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## Hearing one's own voice during phoneme vocalization-Transmission by air and bone conduction

Sabine Reinfeldt, Per Ostli, Bo Hakansson and Stefan Stenfelt

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Original Publication:

Sabine Reinfeldt, Per Ostli, Bo Hakansson and Stefan Stenfelt, Hearing one's own voice during phoneme vocalization-Transmission by air and bone conduction, 2010, JOURNAL OF THE ACOUSTICAL SOCIETY OF AMERICA, (128), 2, 751-762.

<http://dx.doi.org/10.1121/1.3458855>

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Postprint available at: Linköping University Electronic Press

<http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-58777>

**Title:**

Hearing one's own voice during phoneme vocalization – transmission by air and bone conduction.

**Short running headline:**

Hearing one's own voice

**Authors:**

Reinfeldt Sabine,

Chalmers University of Technology, Department of Signals and Systems, Division of Biomechanical Engineering, Göteborg, Sweden

Östli Per,

Chalmers University of Technology, Department of Signals and Systems, Division of Biomechanical Engineering, Göteborg, Sweden

Håkansson Bo,

Chalmers University of Technology, Department of Signals and Systems, Division of Biomechanical Engineering, Göteborg, Sweden

Stenfelt Stefan,

Linköping University, Department of Clinical and Experimental Medicine, Division of Technical Audiology, Linköping, Sweden

**Corresponding author:**

Stefan Stenfelt

Linköping University

Department of Clinical and Experimental Medicine

58185 Linköping, Sweden

Phone: +46 13 222856

Email: stefan.stenfelt@liu.se

Webb: [www.liu.se](http://www.liu.se)

## **Abstract**

The relationship between the bone conduction (BC) part and the air conduction (AC) part of one's own voice has previously not been well determined. This relation is important for hearing impaired subjects as a hearing aid affects these two parts differently and thereby changes the perception of one's own voice. A large ear-muff that minimized the occlusion effect while still attenuating AC sound was designed. During vocalization and wearing the ear muff the ear-canal sound pressure could be related to the BC component of a person's own voice while the AC component was derived from the sound pressure at the entrance of an open ear-canal. The BC relative to AC sensitivity of one's own voice was defined as the ratio between these two components related to the ear-canal sound pressure at hearing thresholds for BC and AC stimulation. The results of ten phonemes showed that the BC part of one's own voice dominated at frequencies between 1 and 2 kHz for most of the phonemes. The different phonemes gave slightly different results caused by differences during vocalization. However, similarities were seen for phonemes with comparable vocalization.

## **PACs numbers:**

43.64.Bt, 43.64.Ha, 43.71.An

## I. INTRODUCTION

During vocalization, a person perceives his or her own voice from sound transmitted via two different pathways; (1) air conduction (AC), which is the “normal” path for the sound to the cochlea via the ear-canal, the tympanic membrane (TM), and the middle ear ossicles; and (2) bone conduction (BC), where vibrations in the skull bone are transmitted to the cochlea in different ways (Tonndorf, 1966; Stenfelt and Goode, 2005). The BC component of a person’s own voice consists of vibrations which are transmitted directly from the oral cavity to the cochlea via the skull bone, while the AC component exits the mouth and is transmitted to the cochlea via the ear-canal. The difference between the perception of the BC and AC components of one’s own voice has been sparsely investigated.

So far, the two components have been estimated to be of similar strength but vary with frequency (von Békésy, 1949; Pörschmann, 2000). Von Békésy (1949) attached tubes filled with cotton to the ears to attenuate the AC component without changing the loudness of the BC sound by avoiding an occlusion effect. The decrease in loudness of the person’s own vocalization after applying the tubes was assumed to be equivalent to the AC component of the person’s own voice. The decrease in loudness was reported to be around 6 dB, indicating that the AC and the BC components are similar in magnitude. In the same study, von Békésy also demonstrated that the BC component is higher for sounds produced by a small opening of the mouth compared to sounds that require larger openings. Pörschmann (2000) used large ear-muffs with incorporated loudspeakers to determine the ratio between the perception of the BC and the AC component of a person’s own voice. First, the test subjects vocalized while listening to pure tones that changed in amplitude; they pressed a button when the tone was audible. The aim was to determine the masked thresholds for the BC component of their own voice. This was done at frequencies between 0.4 and 6.5 kHz. Second, the recorded own voice

from the first test was provided through loudspeakers while presenting pure tones; this gave masked thresholds for AC. The threshold difference between the two tests was assumed to be the BC relative to the AC component of one's own voice. This was done for an unvoiced sound /s/ and a voiced sound /z/. The outcome from Pörschmann's study was that at frequencies between 0.7 to 1.2 kHz, the BC component was greater than the AC component while below 0.7 kHz and above 1.2 kHz, the AC component dominated. Also, the relative BC component was greater for the voiced phoneme than the unvoiced one.

The relation between the contribution of the BC sound and the AC sound to the perception of one's own voice, here termed the BC relative to AC sensitivity of one's own voice ( $BC_{rel}AC_{OV\_Sens}$ ), is complex and not well determined. From von Békésy's (1949) and Pörschmann's (2000) studies, one can conclude that the relationship depend on type of sound production and spoken phonemes. Besides better general understanding of hearing one's own voice, the knowledge about the two routes during vocalization is important for designing and fitting hearing aids, since the perception of one's own voice is affected by a hearing aid fitting (Kuk, 2005). Moreover, it has been hypothesized that recording one's own voice as skull vibrations (BC microphone) gives a better signal-to-noise ratio than an ordinary AC microphone in an extremely noisy environment (Oyer, 1955; Black, 1957; Fujita et al., 2006). Although slightly beside the main focus here, information about the BC component during speech production is important as it is a measure of a person's own voice that is recorded by a BC microphone and how it differs from the recording by an ordinary AC microphone (Ono, 1977; Zeng et al, 2003).

Figure 1 shows a simplified model for the two pathways, AC and BC, when hearