only to examine the relation between vent size and occlusion effect.

The diameter of the tube is calculated as the average of the measured diameters in both ends of the actual vent. This diameter is used in the formula for transmission gain is plotted against the objective occlusion effect, hearing aid turned off, normalised. Figure 6.7 illustrates well that there is no relation between objective occlusion effect and vent size. A correlation analysis shows no significant relation between the actual vent size and occlusion effect taken as the overall level at 100-200 Hz or 200-800 Hz or as the average value in the three audiometric bands (125-250 Hz, 250-500 Hz and 500-1,000 Hz). These analyses are done with the average of the inner and outer diameter. In attempt to make it maybe a bit more correct is to calculate the vent diameter that gives a conical horn and a uniform tube the same volume, when the length is the same. Though, it does not show a more significant result. The reason is probably that it is not possible to define an exact shape of the individual vent, which is neither a uniform tube or a conical horn.

![Figure 6.7 - Occlusion effect, hearing aid off versus vent size. The occlusion effect is measured as the average level for 125-250 Hz and normalised. The non-filled square is subject f51 and the non-filled circle is subject b00.](image)

The absolute size of the occlusion effect is not correlated to the vent size, but the scattering of occlusion effect is. It looks like subject number b00 and f51 are outsiders. The vent of subject f51 is a split and the size was only estimated, hence the vent might be a lot smaller than estimated. There can be found no indication in the data why subject b00 has such a large occlusion effect. If subject b10 and f51 are excluded the scattering of occlusion effect becomes more clear. Small vents cause no occlusion or maximal occlusion. As the vent size gets larger the scattering in occlusion effect becomes smaller. Very large vents cause only minimal occlusion effect. This will be discussed later in chapter 7.

6.3.3 Sensation level
One of the ideas in the survey was to find a coupling between experienced and measured occlusion effect. A basic criteria to experience occlusion must be that the occluded sound pressure level lies above the hearing threshold. The sound pressure level relative to the
hearing threshold is called the sensation level, so the sensation level must be positive in order to experience the sound.

When the sound pressure gets large enough the sound might become uncomfortable, therefore a hypothesis could be that a higher sensation level leads to more annoyance of own voice, as long as the sensation has reached a certain level. The sensation level versus the annoyance of own voice is shown in **Figure 6.8**. The real ear level is not normalised to the open ear situation because the author believes that if the subjects change their voice level in the test situation, they will also do it in the real life situation. The sensation level is very significantly correlated to annoyance for non-tinnitus subjects. The tinnitus subjects do not show a correlation.

![Graph showing sensation level versus annoyance of own voice for non-tinnitus and tinnitus subjects](image)

**Figure 6.8** - Sensation level versus annoyance of own voice. Sensation level = HAon level, not normalised (average 125-250 Hz) - hearing threshold (250 Hz). Non-tinnitus: α << 0.05, ρ = 0.78. Tinnitus: α = 0.44, ρ = 0.21.

### 6.3.4 Objective occlusion versus experienced annoyance and hearing loss.

The experience of the absolute sound level is measured with the sensation level, and as just shown there is a relation between the sensation level and the experience of change in own voice.

The occlusion effect is expressed as a change in sound pressure level, this complicates the matter because of the phenomena called recruitment. A normal hearing person might experience a tone at 70 dB SPL twice as loud as a tone at 80 dB SPL, whereas a hearing impaired person might experience the 70 dB SPL 8 times louder than 80 dB SPL. The growth in perceived loudness depends upon the hearing loss and must be measured for the individual subject. Here, it is only a remark and it will not be analysed into details. Instead, the objective occlusion and hearing loss is compared to the experienced annoyances in the plots in **Figure 6.9**.
The case of non-tinnitus subjects corresponds well with the hypothesis drawn in chapter 3. It is clear that subjects with a small hearing losses and large occlusion effects become annoyed and that subjects with a large hearing losses and minor occlusion effects do not experience a change in own voice. The solid line shows the limit where OEH AoN, not normalised = target according to POGO II, (HL/2-10dB). If an uncertainty of 5 dB is expected then it is found that within the range 5 dB from the solid line, there is 6 persons who does not experience occlusion and 4 persons who does. This corresponds well with the hypothesis that if the occlusion effect equals the target then there will be a 50% chance to experience occlusion.

The tinnitus subjects shows a less clear picture, but it is still true that large occlusion effects and small hearing loss leads to annoyance.

Note that the occlusion effect can be negative because of a large vent and/or because the occlusion effect is not normalised to the open ear situation.

One way to perform a statistical test on these data is to weight the objective occlusion effect with the hearing loss by simply subtract the hearing loss from OEH AoN. This gives only a mathematical value and has no physical meaning. But it will be done anyway just to a statistical relation.
It is only possible to find a significant correlation for non-tinnitus subjects as shown in Table 6.8 and Figure 6.10. Table 6.8 tells also that the not normalised OEHAn gives a more significant correlation to annoyance than the normalised OEHAn. In both cases the hearing loss at 250 Hz seems to be the best measure as the significance level is smallest and the correlation coefficient is largest. The regression line for OEHAn, not normalised - HL at 250 Hz versus annoyance is pictured in Figure 6.10. The plot for tinnitus subjects is interesting as it indicates why the regression is not significant. Very annoyed people seem to react out of trend with the rest. An obvious reason could be a bad fitted hearing aid or distortion but neither of these two possibilities seems to explain the profound annoyances. There is no large distortions and the aids have been fitted quite well according to POGO II. There seem to be no other explanation than these subjects are just more sensitive to their own voice than the other subjects are but they are not in general more sensitive than other tinnitus subjects.

<table>
<thead>
<tr>
<th>(OE - HL) versus annoyance</th>
<th>Non-tinnitus</th>
<th>Tinnitus</th>
</tr>
</thead>
<tbody>
<tr>
<td>OEHAn, not normalised (125-250 Hz) - HL (250 Hz)</td>
<td>0.66</td>
<td>0.01</td>
</tr>
<tr>
<td>OEHAn, not normalised (250-500 Hz) - HL (250 and 500 Hz)</td>
<td>0.55</td>
<td>0.04</td>
</tr>
<tr>
<td>OEHAn, normalised (125-250 Hz) - HL (250 Hz)</td>
<td>0.60</td>
<td>0.02</td>
</tr>
<tr>
<td>OEHAn, normalised (250-500 Hz) - HL (250 and 500 Hz)</td>
<td>0.47</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Table 6.8 - OEHAn subtracted with the hearing loss. Linear regression analysis. OEHAn is calculated as the average value between 125-250 and 250-500 Hz.

Figure 6.10 - OEHAn subtracted with the hearing loss at 250 Hz. Linear regression analysis. Left: non-tinnitus subjects. Right: tinnitus subjects.
When the normalised occlusion effects are used as reference as shown in Figure 6.11 the picture change a bit. Here, some of the 'no changes in own voice' points lie above the target value. It means that these subjects lower their own voice in the occluded situation and according to the results in section 6.2 a lower voice leads to less annoyance. Therefore it might be possible that if the subjects did not lower their voices these subjects would experience a change in own voice.

![Plot of objective occlusion hearing aid on, normalised versus hearing loss compared to own voice annoyance score.](image)

**Figure 6.11** - Plot of objective occlusion hearing aid on, normalised versus hearing loss compared to own voice annoyance score.

### 6.3.5 Objective occlusion versus hearing aid amplification

The experience of occlusion depend on the ratio between the hearing aid amplified sound and the occluded sound level. If the sound pressure level in the open ear canal equals the sound pressure level at the hearing aid microphone, then the experience of occlusion depend on the ratio of the hearing aid insertion gain and the occlusion effect.

A very simple reflection is to say that the insertion gain must at least equal the occlusion effect, if there shall be a chance that occlusion is not experienced. It is more complicated to ensure that the experience of occlusion is suppressed.

If the two signals were not correlated, a common used rule is that the desired signal should be 10 dB greater than the noise, meaning that the insertion gain shall be 10 dB higher than
the occlusion effect. The real situation is that the two signals are correlated and the worst case situation occurs when the hearing aid amplified sound is in phase with the occluded sound and thereby causes a constructive interference. The total sound pressure is then the sum of the two sound pressure sources. If the occluded sound creates 80 dB SPL and the amplified sound level is 98 dB SPL, i.e. 18 dB greater, then the total sound pressure is 99 dB meaning that the amplified sound dominates the sound perception. An example where OEHAn is greater than OEHAd is shown in Figure 6.12.

![Occlusion effect, speech, No. 841](image)

**Figure 6.12** - Occlusion effect with hearing aid turned on and off, normalised.

One way to look at OEHAn-OEHAd is to compare the average difference at 250-500 Hz, where the occlusion effect normally has a maximum, with the experienced change in own voice. The normalised occlusion effects are plotted in Figure 6.13 and the not normalised occlusion effects are plotted in Figure 6.14.

It is clear that even if OEHAn is greater than OEHAd, a change in own voice is experienced both in the normalised and not normalised case. The results is the same for tinnitus and non-tinnitus subjects, so in Figure 6.13 and Figure 6.14 all subjects are considered. It should be mentioned that subjects who says that own voice sounds only louder or higher in frequency are not present in these figures. For example the subjects who has OEHAn-OEHAd nearly 15 dB claims that own voice sounds hollow and that is a very typical description of occlusion.
Instead of looking at difference in occlusion effects, the insertion gain can be compared with OEHAoff, as done in Figure 6.15. It leads to the same observations.
The problem can also be addressed the other way around by looking at the subjects who claim not to experience occlusion, but it does not lead to a clearer conclusion. It turns out that for half of the subjects who do not experience occlusion, the OEHAon equals OEHAnoff, for both normalised and not normalised occlusion effect. Of course only the subjects that actually have an objective occlusion are considered.

The consequence of these analyses is that the available data cannot be used to conclude how large the hearing aid amplification should be to prevent the experience of occlusion from own voice.
7 DISCUSSION

The latter chapter analyses the survey data in proportion to several parameters. Here the results will be presented and discussed in another order. Experienced and measured occlusion effect are compared with other investigations and the individual variations are discussed. The importance of the insertion gain is analysed. The influence of tinnitus on the subjects experienced occlusion is reviewed.

7.1 EXPERIENCED OCCLUSION

The responses on the questionnaire shows clearly that occlusion is a problem for the hearing aid user in the daily life. Change in own voice is far the most common occlusion experience and it seems to be a problem for a lot more people than former surveys estimate as written in Table 7.1.

The survey made by Biering-Sørensen et al. (1994) included 21 subjects with hearing losses 10-55 dB HL, average 30 dB HL at 250-500 Hz. It is comparable to this survey where the average is 34 dB HL at the same frequencies and the ranges 0-58 dB HL. The vent sizes are not the same in the two surveys, but this survey includes larger vents than the Biering-Sørensen survey, which in fact emphasises that the experience of own voice is more profound. The table also shows the percentages of subjects who have difficulties hearing environmental sounds while they chew. This survey shows a little less percentage than the results by Biering-Sørensen et al. (1994).

The non-acoustic experience of occlusion is often related to moisty ears and a feeling of being in a barrel. MacKenzie et al. (1989) investigated this for 3 vent sizes for 106 persons with hearing losses 30-60 dB HL, average of 0.5, 1, 2 and 4 kHz.

In the survey described in this report the average vent diameter is 2 mm and the hearing losses range from 22.5-66 dB HL, average of 0.5, 1, 2 and 4 kHz and the number of subjects who feels blocked up correspond well with MacKenzie et al.’s results.

<table>
<thead>
<tr>
<th>Experience of occlusion</th>
<th>Biering-Sørensen et al. (1994)</th>
<th>This survey</th>
</tr>
</thead>
<tbody>
<tr>
<td>Own voice</td>
<td>57%</td>
<td>73%</td>
</tr>
<tr>
<td>Chewing</td>
<td>48%</td>
<td>40%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MacKenzie et al. (1989)</th>
<th>This survey</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block 0.8 mm vent</td>
<td>22%</td>
</tr>
<tr>
<td>No vent</td>
<td>35%</td>
</tr>
<tr>
<td>Blocked up</td>
<td>38%</td>
</tr>
<tr>
<td>Moist</td>
<td>40%</td>
</tr>
<tr>
<td>Itch</td>
<td>42%</td>
</tr>
</tbody>
</table>

Table 7.1 - Experience of occlusion. Results from different surveys.

MacKenzie et al. (1989) report that among first time users the number of people feeling generally uncomfortable with the earmould fell from 20% to 10% over the first 6 weeks.

Oclusion effects. Part I.
Thus, some people get used to their earmoulds. But is does not mean that the users will get use to the acoustical changes when the ear is plugged. In fact, the analysis reported in chapter 6 shows that the subjects have not adapted to the occlusion effect. Despite that the sample group in the present survey contained fairly new hearing users (fitted within 3 months and very experienced users (more than 5 years) 73% still sense a change in own voice.

Hearing aid users who are annoyed by the change in own voice tends to just wear the hearing aid less than people who are not that annoyed. Of course many other factors plays a role here. Some people do not use their hearing aid much because they spent a most of their time alone and others use their hearing aid more than they might like because their job requires it. For example, one of the subjects who is a teacher, is annoyed by his own voice and he told that he would prefer to take the hearing aid off while he is talking, but he keeps it on, because otherwise he would not be able to understand what the pupils say.

7.2 TINNITUS

The analyses have shown that while non-tinnitus subjects act rather predictable, the tinnitus subjects do not. As a short reminder, it was found that for non-tinnitus subjects the annoyance from own voice is related to the hearing loss and that the difference in speech level is related to hearing loss and annoyance. When taking account for the hearing loss, the objective occlusion effect is correlated with annoyance. Whereas for tinnitus subjects there is no such relations. Consequently, it makes only sense to try to predict an experience of occlusion for persons who do not suffer with tinnitus.

The results also show that tinnitus subjects are more annoyed than subjects who does not have tinnitus and that tinnitus subjects in some way seem to get used to the occlusion effect.

The question is now, why is it so. Theoretically it could be caused by a coincidence between several factors. The most obviously reason could be a bad fitted hearing aid or distortion. but neither of these two possibilities leads to a conclusion. There is no large distortions and the aids have been fitted quite well according to POGO II. There seem to be no other explanation than these subjects are just more sensitive to their own voice. As already reported in 3.1.5, Hickok et al. (1993a) suggest that tinnitus might have a masking effect on own voice and that the sound of tinnitus might increase when the ear canal is occluded. Tinnitus subjects might concentrate more on the buzzing tinnitus sound than on the actual change in own voice.

Special care must be taken when fitting a hearing aid to a person suffering from tinnitus. The annoyance caused by occlusion seems very unpredictable so it is questionable how well a standard fitting estimate works for a tinnitus patient. There is reason to believe that tinnitus patients will prefer a larger vent than patients without tinnitus because they in general are more annoyed. This is especially important to remember for patients that does not have tinnitus every day, implying that they might not have tinnitus the day the hearing aid is being fitted. These results gives a reason to go into a more detailed investigation about tinnitus and the effect of different types of tinnitus.
7.3 MEASUREMENT METHOD

It may be necessary to perform an occlusion test when a new hearing aid is fitted. The most straightforward way is to ask the patient if he/she thinks that own voice sounds different. This is a good method if the patient is capable of judging the occlusion in the fitting procedure. But the patient might soften or raise own voice without being aware of it, so in this situation the subjective sense of occlusion does not reflect the actual occlusion effect. In chapter 6.2.1 it was concluded that the subjects on an average soften their voices with 3 dB when they use their hearing aids.

It is of course not acceptable that the hearing aid user tries to compensate for the change in own voice even if the user is not instantly annoyed by occlusion. The hearing aid should therefore be fitted in a way so the user does not feel that he/she has to speak softer while using the hearing aid. It means that the objective occlusion effect must be normalised so the speech level is the same for the open ear and occluded ear measurement.

The disadvantage is that such a measurement cannot be performed with a standard insertion gain equipment where only the probe microphone response can be displayed. It is necessary to access the output of a reference microphone in order to compare the speech level in the open ear and occluded ear situation.

The performance of the available equipment will limit the choice of measurement technique if the equipment for example does not support the necessary signal processing. However, once again it shall be pointed out that the pilot study showed that the most reliable way is to record continuous speech. The second best solution is to use vowels but it demands a better instruction to the patient and it might be necessary to repeat the measurement a couple of times. A well performed vowel measurement will take just as long time as continuous speech, it might even take longer if the patient has difficulties reproducing the same pitch.

Another experiment, that took place after the ending of this pilot study, looked into the use of different stimuli for occlusion measurements, [Thorup, 1996]. The experiments involved 18 persons fitted with standard earmoulds and same vent dimensions. The occlusion effect was measured with speech, different vowels and crunchy chewing. The experiment gave the same conclusion as the pilot study. Speech is the best stimulus because it is difficult to repeat the same vowel twice and crunchy chewing varies to much to be consistent.

7.4 INDIVIDUAL VARIATIONS

The objective occlusion effect varies between subjects even though the same design of earmould is used. The occlusion effect can in fact vary up to 30 dB as illustrated in Figure 7.1. The figure shows the maximum and minimum as well as the average and standard deviations for 10 subjects [May & Dillon, 1992].
The same investigation included several earmould designs. Another experiment performed at the Technical University of Denmark also shows these large deviations. Among 16 subjects fitted with a non-vented standard earmould the smallest occlusion effect was about 5 dB and the largest was about 30 dB at low frequencies [Thorup, 1996].

In the present survey the largest detected occlusion effect reached also 30 dB with the hearing aid turned off. One of the largest occlusion effects are shown in Figure 7.2.

Due to large variations, an average value for the occlusion effect for a certain earmould must be taken with care. Because of large individual differences, a person might have an occlusion effect 10-20 dB larger or smaller than the average.

It must be concluded that other physical factors than the vent size decide the objective occlusion effect. Individual factors could be: the size of the occluded ear canal volume, jaw
movements that create leakage between the earmould and the ear canal wall or maybe the amplitude of the body conducted sound varies from person to person. The appearance of individual differences are created does certainly need more detailed investigation.

7.5 VENT DESIGN

The occlusion effect can vary much for people fitted with the same earmould design, therefore a strong correlation between vent or leakage and occlusion effect cannot be expected when looking at more subjects. Consequently, it was not possible to show a significant relationship in this survey. However, May & Dillon, (1992) found a right trend as illustrated in Figure 7.3. Other investigators have also proven a trend. For example MacKenzie et al. (1989) as shown in Table 7.1. Looking at non-acoustic occlusion effects, they conclude that the vent size does not matter. That corresponds with the findings in the present survey. But again the occlusion effect varies nearly 30 dB between persons fitted with the same earmould design. In contrary the scattering of occlusion effect is related to the vent size and here the results given in chapter 6 shows the same pattern as the results in Figure 7.3. The physical explanation is that if the vent is large enough, the occlusion effect can only reach a certain level. For example, if the short open vent cannot create an occlusion effect larger than 10 dB, then the scattering between subjects will be less than if it was possible to create an occlusion effect of 30 dB.

![Figure 7.3 - Occlusion effect versus earmould vent. Occlusion effect = maximum boost for 200-800 Hz. [May & Dillon, 1992.](image)

It must be concluded that it is indeed impossible to predict the individual occlusion effect based only on the vent size. This is important to remember when fitting a hearing aid because several hearing companies provide guidelines to choose the right vent size on order to avoid occlusion. When using these guidelines one has to remember that the individual occlusion effect might differ up to ± 15 dB from the prediction.
7.6 OBJECTIVE AND EXPERIENCED OCCLUSION

The investigation made by May and Dillon (1992) involved only normal hearing persons. They found a significant relation between the measured occlusion and the rating of annoyance but the variance is large as seen in Figure 7.4.

Figure 7.4 - Rating of experienced change in own voice versus objective occlusion effect, maximum boost for 200-800 Hz. 10 subjects. [May & Dillon, 1992].

Figure 7.5 - Rating of experienced change in own voice versus OEHAnon, normalised, maximum boost for 200-800 Hz. The regression line is not significant.

Figure 7.4 shows that the experience of normal reproduction of own voice can be perceived for -5 to 17 dB occlusion effect and that 3-33 dB occlusion effect can take the score 'acceptable'. In the present user survey the range of not experience occlusion is 26 dB
(11-37 dB) and to be slightly annoyed lie between 16-39 dB as seen in Figure 7.5. The variances occurring the user survey are acceptable compared to the May&Dillon's results.

7.7 HEARING LOSS AND INSERTION GAIN

In section 6.3.4 OEHAon and experienced annoyance was compared to the theoretical target gain (POGO II). In some cases OEHAon was more than the target and in a few cases lower. OEHAon might be higher because the target gain is not fulfilled as shown in Figure 7.6. At low frequencies it occurs that the actual insertion gain is 15 dB lower than the target gain. The insertion gain corresponds better to the target at higher frequencies.

![Graphs showing insertion gain vs. HL](image)

Figure 7.6 - Insertion gain and target (POGO II) for all subjects at three frequency ranges.

Three things explain this, firstly it is difficult to fit the hearing aid so that both the low-frequency and the high-frequency amplifications equal the target. A vent acts as a low-pass filter and a larger vent makes it therefore more difficult to obtain the required
amplification. A large vent could have been chosen in order to avoid occlusion. Secondly the volume control was set by the subject to the most comfortable level in the current situation which might not be exactly the same setting as when the fitting procedure took place or thirdly the subjects prefer a lower amplification than the fitting rule predicts as optimal.

7.8 OCCLUSION EFFECT AND CORRECT AMPLIFICATION
A consequence of an insertion gain, that is too low according to the fitting rules might affect a larger objective occlusion effect than necessary.

Figure 7.7 shows the difference in insertion gain and occlusion effect compared to the difference in target gain and occlusion effect. The solid line marks the values where the insertion gain equals the target gain. If a subject lies in the right lower square, where the insertion gain is lower than OEHAnoff and the target is larger than OEHAnoff, then the experienced annoyance might be prevented by fitting the hearing aid more correctly. It is most likely to believe that it will be solution for the subjects who experience a change but are not annoyed. This is of course only a consideration and should be tested.

If a subject lies in the left lower square where both the insertion gain and target are lower than OEHAnoff, then experienced occlusion should not be expected. Consequently the experience of occlusion will not disappear by adjusting the insertion gain to the correct target gain. Even when the insertion gain equals the target gain the subjects are still slightly annoyed. A correct insertion gain might prevent the experience of occlusion but in most cases this will still not be enough and another solution must be used.

![Figure 7.7 - Comparison of occlusion effect, hearing aid off, normalised, insertion gain and target and the corresponding annoyance scores. All subjects are included.](image-url)
8 CONCLUSION

This investigation has by mean of a questionnaire and laboratory measurements shown that most hearing aid users experience occlusion. The experience of occlusion occurs in several ways. It can be related to acoustical, mechanical or biological annoyances. The experienced annoyance was found to be related to some objectively measurable parameters. The following list summarises the most important findings:

* Change in the perception of own voice is the far most dominant nuisance which 73% of the users experience. Subjects suffering from tinnitus are more annoyed by own voice than subjects without tinnitus.

* Experienced hearing aid users do not accept occlusion more than non-experienced users, which means that the users do not adapt to occlusion. There is a trend towards that tinnitus subjects become less annoyed the more they use their hearing aid. It was found that the weekly use of hearing aids is significant correlated to the annoyance of the change in own voice.

* It was found that for subjects without tinnitus, the annoyance of change in own voice is significant correlated with the sensation level (sound pressure level minus hearing loss) when the hearing aid is turned on, not normalised. Also, the difference in sound pressure level between the occluded and the open ear situation with the hearing turned on (OEHAn, not normalised) is significant correlated to the annoyance of own voice, when the hearing loss is taken into account. Such significant correlations could not be found for subjects suffering from tinnitus.

* The latter conclusions are made upon the occlusion effect not normalised with the reference speech level. Most hearing aid users soften their own voice 3 dB when they use their hearing aid and for subjects without tinnitus it is significant that a more soft voice corresponds to less annoyance.

* When the occlusion effect with the hearing aid turned on is 5 dB larger than the theoretical target gain (POGO II), the subjects experience a change in own voice. When the occlusion effect equals the target gain there is about 50% chance to experience occlusion.

The survey has provided some data that leads to questions which should be further investigated:

* The objective occlusion effect is not significantly correlated with the absolute vent size, but when the vent becomes larger, the inter-subjective variations should become smaller. Other investigations have shown that the objective occlusion effect varies up to 30 dB between subjects, even with the same vent. There could be several explanations, for example that the energy of the body conducted sound might be different from person to person, the leakage between the earmould and the ear canal wall created by speaking varies between subjects and the individual ear canal size will
influence the generated sound pressure level in the occluded ear canal. These matters should be investigated more carefully.

- The survey holds examples of subjects where the occlusion effect with the hearing aid turned on is 15 dB larger than when the hearing aid is turned off. These subjects still feel occlusion of own voice. The interesting point here is to be able to predict how much larger the occlusion effect with the hearing aid on must be if the experience of occlusion shall be avoided. In order to predict this it will be necessary to perform a study that included larger insertion gains and more profound hearing losses than in the present survey.

- The insertion gain was in most cases lower than the predicted target gain at low frequencies. However, the data indicate that even if the correct insertion gain was to be applied most subjects will still experience occlusion from own voice. Only few subjects might avoid the experienced occlusion if the hearing aid was fitted correctly, but the actual effect of an insertion gain that is too low cannot be concluded from these data.

- It was concluded that tinnitus has a significant effect on the experience of occlusion. This effect should be analysed into details in order to explain how and why tinnitus affect the perception of own voice, whether it is because the level of external sounds decreases or whether it is the level of the tinnitus sound that increases.
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Hearing Instruments, Vol. 37, No.12, p.19
APPENDIX A:

LITERATURE REVIEW

Biering-Sørensen M., Pedersen F. & Parving A.: "Is There a Relationship Between the Acoustic Occlusion Effect and the Sensation of Occlusion?"


The purpose of the investigation was to determine relationships between the objective acoustic occlusion and the subjective occlusion. Objective acoustic occlusion is the measurable change in sound pressure level with and without ear mould. Subjective occlusion is the effects of sound quality of own voice and body sounds which the subject perceive.

Method

45 subjects were divided into two groups, one with conductive hearing impaired and one with sensorineural hearing impaired. Due to the fact that clinical occlusion tests shows no occlusion effect for conductive losses, it was assumed that the group of conductive hearing impaired subjects would not experience any occlusion effect.

Conductive losses were classified by a negative Bings test and a airbone gap > 15 dB (average of 250 and 500 Hz) and by a difference in bone conduction < 10 dB (average of 250 and 500 Hz) measured with occluded outer ear canal. Subjects who could not be classified or had different hearing impairment in both ears were excluded. The conductive group had an average hearing loss at 55 dB HL (500 Hz, air borne) and the sensorineural group had an average hearing loss at 35 dB HL (500 Hz, air borne).

It was assumed that the individual ear moulds had a maximum vent diameter of 0,8 mm.

The subjective perceived occlusion was measured by a personal interview two months after the fitting.

Results

No relation between objective and subjective occlusion were found. This relationship was evaluated by comparing the airbone gap (averaged at 250 and 500 Hz) and the measured acoustic occlusion and the answers from the interview. No significant differences were found. Therefore it seems that the ear mould is not the reason for changes in own voice. Including 1.000 Hz in the airbone gap do not alter the results.

No significant differences in the subjective occlusion between the two groups were found, thus twice as many sensorineural hearing impaired as conductive hearing impaired experienced a change in own voice.
Killion M. C., Wilber L. A. & Gudmundsen G. I. "Zwislocki was right..."


This paper refers among others to an earlier investigation which showed that a non-vented earmould could create levels at 100 dB SPL of own voice in the ear canal. A man and a woman was fitted with a shallow ear tip and a deep inserted foam ear tip. The deep inserted tip (to the edge of the bony part) gave a reduction of 13 -19 dB at 250 Hz in the ear canal, while the subject was pronouncing an /ee/. The sound /aaa/ gave no difference. Several different earmoulds were tried on the subjects while they vocalised /ee/, /aaa/ or /uuu/. It was possible to obtain a non-vented earmould with very little difference in sound level between the occluded ear and the open ear.

Deep fitted and sealed earmoulds created minimal occlusion effects and deep fitted non-sealed (tapered tip) earmoulds gave large occlusion effect. In the last experiment two female and one male subject were fitted with a shallow inserted and a deep inserted earmould. The sound pressure level were measured while the subjects vocalised /ee/, /aaa/ or /uuu/. In two cases the deep fitted earmoulds resulted in a sound level more similar in the open ear at 250 Hz than a shallow inserted earmould did.

The paper concludes, that to eliminate the hollow voice requires that the low frequency output of the hearing instrument exceeds the residual ear canal SPL, which is build-up due to the occlusion effect.

Kuk Francis K. "Perceptual consequence of vents in hearing aids"


The perceptual consequence of venting an earmould while maintaining the insertion gain at a preferred listening level was examined in consideration to the following three points: preferred insertion gain with a vented and an unvented earmould, preference for one venting condition over the other in consideration to word recognition and quality, corresponding real-ear measurements and subject performance. The examination were carried out with 9 hearing impaired subjects using a plugged earmould and a vented earmould (2.2 mm parallel vent).

Word recognition ability was measured at 70 dB SPL. The subjects judged the sound quality by listening to discourse passages at 70 dB SPL and by reading the passages aloud. Real-ear measurements were made while the subjects were vocalising /ee/. The selected insertion gain was measured with a 70 dB SPL speech-shaped signal.

The results showed that the preferred insertion gain for vented and unvented earmoulds are very similar (the same) and the word recognition ability was the same too. In listening situations the vented earmould seemed to give a more clear sound and in the speaking situation the vented earmould gave a more clear, less hollow voice. The overall preference was the vented earmould. The mean real-ear sound pressure level was measured to 70 dB SPL at 250 Hz and 80 dB SPL at 500 Hz in open ear condition. In the aided and not vented situation the same measurements gave 97 dB SPL at 250 Hz and 92 dB SPL at 500
Hz. In the aided and vented situation the results were 87 dB SPL at 250 Hz and 86 dB SPL at 500 Hz. At frequencies above 2,000 Hz there was no difference between unvented and vented conditions. The problem is the risk of feedback.

MacKenzie Kenneth, Browning George G. and McClymont Leo G.: "Relationship between earmould venting, comfort and feedback".


This paper is concerned about the advantages of venting an earmould, which can be:

- reduced low frequency gain
- direct access of unamplified sound
- increasing comfort by eliminating a blocked up feeling
- alleviate chronic suppurative otitis media (inflammation of the middle ear)
  or chronic otitis externa (infection in the ear canal)

Method

In this investigation mild or moderate hearing impaired subjects participated. All were first time users and divided into a group of 106 and a group of 24. For each subject three hard acrylic earmoulds were made: one unvented, one with a 0.8 mm parallel vent and one with a 2 mm parallel vent. Each earmould were coupled to a BTE hearing aid and fitted on subjects from the first group for 2 weeks at a time. Every 2 weeks the subjects were then asked to evaluate the earmould.

The second group participated in a laboratory examination of preferred insertion gain. The gain of the aid was adjusted until the researcher heard that feedback occurred or the subject meant that the sound was uncomfortable loud or full gain was achieved without feedback or loudness discomfort appeared. The test stimulus was babble noise.

Results

The results from the first group showed that 37% complained of being blocked with the unvented earmould. In comparison 23% with the 0.8 mm vent and 14% with the 2 mm vent complained of being blocked. There were no significant difference to be found in consideration to moist and itch. Fewer than 20% found the earmoulds to be uncomfortable in general. Over the first 6 weeks the proportion considering the earmoulds to be uncomfortable went from 21% to 10%.

The results from the second experiment showed that feedback occurred at a mean gain of 42 dB when the noise was 50 dB SPL. At a noise level of 75 dB SPL and a mean gain of 32 dB the sound seemed to be too loud.
May A. & Dillon H.: Comparison of physical measurements of the occlusion effect with subjective reports.


The purpose of this experiment was to investigate the relation between earmould configuration and occlusion effect and the subjective experienced occlusion effect from own voice.

Method

The experiment involved 10 normal hearing subjects. Each subject was fitted with several earmould configurations: an unvented carved shell, an unvented skeleton, a skeleton with a 1 mm vent, a skeleton with a 2 mm vent, a BTE mould with a long open vent, one with a short open vent, one with a tube vent and one with a small cavity vent. The occlusion effect was measured while the subjects were speaking. After each trial the subjects should rate the perception of own voice as normal, acceptable or unacceptable.

Results

The four most occluding moulds turned out to be the cavity mould, the unvented shell and skeleton and the skeleton with a 1 mm mould. The occlusion effect varies a lot between subjects, thus a variation of 30 dB for the unvented skeleton was found.

The measured occlusion effect was compared with the subjective ratings of own voice. The objective level of occlusion was detected with four values: the peak boost between 200-800 Hz, the average boost between 200-800 Hz, the maximum frequency cut between 1,25-5 kHz and the average frequency cut between 1,25-5 kHz. It turned out that each of the four values could be used but the peak boost showed a slightly larger correlation with the subjective ratings with a correlation coefficient at 0.63.

The results leads to the conclusion that a low frequency boost of more than 15 dB is likely to be unacceptable and only an open vent seems to give consistently less than 15 dB occlusion effect. The authors assume that hearing aid users with unvented moulds will object if they have a hearing loss less than 40 dB at 250 Hz and that a 2 mm vent leads to objection if they have a hearing loss less than 25 dB at 250 Hz.

Revit L. J. "Two techniques for dealing with the occlusion effect"

Hearing Instruments, Vol. 43, No. 12, 1992, p.16-18

This paper talks about venting and deep fitting as solutions to the occlusion effect.

Some measurements with different vent sizes are referred. A 0.6 mm vent diameter with a pressure-release plug gave 2 dB less occlusion at 200 Hz than a sealed earmould. A 2mm vent gave 8.5 dB less occlusion, but feedback was a problem.
Deep canal seal is another solution. At $f < 500$ Hz the occlusion effect is max. 5 dB compared to the normal sealed earmould. It shall be noted, that these measurements was only made on one sample ear.

**Wimmer V.H. : The occlusion effect from earmoulds**

**Hearing instruments, Vol.37, No. 12, 1986, p.19+57**

This paper is a summary of measurements made by Peter Lundh in Oticon. The purpose of the experiment was to investigate the occlusion effect with different stimuli.

**Method**

Two earmoulds were made for each subject. A closed tight fitting earmould and an earmould with a large opening. Four subjects participated and each subject was measured on both ears. The occlusion effect was measured with continuos speech, bone vibrator and no stimuli in order to detect body sounds.

**Results**

The body sound measurement showed that the occlusion effect is at least 8 dB at 200 Hz. The own voice measurement illustrated that the occlusion effect varies between subjects. The mean occlusion effect was 23 dB at 200 Hz, 12 dB at 500 Hz and 0 dB at 1,500 Hz. The occlusion effect created by bone vibration varies also between subjects. The mean occlusion effect was 20 dB at 300 Hz, 16 dB at 500 Hz and 0 dB at 2,000 Hz.
APPENDIX B: PILOT STUDIES

PRE-QUESTIONNAIRE TEST

Relevant questions about the user problems has been derived from the litterature and from a minor experiment. The purpose of this experiment was to examine the problems derived from the litterature and to detect other problems that have not been found in the litterature.

Method

The experiment can be considered as a worst case situation involving four normal hearing subjects. Individual closed earmoulds were made for all subjects. One subject had an earmould made of real earmould material (subject 4), the three others had earmoulds made of the impression material. The subjects wore the earmoulds in five days as described below:

- **Day 1**: Both earmoulds for 15 minutes.
- **Day 2**: Both earmoulds for 15 minutes. After that changing between left and right earmould for as long as the subject liked to.
- **Day 3**: Both earmoulds for at least 1 hour. After that changing between left and right earmould for as long as the subject liked to.
- **Day 4 and 5**: Both earmoulds were worn for at least 2 hours. After that changing between left and right earmould for as long as the subject liked to.

The subjects were asked to wear the earmolds while walking, eating something crispy, eating something not crispy, drinking, turning the head, scratch the face, scratch the head, talking with one other person and while speaking in the phone with an earmould in the other ear. The subjects described all their observations in a dairy.

Results

The general observations which are relevant to occlusion are summarized in table 1 and special observations are commented below.

<table>
<thead>
<tr>
<th>Monoaural/ Binaural</th>
<th>Observation</th>
<th>Observed by subject no.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binaural</td>
<td>Own voice controlling is difficult</td>
<td>1,2</td>
</tr>
<tr>
<td>Binaural</td>
<td>Own voice sounds louder than normally</td>
<td>2,4</td>
</tr>
<tr>
<td>Binaural</td>
<td>Own voice sounds different than normally</td>
<td>1,2,3,4</td>
</tr>
<tr>
<td>Binaural</td>
<td>Own voice sounds like speaking in a barrel</td>
<td>2,4</td>
</tr>
<tr>
<td>Binaural</td>
<td>Scratching the face or head sounds louder than normally</td>
<td>1,2,3,4</td>
</tr>
<tr>
<td>Binaural</td>
<td>Turning the head a crunchy sound is heard</td>
<td>1,4</td>
</tr>
<tr>
<td>Binaural</td>
<td>Touching the earmould sounds extremely loud</td>
<td>3,4</td>
</tr>
<tr>
<td>Binaural</td>
<td>Breathing is audible</td>
<td>1,2,3,4</td>
</tr>
<tr>
<td>Binaural</td>
<td>Breathing becomes more heavy</td>
<td>4</td>
</tr>
<tr>
<td>----------</td>
<td>-----------------------------</td>
<td>----</td>
</tr>
<tr>
<td>Binaural</td>
<td>Drinking and swallowing sounds louder than normally</td>
<td>1,2,3,4</td>
</tr>
<tr>
<td>Binaural</td>
<td>Eating something not crispy a noise is heard</td>
<td>1,2,3,4</td>
</tr>
<tr>
<td>Binaural</td>
<td>Eating something crispy a very loud noise is heard</td>
<td>1,2,3,4</td>
</tr>
<tr>
<td>Binaural</td>
<td>Walking on a wodden floor is heard or felt as heavy jolts inside the head</td>
<td>1,2,3,4</td>
</tr>
<tr>
<td>Binaural</td>
<td>Feeling of being in a barrel</td>
<td>2,3,4</td>
</tr>
<tr>
<td>Binaural</td>
<td>The ears plop to equalise the pressure</td>
<td>2</td>
</tr>
<tr>
<td>Binaural</td>
<td>Coughing sounds loud</td>
<td>2,3</td>
</tr>
<tr>
<td>Binaural</td>
<td>Increased production of ear wax</td>
<td>2</td>
</tr>
<tr>
<td>Binaural</td>
<td>Heavy sights sounds clearly</td>
<td>2</td>
</tr>
<tr>
<td>Monoaural</td>
<td>Own voice controlling is difficult</td>
<td>2</td>
</tr>
<tr>
<td>Monoaural</td>
<td>Own voice sounds different</td>
<td>1,2,3,4</td>
</tr>
<tr>
<td>Monoaural</td>
<td>Breathing is audible</td>
<td>2</td>
</tr>
<tr>
<td>Monoaural</td>
<td>Turning the head a crispy sound is heard</td>
<td>4</td>
</tr>
<tr>
<td>Monoaural</td>
<td>Eating sounds louder than normally</td>
<td>2,4</td>
</tr>
<tr>
<td>Monoaural</td>
<td>Chewing creates a loud ringing in the head.</td>
<td>2</td>
</tr>
<tr>
<td>Monoaural</td>
<td>Walking on a wodden floor is heard or felt as jolts inside the head</td>
<td>4</td>
</tr>
<tr>
<td>Bin / Mono</td>
<td>Slightly soreness</td>
<td>1,2</td>
</tr>
<tr>
<td>Bin / Mono</td>
<td>Itch</td>
<td>1,2,3,4</td>
</tr>
<tr>
<td>Bin / Mono</td>
<td>Moist</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 1: Observations made by normal hearing subjects wearing closed earmoulds.

Table 1 shows that the subjects had experienced the same kind of changes and noises but they might perceive or describe it in different ways.

All subjects experienced a change in own voice, which they described as a louder voice, a darker voice, a resounding voice or a voice in a barrel. Three out of four subjects had a general feeling of being inside a barrel.

Everyone either heard or felt heavy jolts while walking. Some described it as low frequency bumps or like hitting two metal pipes against each other. Loud sounds were also heard while drinking and chewing and could be described as a ringing inside the head. All subjects also found that their own breathing was audible, but normally they did not take any notice of it. Only one subject noticed a change in breathing. The interesting aspect of this, is that the subjects found the noises from breathing, chewing, drinking, walking and coughing annoying while listening to other people.

The subjects changed between two and one ear mould and they reacted different. One subject found that one ear mould was more comfortable than two ear moulds and another subject had the opposite opinion due to a feeling of no balance between right and left side of the head.
The results indicates what people in general might experience and how they will describe their experiences.

**Special remarks**

**Subject 1:**
- Scratching the face sounds like sandpaper rubbed at a wooden plate.
- Hearing own breathing is disturbing when listening to someone who is talking.
- Hearing the sound of swallowing is not annoying.
- Chewing gum is annoying, sounds like you are in a washing machine.
- It is annoying to hear own breathing while talking with others.
- Drinking and swallowing is heard, but it is not annoying.

**Subject 2:**
- The feeling of own footsteps is not annoying.
- It is difficult to understand what others are saying while I am chewing.
- Did not notice breathing or heart beats in the beginning but I did later on.
- Own voice resounds (monoaural).
- It is worse wearing one earmould than two because the perception is not balanced to both sides.
- A feeling of being inside yourself is nice when you have to concentrate.
- It is difficult to hear what others are saying while walking.
- It is not annoying to scratch in the face.
- Blowing one’s nose sounds loud
- Cannot hear other talking while coughing.
- Does not notice the earmoulds while contentrating on something.
- Own voice sounds different, which is annoying.
- It is nice to take the earmoulds out and get some air into the ear canal again.
- Speaking in the phone is not annoying.
- It is difficult to talk with others while chewing or coughing.
- Shaking the hair sounds loud (long hair)

**Subject 3:**
- Does not notice the earmoulds while concentrating on something.
- Had a feeling of having a sleeping quilt over my head
- Hard skin in the ear
- Breathing sounds loudly, but I do not normally notice it
- Own voice sounds better with only one ear plugged instead of two
- Own voice sounds uncomfortable, dark and resounding
- Own voice sounds darker but it is no problem to conversate.
- Shaving sounds very loud
- Walking on wooden floor creates a low frequency bump in the head and can mayby be perceived as a short change in pressure
- In general it is uncomfortable wearing two earmoulds.
Subject 4:
- Walking on wooden floor sounds like hitting two metal pipes against each other and it is very annoying.
- Scratching the face generates a lowfrequency sound.
- A crispy sound is heard when I turn my head. It is much softer with only one ear mould than two.
- It is not a problem to use the phone but the change in own voice can be noticed.
APPENDIX C: EQUIPMENT

ANTI-ALIASING FILTER

The acoustic signal is sampled at 20.833 kHz and to avoid "noise" created in the Fast Fourier Transformation the two acoustic signals were filtered by 10 kHz sharp lowpass filters. The filter characteristics were the same for the two filters and has the shape shown in Figure C.1. The filter characteristic was measured using an audio analyzer Brüel&Kjaer 2012 in Steady State Response mode with a 20 kHz span.

![Anti-aliasing filter graph](image)

*Figure C.1 - 10 kHz lowpass filter used as anti-aliasing.*

AMPLIFIERS

The preamps were homemade with 1 dB step ranging from 0-90 dB. There was one preamp for each signal channel.

**Linearity**

The linearity amplification was measured on an audio analyzer Brüel&Kjaer 2012 in Steady State Response mode. The signal used was a sweep, Log Iso in 1/12 octave bands ranging from 10 Hz to 10 kHz, detector delay was 10 ms and detector max. time was 80 ms. The signal was power linear averaged.

Electrical input and output was used and the analyzer was calibrated electrical by connecting the output directly to the input of the analyzer. Input sentivity was set to 1,0 V/V and output calibrated to 1,014 V/V. The system repsonse is shown at Figure C.2, the graphs called in out.
Figure C.2 also shows the response of the pre-amp set to 0 dB amplification. The response of the pre-amp falls with 0.15 dB from 5 kHz to 10 kHz.

![System response and pre-amp at 0 dB](image)

**Figure C.2** - System response (inout) and pre-amp at 0 dB gain. Output level = -29.98 dB.

Figure C.3 confirm that the pre-amplifiers are sufficient linear for the present purpose. The output levels from the generator was set to avoid distortion in the pre-amp is made a compensation for the different generated output levels. The pre-amp seems to function well at least up to 60 dB amplification, where the average amplification 59.89 dB at 10-10.000 Hz. At 80 dB two significant dips appaer at 150 Hz and 250 Hz, which corresponds to the dips seen in the system response at **Figure C.2**.

![Pre-amp](image)

**Figure C.3** - Characteristic for preamps at 100-10 kHz. Amplification at 0-80 dB.

**Output level**

The preamps are designed to be connected to the signal processor input channels. Therefore the maximum output level of the preamps are ± 15 V.
DSP PROCESSOR

For signal analysis purpose a DSP-16+ TMS320C25 board with A/D and D/A conversion was used.

Input
Input impedance:  Balanced 10 kohm + to -
                 Unbalanced  5 kohm + to ground
                 10 kohm - to ground
Input filter:     3rd-order Chebyschev lowpass anti-aliasing filter, roll off slowly at 20 kHz

Output
Output impedance: 100 ohm
Output level: 10 V peak full scale
Output dynamic range: 95 dB typical in a 20 Hz to 20 kHz bandwidth
Output filter: 5rd-order Chesbyschev lowpass filter, roll off at 20 kHz
                2rd-order sinx/x filters

Digital specifications
Processor: TMS320C25, 100 nsec
Data memory: 64 K words
Sample rate: Programmable form 20 Hz to 50 kHz
Data format: fixed-point, 16 bit *

Overall system performance
Dynamic range: 88 to 90 dB, 85 minimum
Crosstalk: 82 dB at 1 kHz, 60 dB at 10 kHz typical

* Log magnitude precision is about -67 dB for a 16-bit fixed point device.

PROBEMICROPHONE

Insulation
The probemicrophone is isolated in a box made of 2 mm acrylic. Power of penetration for this acrylic is 16-20 kV/mm.
The probemic is put on the ear with an insulated metal string. Insulated with schrinkable rubber.

Characteristic
The frequency characteristic of the probemicrophone, and the tube is shown at Figure C.4 where the average characteristic of 4 tubes are shown. Not two tubes are exactly identical
and the four measured tubes have a standard deviation less than 1.3 dB below 6 kHz and less than 3 dB below 10 kHz.

The curves are measured with an Audio Analyzer Brüel&Kjær 2012 in an anechoic box (box 2 at Oticon, Strandvejen). The response of the system consisting of a loudspeaker, an attenuator for the loudspeaker, a lowpass filter (10 kHz), an amplifier was measured with an Brüel&Kjær ½" microphone type 4134 and all measurements was filtered with this system response. The Audio Analyzer was used in Staedy State Response mode, with a sweep from 20-10,000 Hz in 1/12 octave bands. The input signal was power linear averaged.

The probemicophone was calibrated using a Brüel&Kjaer pistonphone type 4220 with adaptor DP 0774. The microphone was placed in the box facing the center of the loudspeaker and the opening of the tube was placed also to face the loudspeaker in the same distance as the microphone.

![Probe Microphone, Tube and Tube Put on Microphone](image)

**Figure C.4** - Characteristic of probe microphone, tube and tube put on microphone.

**Tube damping**

The damping of the tube walls was found by measurements of the steady state responses of four open and closed tubes. The tubes provide a damping of 30-40 dB at 100-700 Hz, at 1.000 Hz it has a minimum on 21 dB and above this frequency the higher modes anti-resonances and resonances causes damping between 13dB and 52 dB. The damping is shown at **Figure C.5**.

![Tube Damping](image)

**Figure C.5** - Damping of tube walls. Damping=Open tube - closed tube.
System noise
When the probe microphone is placed in the sound booth and the preamp is set to 60 dB the noise signal is less than 0.1 V for the largest peaks. With maximum peak value of 15 V the signal to noise ratio is 43.5 dB.

PROBEMICROPHONE AMPLIFIER
The probemicrophone is originally designed to work with an Interacoustic Hearing Analyzer MS40. In order to make the probemicrophone work with the signalprocessor board a copy of the input filter in the Hearing Analyzer was build as shown in Figure C.6.

![Figure C.6 - Probemicrophone amplifier. (Manual from Interacoustic MS40).](image)

REFERENCE MICROPHONE
A reference microphone was placed in front of the subject in the sound box. The box is not free from reflexions especially at high frequencies, therefore is was decided to use a directional microphone, which gives a much better proportion of the frontal sound relative to the reflected sound than a 1" microphone.

The reference microphone was a shotgun from Beyerdynamic type MC 737 with an internal electrical noise at 13 dBA. It has a frequency response as shown in Figure C.7.

![Figure C.7 - Frequency response for reference microphone Beyerdynamic MC 737.](image)
The directivity is a tight hypercardioid pattern, see Figure C.8. If a sound source is placed 25 cm from the microphone at exactly 0 degrees, a movement of 10 cm away form the axis affects an angle deviation of 22 degrees and a movement of 20 cm affects an angle deviation at 39 degrees. Figure C.8 shows that at 250, 500 and 1.000 Hz a movement of 10 cm gives nearly no attenuation in measured sound pressure level. A movement of 20 cm gives approximately less than 1 dB attenuation for frequencies below 1.000 Hz, 5 dB for 1.000 Hz and 8 dB for 2.000 Hz.

![Diagram of directivity pattern](image)

**Figure C.8** - Directivity for reference microphone Beyerdynamic MC 737.

**SAFETY**

The safety requirements for these instruments were fullfilled. The set up for the occlusion measurements was secured in different ways. The probemicrophone was insulated with acrylic so the subject did not have skin contact with metal. The reference microphone was made of metal but the subject was sitting in a distance from it and was told not to touch it. Except from the microphones and a power supply all other equipment was placed outside the booth. In order to avoid large potential differences, all parts were hold at the same potential by connecting it to the same protective earth. The set up was checked out by measuring the potential from the protective ground to the frame on each part, when it was turned on but not connected to any other part. The measurements were made with a HP Multimeter 34401A with a DC input impedance at 10 MΩ and AC at 1 MΩ. Because of the high impedance of the Multimeter a small capacitive potential difference will always be measured. The largest potential difference was 5.5 mV, which means that the potential difference between ground and frame was negligible.

**CALIBRATION OF INSERTION GAIN EQUIPMENT**

The open ear and aided ear responses were measured with Rastronics 2000, which is a transportable hearing aid tester instrument for free field and coupler measurements. Rastronics 2000 was calibrated in accordance with the Reference Guide.
The microphones were calibrated in order:

1. Coupler microphone
2. Test box reference microphone.
3. Free field microphone.
4. Probe tube microphone.

ad. 1. The coupler microphone was calibrated using a ½" microphone Brüel&Kjaer, Type 4134 and a calibrated measuring amplifier Brüel&Kjaer Type 2606 (scala SA 0057). The microphones was held close together in front of the speaker and the level was set to 80 dB SPL.

ad. 2. The test box reference microphone was placed on the foam in the test box as marked and the coupler microphone was placed closed to it. The microphone membranes was placed just in front of each other.

ad. 3. The two microphones was held close together with facing membranes in front of the speaker.

ad. 4. The probe tube microphone was calibrated before each test session holding the tube tip on top of the free field reference microphone.

Control of calibration
The Rastronics display the output level of the loudspeaker measured by the reference microphone, so if the output level is set to 60 dB SPL this should be the level at the reference microphone position. The calibration was checked by holding the free field microphone close to a ½" microphone 25 cm from the speaker and in the center axis of the speaker. The ½" microphone was connected to the measuring amplifier, RMS fast mode. Rastronics 2000 was set to give an output of 60 dB SPL wide band noise and with the ½" microphone was measured 61,5 dB SPL. The difference could be due to the fact the microphones was not placed at exactly the same spot in the sound field neither while calibrating or when measuring.

At the 27th of November 1995 (at 2 pm) the Rastronics 2000 was exchanged with another one. The new was calibrated by Rexton. The calibration was checked like above and the results were:

60 dB SPL output, wideband noise: measured to 61,5 dB SPL
70 dB SPL output, wideband noise: measured to 71,0 dB SPL
80 dB SPL output, wideband noise: measured to 81,5 dB SPL

CALIBRATION OF OCCLUSION MEASUREMENT SYSTEM
The signal from the probemicrophone were fed to a computer operating with a 16 bit fixed point digital signal processor board, TMS320C25. An associated software named
Hypersignal was used for recording, analog to digital conversion, FFT and spectrum analysis.

Hypersignal was calibrated by setting the level of a well defined signal provided by a calibrator with an output of 94 dB SPL at 1,000 Hz. The preamp was set to 30 dB.

The level of a spectrum created in Hypersignal (f<sub>s</sub> = 20.833 Hz, framesize = 512, Hanning-weighted, 50% overlap, FFT-order = 10) was checked with an audio analyzer Brüel&Kjær 2012. The audio analyzer was used in FFT mode to generate a single tone (100 ms) with electrical input and output. The input to the audio analyzer was power averaged and Hanning-weighted, 9% overlap. The output was fed via an amplifier back to the analyzer and the DSP-board respectively. The amplifier was adjusted to 30 dB gain. The level of the tone measured with the analyzer was compared with the spectrum made by Hypersignal and as can be read from table A the deviation in levels are less than 0.4 dB for f<sub>c</sub><5 kHz. The deviations is partly caused by the FFT and that the frequency resolution is not the same in Hypersignal as in the analyzer. The data are shown in Table C.1.

<table>
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<th>Frequency [Hz]</th>
<th>Output level [dB re 1,0 V]</th>
<th>Input level [dB re 1,0 V]</th>
<th>Hypersignal Frequency [Hz]</th>
<th>Level [dB re 1,0 V]</th>
<th>Deviation Hypersignal - Analyzer [dB]</th>
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<td>15,81</td>
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</table>

Table C.1 - Pure tone levels measured at audio analyzer and Hypersignal.

The absolute level was set in Hypersignal by recording the signal from a calibrator (1,000 Hz, 94 dB SPL) with a 1" microphone fed through an amplifier with 30 dB gain. The rms-value of the timesignal is set to 94 dB SPL and the calibration coefficient, α, is found by:
\[ \alpha = 10^{\frac{60}{20}} / p_s \]

where;
\( p_s \) = sound pressure of the signal measured as a rms-value

The calculation of the absolute level of a recorded signal was corrected with the reference gain of 30 dB and the gain used in the specific recording.

The occlusion was measured with a probe microphone, that does not have a flat frequency response like a 1" microphone. The recorded signal must therefore be corrected with a filter shaped as the inverse of the probemicrophone plus tube frequency characteristic.
INSTRUCTIONS OF HOW TO FILL IN A QUESTIONNAIRE

The purpose of this questionnaire is to survey possible problems experienced by hearing-aid users. It is essential that you fill in the questionnaire irrespective of how seldom or how often you wear your hearing-aid. Please answer as many questions as possible, even if you never wear your hearing-aid or only seldom.

Hearing-aid users may experience many different problems in connection with the wearing of their hearing-aid. But not all users experience the same problems. Therefore the questionnaire may describe some problems that you do not experience.

We ask you to read each question carefully in order to be sure of the meaning of the question before you answer it. Most of the questions are to be answered by making a cross (x) in the boxes. If more than one cross is allowed then it is indicated in the question.

Please answer the questions consecutively. Each main question is indicated by a number and each sub-question is indicated by a number and a letter, eg 2a. The sub-questions are only to be answered if you have answered something particular to the corresponding main question. Here is an example of two different ways of answering.

Example 1:

2. Did you have breakfast today?  

   □ Yes  [X] No

If Yes:

   2a. How many rolls did you have?  

(Here question 2a is not to be answered)

Example 2:

2. Did you have breakfast today?  

   [X] Yes  □ No

If Yes:

   2a. How many rolls did you have? 2 rolls

(Here question 2a must be answered)
HEARING-AIDS AND EARMOULDLS

**Question 1**
For which ear do you have hearing-aids?

- For the right ear only
- For the left ear only
- For both right and left ear

**Question 2**
Question 2 is to be answered if you have hearing-aids for both ears:

**Question 2a**
How long do you wear both hearing-aids concurrently?

- Less than one hour
- 1-2 hours
- 3-5 hours
- 6-8 hours
- More than 8 hours

**Question 2b**
How long do you wear only one hearing-aid?

- Less than one hour
- 1-2 hours
- 3-5 hours
- 6-8 hours
- More than 8 hours

**Question 2c**
If you wear only one hearing-aid now and then, what may the reason be?

________________________________________________________________________
________________________________________________________________________

Occlusion effects. Part I.
Question 3
Question 3 is answered if you only have hearing-aid for one ear:

How long do you wear your hearing-aid?

☐ Less than one hour
☐ 1-2 hours
☐ 3-5 hours
☐ 6-8 hours
☐ More than 8 hours

Question 4
How often do you wear your hearing-aid?

☐ Never
☐ Less than one day a week
☐ 1-3 days a week
☐ 4-6 days a week
☐ Every day

Question 4a
If you never or less than one day a week wear your hearing-aid, what may the reason be?

__________________________________________________________________________

__________________________________________________________________________

Question 5
In which situations do you normally wear your hearing-aid?
(You are welcome to put more than one cross).

☐ When talking to one other person
☐ When watching TV or listening to the radio
☐ At lectures, meetings and the like, where only one person is talking
☐ At small dinner parties (4 persons or less)
☐ At big dinner parties (more than 4 persons)
Question 6
Do you experience some of the following situations when using your hearing-aid?
(You are welcome to put more than one cross)

☐ The environmental sounds become distinct
☐ My own voice sounds different
☐ I can hear my own footsteps more clearly
☐ I can hear my own breathing more clearly
☐ I can hear loud sounds when I am chewing
☐ Sometimes I feel locked up
☐ I feel I have moist ear canals
☐ It sounds very loud when I cough

Question 7
Does your own voice sound different when you use your hearing-aid compared to when you do not use your hearing-aid?

☐ Yes  ☐ No

If Yes:

Question 7a
Try briefly to describe in what way your voice sounds differently:

_____________________________________________________________________

Question 7b
Can the change in your voice be described by some of the below-mentioned changes?
(You are welcome to put more than one cross)

☐ Darker
☐ Compressed (as if talking in a barreæ)
☐ Louder
☐ Less clear
☐ Resounding (a kind of echo in the voice)
☐ Hoarse
☐ Grating

Question 7c
Do you experience the change in your voice as:

Not annoying  Slightly annoying  Annoying  Very annoying

_____________________________________________________________________

Occlusion effects. Part I.
Appendix D: Questionnaire

Question 8
When you are at rest, which body noises can you hear more clearly when using your hearing-aid compared to not using your hearing-aid?
(You are welcome to put more than one cross)

☐ Own breathing
☐ Heart beating
☐ Blood circulating
☐ A kreaking when I turn my head

☐ I cannot hear any of the above-mentioned sounds

Other sounds: __________________________

Question 9
When drinking, can you hear the swallowing more clearly when using your hearing-aid compared to not using your hearing-aid?

☐ Yes ☐ No

Question 10
Do you feel that your earmould fit less good or bad into your ear?

☐ Yes ☐ No

Question 11
Do you experience some of the belowmentioned annoyances when you use your hearing-aid?
(You are welcome to put more than one cross)

☐ Feeling of having moist ear canal
☐ Itching in the ear canal
☐ Smarting pain in the ear canal
☐ Eczema in the ear canal
☐ Pain in the ear canal

☐ I do not experience any of these annoyances

Other comments: __________________________
**Question 11 a**
How and how often do you clean your earmould / hearing-aid?

---

**Question 12**
Do you have a feeling of constant pressure on the eardrum?

☐ Yes  ☐ No

**Question 13**
Does it sound as if your voice is coming from somewhere else when you use your hearing-aid compared to not using your hearing-aid?

☐ Yes  ☐ No

If Yes:

**Question 13a**
When you speak while using your hearing-aid, how do you experience the sound of your own voice?

☐ Inside my head  
☐ All around me  
☐ Just in front of me  
☐ A place further apart  
☐ Do not know

**Question 14**
When eating something crunchy (eg crispbread), does the chewing sound more clearly when you use your hearing-aid compared to not using your hearing-aid?

☐ Yes  ☐ No

**Question 15**
Do you feel any pressure from the earmould / hearing-aid when your mouth is closed?

☐ Yes  ☐ No
If Yes:

**Question 15a**
Do you experience this as:

<table>
<thead>
<tr>
<th>Not annoying</th>
<th>Slightly annoying</th>
<th>Annoying</th>
<th>Very annoying</th>
</tr>
</thead>
</table>

**Question 16**
Do you sometimes experience that your hearing-aid turns off by itself from other reasons than batteries dying out?

☐ Yes ☐ No

**Question 17**
Do you feel you get too little ventilation into the ear canal when you use your hearing-aid?

☐ Yes ☐ No

**Question 18**
Do you experience some of the below mentioned as annoying when you use your hearing-aid?
(You are welcome to put more than one cross):

☐ Headache  ☐ Nausea  ☐ Running eyes  ☐ Running nose  ☐ Coughing  ☐ Hoarse voice  ☐ Sore throat  ☐ Changed heart beat

☐ I do not feel any of that kind of annoyance because of my hearing-aid

Other comments

__________________________________________

---

Occlusion effects. Part I.
**Question 19**
When you walk on a hard floor (e.g., wood, tiles etc) while you are wearing your hearing-aid, do you then hear loud sounds?

☐ Yes  ☐ No

If Yes:

**Question 19a**
Do these sounds come from within the head or the body?

☐ Yes  ☐ No

**Question 19b**
Do you experience this as:

- Not annoying
- Slightly annoying
- Annoying
- Very annoying

**Question 20**
Do you feel that the earmould / hearing-aid presses against your ear canal when you speak?

☐ Yes  ☐ No

If Yes:

**Question 20a**
Do you experience this as:

- Not annoying
- Slightly annoying
- Annoying
- Very annoying

**Question 21**
Is your breathing changing when you wear your hearing-aid?

☐ Yes  ☐ No

If Yes:

**Question 21a**
Are you normally aware of this?

☐ Yes  ☐ No
**Question 21b**
How is your breathing changed?
- [ ] It becomes deeper
- [ ] It becomes slower
- [ ] It becomes quicker
- [ ] It becomes more intense
- [ ] It becomes shorter

**Question 22**
Is it more difficult for you to hear sounds around you while you are eating something crunchy (e.g. crispbread) wearing your hearing-aid compared to not wearing your hearing-aid?
- [ ] Yes
- [ ] No

If Yes:

**Question 22a**
Do you experience this as:
- [ ] Not annoying
- [ ] Slightly annoying
- [ ] Annoying
- [ ] Very annoying

**Question 23**
Do you feel any pressure from the earmould /hearing-aid while chewing?
- [ ] Yes
- [ ] No

**Question 24**
Do you feel locked up while wearing your hearing-aid?
- [ ] Yes
- [ ] No

**Question 25**
Is it more difficult for you to hear sounds around you, while drinking wearing your hearing-aid compared to not wearing your hearing-aid?
- [ ] Yes
- [ ] No
If Yes:

**Question 25a**  
Do you experience this as:

- Not annoying  
- Slightly annoying  
- Annoying  
- Very annoying

**Question 26**  
When did you get your first hearing-aid?

- 0-3 months ago  
- 3-6 months ago  
- 6-12 months ago  
- 1-5 years ago  
- More than 5 years ago

**Question 27**  
How long have you used your present hearing-aid(s)?

- 0-4 weeks  
- 1-3 weeks  
- 3-6 weeks  
- 6-12 weeks  
- More than one year

**Question 28**  
Do you suffer from tinnitus (ringing or buzzing in the ears)?

- Yes, always  
- Yes, sometimes  
- No

Thank you for your help

Yours faithfully

Mie Østergaard Hansen  
MSc, Industrial PhD-student
# APPENDIX E: SUBJECTIVE DATA

## APPENDIX E1: INDIVIDUAL DATA

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<td></td>
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Title: Occlusion effects. Part I.
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Oclusion effects. Part I.
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1 If it is a split a diameter of 1.8 mm is used
### Appendix E: Subjective data

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Occlusion effects. Part I.
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APPENDIX F: MEASUREMENT DATA

APPENDIX F1:
Occlusion effects, normalised

APPENDIX F2:
Reference speech difference

APPENDIX F3:
Retest of occlusion effects and insertion gains

APPENDIX F4:
Preamp settings
Appendix F1: Occlusion effect, normalised

Oclusion effects. Part I.
Occlusion effects. Part I.
Appendix F1: Occlusion effect, normalised

Occlusion effect, speech, No. d00

Frequency [Hz]

Occlusion effect, speech, No. d01

Frequency [Hz]

Occlusion effect, speech, No. e10

Frequency [Hz]

Occlusion effect, speech, No. e20

Frequency [Hz]

Occlusion effect, speech, No. e30

Frequency [Hz]

Occlusion effect, speech, No. e40

Frequency [Hz]

Occlusion effects. Part I.
Appendix F1: Occlusion effect, normalised

Occlusion effects. Part I.
Appendix F1: Occlusion effect, normalised

Occlusion effect, speech, No. 110

Occlusion effect, speech, No. 120

Occlusion effect, speech, No. 130

Occlusion effect, speech, No. 140

Occlusion effect, speech, No. 150

Occlusion effect, speech, No. 160

Occlusion effects. Part I.
Appendix F2: Reference speech, difference

Oclusion effects. Part I.
Appendix F2: Reference speech, difference

Occlusion effects. Part I.
Appendix F2: Reference speech, difference

Speech reference, difference, No. e50

Speech reference, difference, No. e60

Speech reference, difference, No. e72

Speech reference, difference, No. e81

Speech reference, difference, No. e91

Speech reference, difference, No. 101
Appendix F2: Reference speech, difference
APPENDIX F3: RETEST

Retest difference. No. b71

Retest difference. No. c90

Retest difference. No. c70

Retest difference. No. d90

Retest difference. No. e01

Retest difference. No. e91

Occlusion effects. Part I.
RETEST OF INSERTION GAIN
## APPENDIX F4: PREAMP SETTINGS

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APPENDIX G: PROGRAMS

Loading of time files and estimation of spectrum

%FILENAME: speechsp.m

%Loads time domain files, down samples and calculates the spectrum
% of each measurement for each subject
%INPUT: Timedomain files in binary format
%OUTPUT: A spectrum of each of the input files

% so0 file - open ear, probe mic
%########################
filename=['c:\matlab\occeff\',fpnr,'so0.tim'];
s=sdatacon(filename,n); %Reads the n number first samples of
% of a binary file, integer 16 bits
[clear s;
 t=s(lfile,1); %Removes header and every second sample in infile
 ssp=psd(t,1024,10417,512,256); %Calculates the spectrum
 savefile=('c:\matlab\occeff\',fpnr,'so0.asc ssp -ascii');
 eval(savefile);
 clear t;

% sc0 file - closed ear, hearing aid off, probe mic
%########################
filename=['c:\matlab\occeff\',fpnr,'sc0.tim'];
s=sdatacon(filename,n);
filename=[fpnr,'sc0'];
loadfile=('c:\matlab\occeff\',filename,'.mat');
eval(loadfile);
 t=s(lfile,1); %Removes header and every second sample in infile
 clear s;
 ssp=psd(t,1024,10417,512,256); %Calculates the spectrum
 savefile=('c:\matlab\occeff\',fpnr,'sc0.asc ssp -ascii');
 eval(savefile);
 clear t;

% sn0 file closed ear, hearing on, probe mic
%########################
filename=['c:\matlab\occeff\',fpnr,'sn0.tim'];
s=sdatacon(filename,n);
 t=s(lfile,1); %Removes header and every second sample in infile
 clear s;
 ssp=psd(t,1024,10417,512,256); %Calculates the spectrum
savefile=('c:\matlab\occeff\,fprn,'sn0sp.asc ssp -ascii');
eval(savefile);
clear t;

% so1 file open ear, reference mic
%#
filename=['c:\matlab\occeff\,fprn,so1.tim'];
s=sdatacon(filename,n);
t=(ffile,1); %Removes header and every second sample in infile
clear s;
ssp=psd(t,1024,10417,512,256); %Calculates the spectrum
savefile=('c:\matlab\occeff\,fprn,so1sp.asc ssp -ascii');
eval(savefile);
clear t;

% sc1 file closed ear, hearing aid off, reference mic
%#
filename=['c:\matlab\occeff\,fprn,sc1.tim'];
s=sdatacon(filename,n);
filename=[fprn,'sc1'];
loadfile=('load c:\matlab\occeff\,filename,mat');
eval(loadfile);
t=(ffile,1); %Removes header and
%every second sample in infile
clear s;
ssp=psd(t,1024,10417,512,256); %Calculates the spectrum
savefile=('c:\matlab\occeff\,fprn,sc1sp.asc ssp -ascii');
eval(savefile);
clear t;

% sn1 file closed ear, hearing aid on, probe mic
%#
filename=['c:\matlab\occeff\,fprn,sn1.tim'];
s=sdatacon(filename,n);
t=(ffile,1); %Removes header and every second sample in infile
clear s;
ssp=psd(t,1024,10417,512,256); %Calculates the spectrum
savefile=('c:\matlab\occeff\,fprn,sn1sp.asc ssp -ascii');
eval(savefile);
clear t;

% FILENAME: sdatacon.m

%Reads a binary file with integer 16 bits
% INPUT: filename of a binary file (filename)
% OUTPUT:the loaded file (s)
%---------------------------------------------------------
function s=sdatacon(filename)

fid=fopen(filename,'r');
s=fread(fid,inf,'short');
fclose(fid);
end;

Calibrations of spectra to dB SPL and functions that can be used for smoothing and finding the difference between two spectra

%FILENAME: realear.m

% Normalises, filteres and calibrates the real ear measurements and plots
% the open ear, the occluded ear and the hearing aid on curves.
% INPUT: screen entry
% OUTPUT:saves the normalised, filtered and calibrated spectra (so0f),(sc0f),(sn0f)
%--------------------------------------------------------------------------------------------------------
clear;

fpnr=input('Subject code number : ','s');

% Preamp settings
%#########################################################################
preampsn=60;
preamptic=35;
preampsn=50;

% Open files
%#########################################################################
cat=['c:\p521\brugere\occeff'];
catrea=['c:\p521\brugere\realear'];
catref=['c:\p521\brugere\oveeff'];
load c:\p521\brugere\occeff\frequsp.asc  %Open frequency file
load c:\p521\brugere\occeff\alfa.asc    % Calibration coefficient
load c:\p521\brugere\tekni\probemic\pmicfiles.asc  % Probe mic characteristic filter
filename=[fpnr,'so0sp'];                 % Open ear, probe mic
loadfile=['load ','cat,\',filename,\',asc'];
eval(loadfile);
So=eval(filename);
clearfile=['clear ','filename'];
eval(clearfile);
filename=[fpnr,'sc0sp'];                 % Occluded ear, HA off, probe mic

Occlusion effects. Part 1.
loadfile=['load ','cat','",',filename,'.asc'];
eval(loadfile);
Sc=eval(filename);
clearfile=['clear ','filename'];
eval(clearfile);

filename=[fpnr,sn0sp']; % Occluded ear, HA on, probe mic
loadfile=['load ','cat','",',filename,'.asc'];
eval(loadfile);
Sn=eval(filename);
clearfile=['clear ','filename'];
eval(clearfile);

filename=[fpnr,scso']; % Reference difference, HA off - open ear
loadfile=['load ','catref','",',filename,'.asc'];
eval(loadfile);
Sscso=eval(filename);
clearfile=['clear ','filename'];
eval(clearfile);

filename=[fpnr,snso']; % Reference difference, HA on - open ear
loadfile=['load ','catref','",',filename,'.asc'];
eval(loadfile);
Snso=eval(filename);
clearfile=['clear ','filename'];
eval(clearfile);

% Normalising
%#################
Sc=Sc./Sscso;
Sn=Sn./Snso;

% Calibration to dB SPL
%#############################
So=calib(Sc,alfa,preampso);
Sc=calib(Sc,alfa,preampsc);
Sn=calib(Sn,alfa,preampsn);

% Probe microphone filtering
%############################
So=So-pmicfls; % pmicfls is in dB
Sc=Sc-pmicfls;
Sn=Sn-pmicfls;

% Save files
%########################
savefile=['save ',carea,\\,fpnr,'so0f.asc Sof-ascii'];
eval(savefile);
savefile=['save ',carea,\\,fpnr,'sc0f.asc Scf-ascii'];

Occlusion effects. Part I.
eval/savefile;
savefile=['save ',catrea,'\',fprn,'sn0f.asc Snf -ascii'];
eval/savefile);

% Plots
%#####
semilogx(freqsp,Sof,'g',freqsp,Scf,'r',freqsp,Snf,'m');
axis([100 10000 0 100]);
grid;
titletext=['Real ear measurements. No. ',fprn];
title(titletext);
xlabel('Frequency [dB]')
ylabel(['dB SPL']);
text(120,18,' = open ear');
text(120,14,' = occluded ear, HA off');
text(120,10,' = occluded ear, HA on');

savefile=['print -dmeta c:\p521\brugere\realear\',fprn,'rea.wmf'];
eval/savefile);

%FILENAME: calib.m

% Calibrates the signal to dB SPL with a 250 Hz tone at 124 dB SPL
% INPUT: scaling factor (alfa), spectrum (S)
% OUTPUT: calibrated spectrum (Sc)
%---------------------------------------------------------------

function [Sc]=calib(S,alfa,preamp)
n=length(S)-1;
tmp=alfa^2*S/n;
Sc=10*log10(tmp);
Sc=Sc+30-preamp;  %Reference preamp = 30dB

%FILENAME: findalfa.m

% Calculates scaling factor using the rms-value of a time signal
% INPUT: time domain signal (s), wanted dB value (dB)
% OUTPUT: scaling factor (alfa)
%---------------------------------------------------------------

function [alfa]=findalfa(s,dB)
srms=rms(s);
alfa=10^(dB/20)/srms;
%FILENAME: oceff.m

%Calculates the difference between two power spectra
%INPUT: reference spectrum (ref), signal spectrum (s)
%OUTPUT: difference spectrum (diff)
%------------------------------------------------------------

function [diff]=oceff(ref,s)

diff=s./ref;

%FILENAME: smooth.m

%Smooth the spectrum with 1/3 octave bandpass filter, length=513
%INPUT: spectrum to be smoothed (S), frequency axis (f)
%OUTPUT: smoothed spectrum (Ssmooth)
%------------------------------------------------------------

function [Ssmooth]=smooth(S,f)

hlp=f(101)-f(100);           % Difference between two freq. components
f1hlp=2^(1/6);
f2hlp=2^(1/3);
Ssmooth=S;
     %Initialising Smooth
     %The first 10 samples are not smoothed

for i=11:457,
    %Smoothing for sample 11 to 457 (102-4639 hz)
    f0=f(i);
    %Defines new f0
    f1=f0/f1hlp;
    %Defines new f1
    f2=f1*f2hlp;
    %Defines new f2
    tmp=round((f0-f1)/hlp);
    %Calculate nearest sample number
    f1=i-tmp;
    tmp=round((f2-f0)/hlp);
    f2=i+tmp;
    Ssmooth(i)=magnave(S,f1,f2); %Calculates the 1/3 octave average at sample i
end;

for i=458:512,
    %f2 is permantly set to the last sample
    %Smoothing of the last samples
    f0=f(i);
    %Defines new f0
    f1=f0/f1hlp;
    %Defines new f1
    tmp=round((f0-f1)/hlp);
    %Calculate nearest sample number
    f1=i-tmp;
    Ssmooth(i)=magnave(S,f1,f2); %Calculates the 1/3 octave average at sample i
end;
\% FILENAME: occeff.m

\% Calculates the difference between two power spectra
\% INPUT: reference spectrum (ref), signal spectrum (s)
\% OUTPUT: difference spectrum (diff)
\%---------------------------------------------------------------

function [diff]=occeff(ref,s)

diff=s./ref;

end

Calculations of statistical values for the occlusion effect

\% FILENAME: stataecn.m

\% Loads all subject files of OEHAn, normalised and calculate
\% the overall levels and peaks and the average level within 5 frequency
\% ranges according to the Bark scale
\% Put all results in one file
\% This file can also be used for OEHAn then the postfix 'oeen' shall
\% be changed to 'oen'
\%---------------------------------------------------------------

clear,

load c:\p521\brugere\occeff\fparray.mat; \% Vector with all subject indices
load c:\p521\brugere\occeff\freqsp.asc;

i=1; \% Initialising index for subject name
j=1; \% Initialising index for subject number

while i < 4,

\% Load files
\%---------------------------------
loadfile=['load c:\p521\brugere\oeres\fparray(i:i+2),oeen.asc'];
eval(loadfile);
filename=['fparray(i:i+2),oeen']
oecn=eval(filename);
clearfile=['clear ',filename];
eval(clearfile);

\% Enter function
\%---------------------------------
oechnaln=ones(1,8); % Initialising the output matrix

oechnaln(j,1)=10*log10(sum(oechn(21:80))); % Overall level 200-800 Hz
oechnaln(j,2)=10*log10(max(oechn(11:80))); % Maximum value 100-800 Hz
[peak,k]=max(oechn(81:400));
oechnaln(j,3)=10*log10(peak); % Maximum value 800-4000 Hz
oechnaln(j,4)=freqsp(k+80); % and frequency

clear peak;
clear k;
oechnaln(5)=10*log10(sum(oechn(11:20))); % Overall value 100-200 Hz
oechnaln(j,6)=sum(10.*log10(oechn(13:26)))/(26-13+1); % Average 125-250 Hz
oechnaln(j,7)=sum(10.*log10(oechn(27:50)))/(50-27+1); % Average 250-500 Hz
oechnaln(j,8)=sum(10.*log10(oechn(51:100)))/(100-51+1); % Average 500-1000 Hz

j=j+1;
i=i+3;
end

% Save output matrix
##
save c:\p521\brugere\oesg\tmp.asc oecnaln -ascii;
APPENDIX H:

STATISTICAL METHODS

This is a summary of the statistical test methods used in the report. The statistical tests are performed with the program "Statgraphics".

DATA PROCESSING

Welch method
The spectral density is estimated with the Welch method. This method basically divides the time signal into a certain number of overlapping windows. It then multiply the time signal with the first window and performs a FFT. This FFT is then added to the FFT of the next window and so on. In order to un bias the spectrum, the final sum of all the FFT's are squared and normalised with the number of windows and the norm of the window. The theoretical power spectral density, PSD, is given by the auto-correlation:

\[ PSD = P_{xx}(\omega) = \sum_{m=-\infty}^{\infty} R_{xx}(m)e^{-j\omega m} \]

The Welch estimate of the spectrum can be written as:

\[ P_{xx}(\omega) = \frac{1}{K} \sum_{k=1}^{K} \left| \sum_{n=0}^{M-1} x^{(i)}(n)w(n)e^{-j\omega n} \right|^2; i = 1, 2, \ldots, \]

where;
K = number of windows
M = window length
w = window

DATA ANALYSIS

Missing values
If a data set is not complete it will contain "missing values". Statgraphic can handle missing values either listwise or pairwise. Listwise means that a case is excluded if there are any missing values for any variable. Pairwise means that all cases are included and all non-missing values for each variable are used whenever possible. Statgraphics will prompt for which method to use. The listwise method method is default.
Standard deviation
A short notice shall be given on the standard deviation because it is an extremely important statistical value and care have to be taken on how to use it.

The best estimate for the empirical standard deviation is derived by the Maximum Likelihood estimate:

$$\sigma = \left[ \frac{\sum (X_i - \mu)^2}{n-1} \right]^{\frac{1}{2}}$$

where;
$\sigma$ = standard deviation
$\mu$ = calculated mean
n = sample size

This express the standard deviation of the sample, also called the sample standard deviation. For normal distributed data there is a probability of 0.68 that a test value will lie in the range of $\mu \pm \sigma$, 0.95 within $\mu \pm 2\sigma$ and 0.997 within $\mu \pm 3\sigma$. Example: If the empirical mean for human height is 170 cm and $\sigma = 20$ cm, then a randomly chosen person would with 95% probability be 170 cm ± 20 cm tall.

Instead of looking at a single test value one could look at the mean of all sample values. The more samples available the closer the mean of these samples will be to the empirical mean.

The standard deviation of the sample mean, $\sigma_s$, can be estimated from $\sigma$ by weighting it with the sample size, (Holscher, 1971):

$$\sigma_s = \left( \frac{1}{n} \right)^{\frac{1}{2}}$$

Example: consider the human height again. Now, instead of picking one person, then 25 persons heights are measured. The mean height of these 25 persons will with 95% chance lie within 170 cm ± (20 cm/(25)^{\frac{1}{2}}) = 170 ± 4 cm.

Significance
The level of significance, $\alpha$, can be seen as the probability of rejecting a true hypothesis. In most cases a deviation from the hypothesis is considered significant if the probability of obtaining by chance a deviation is less than 0.05 and highly significant if the probability is less than 0.01. The hypothesis is then rejected at a significance level $\alpha$.

TEST FOR NORMAL DISTRIBUTION
Many analysis methods assumes normally distributed data. Estimations of the sample mean and variance are used for fitting the data to a normal distribution. The fitting is tested with a chi-square test and if $\alpha < $ desired significance level the data cannot be accepted as normally distributed. Usually a confidence interval of 95% and $\alpha = 0.05$ is appropriate.
ONE SAMPLE ANALYSIS
This analysis method is used for testing the variance and mean of a single random sample or two paired samples. A t-test is used to test if the estimated mean value of the sample can be accepted to correspond to the hypothetical value. If \( \alpha \) < the desired significance level then the hypothesis is rejected. The test assumes normally distributed data.

TWO SAMPLE ANALYSIS
A two sample analysis estimates the means and variances of two non-paired samples and uses a t-test to test the difference between the two means. As in one sample analysis the data must be normally distributed.

ONE WAY ANALYSIS OF VARIANCE
One way analysis of variance is used for testing whether two or more independent samples have the same mean values.

The test value is F-distributed and found by:

\[
F = \frac{MS_{\text{between groups}}}{MS_{\text{within group}}}
\]

where \( MS = \) means square

The test value is tested against the F-distribution for \( F(n,m) \) where \( n = \) degrees of freedom in the denominator of the test value and \( m = \) degrees of freedom in the numerator of the test value.

The significance level, \( \alpha \), is the level of probability where the F-distribution is smaller than the test value: (one tailed test)

\[
F(n,m)_{\alpha} < F
\]

If \( \alpha \) is less than the defined test level, then the two samples can be regarded as homogen with the same mean values.

KRUSKAL-WALLIS ONE WAY ANALYSIS OF VARIANCE
This test is used when the data are measured on an ordinal scale and there are more than two independent samples.

The samples cannot be assumed to be drawn from the same sample \( (H_0 = \text{false}) \) if:

\[
H >= \chi^2_{\alpha} (df)
\]

where: \( H = \) test value, \( df = \) degrees of freedom
This means that $H_0$ is true if the corresponding $\alpha >$ the desired $\alpha$ (5%).

If the number of cases in each sample exceeds 5 then $H$ is $\chi^2$ distributed. If there are 3 samples with 5 cases or less in each sample then a special table must be used, e.g. Siegel (1956) table O.

**LINEAR REGRESSION AND CORRELATION**

**Regression**
Regression should be used if it is believed that values of a sample data set, $Y$, are a consequence of the values of another data set, $X$.

A linear regression plots the best fitted line between a pair of variables. It gives an estimate of the intercept and slope of the regression line. The regression line can be regarded as reliable if most of the sample points lie in the 95% confidence interval range. The regression intercept and slope estimates is tested using Students t-distribution. If the t-value of a desired significance level is smaller than the test value, then the estimated parameter is significant. A two-tailed test must be made if the interest is to know whether or not there is a correlation regardless of the sign. In this case the t-value for $\alpha/2$ is used.

The standard error of estimate is a measure of the error to be expected in estimating $Y$ for a given $X$.

**Example:**
If the sample data are exactly $Y = 2X$ the regression slope will be 2 with a probability level of 0. The correlation coefficient will be exactly 1, and the standard error of estimate is 0.

Statgraphics displays the result of a regression analysis as shown in **Figure H.1**.

![Image of a scatter plot with regression line](image)

**Figure H.1** - Example of regression line calculated in Statgraphics.
The middle line is the linear regression line. The two lines closest to the middle line are the confidence intervals (default = 95%) and the two lines farthest away from the regression line are the prediction intervals (default = 95%) i.e. the range within the given percentage of observations will occur for each new prediction.

**Correlation coefficients**

Correlation coefficients should be used when it is believed that there is some kind of relation between two data sets, but where the one does not have to be a consequence of the other. Pearsons correlation coefficient, $\rho$, provide an estimate of how well the two data sets are related. This estimate is useful if:

- a linear regression model is significant
- the dependent sample values are normally distributed
- the regression slope is significant
- the variance of the dependent sample data are the same for all independent values

The empirical way of calculation the correlation coefficient is:

$$\rho = \frac{\text{Cov}(X,Y)}{\sqrt{\text{V}(X)\text{V}(Y)}}$$

where;

$\text{Cov}(X,Y) =$ covariance of X and Y

$\text{V} =$ variance

If the data are exactly the same, Pearsons coefficient is numeric 1, if they are fully non-correlated it is 0. The coefficient lies between -1 and +1, the sign indicates whether the slope of the regression is negative or positive. The correlation can be considered as zero (no correlation) if the test value is smaller than the t-value for a given significance level.

$R^2$ is the ratio of the variance of the estimated value to the variance of the observed value of the regression line. If $R^2$ equals 1=100%, the variances are the same. A small value of $R^2$ means that the variance of the estimated value is much smaller than the variance of the observed value.

**Relation between regression and correlation**

The slope of the regression line can be estimated from the least deviation parallel to the X-axis or the Y-axis. If the two estimated slopes are multiplied it gives $R^2$:

$$R^2 = bb'$$

where b and b' are the two slopes.
The correlation coefficient can be written as:

$$\rho = \frac{SAP}{\sqrt{SAK_x \cdot SAK_y}}$$

where:
SAP = the sum of the deviation on the products on x and y
SAK_x = the sum of the squared deviations between the regression line and the x values
SAK_y = the sum of the squared deviations between the regression line and the y values

The slope of the regression line is calculated by:

$$b = \frac{SAP}{SAK_x}$$

The correlation coefficient equals the normalised slope:

$$\rho = b \sqrt{\frac{SAK_x}{SAK_y}}$$

**KENDALLS CORRELATION COEFFICIENT**

Data that are not normally distributed can be analysed by non-parametric methods. Kendall's correlation coefficient is estimated by the rank number of the data instead of using the actual data values. The coefficient lies between -1 and 1. The significance of the coefficient is tested by the normal distribution because when the sample is larger than at least 10 the correlation coefficient follows the normal distribution.

**PARTIAL CORRELATION ANALYSIS**

A partial correlation analysis is useful when the data consist of several observation sets which are related. This analysis method measures the relationship between two observed data sets while controlling others. The weakness of this method is that it is not possible to find the significance level of the estimated correlation.

The most known is Kendall's partial rank correlation coefficient, which is a non-parametric method and assumes that the data are measured in at least an ordinal scale. This method is not available in the used version of Statgraphics, therefore a parametric partial correlation analysis must be used.

**CALCULATION OF VENT TRANSMISSION LOSS**

A parallel vent in an earmould can be considered as a uniform tube open in both ends. If the radiation at the ends is neglected, the acoustic impedance of the tube can be found by (Rasmussen, 1981):
$$Z_a = \sqrt{\frac{2\omega \rho \eta}{\pi a^2}} + j\omega \frac{\rho L}{\pi a^2}$$

where;
\(\omega\) = frequency
\(\rho\) = density of air
\(\eta\) = viscosity of air
\(L\) = length of tube
\(a\) = radius of tube

This formula is only valid if:
$$\frac{0.01}{\sqrt{f}} < a < \frac{10}{f}$$

If \(a\) lies between 0.4-10 mm then the formula is valid between 100-1,000 Hz.

The transmission loss through a vented earmould inserted in the ear canal is the open ear pressure divided by the closed ear pressure. In terms of impedance it can be written (Lybarger, 1980):

$$20 \log \left( \frac{P_{\text{open}}}{P_{\text{closed}}} \right) = 20 \log \left( \frac{Z_{\text{vent}} + Z_{\text{earcanal}}}{Z_{\text{vent}}} \right)$$

The can be factorised and if it is assumed that \(a^3 \gg a^2\) then a simple equation for the proportion of transmission loss is derived:

$$20 \log \left( \frac{P_{\text{open}}}{P_{\text{closed}}} \right) \propto 20 \log \left( \frac{Z_{\text{earcanal}}}{\omega \rho/\pi} \right) + 20 \log \left( \frac{a^2}{L} \right)$$

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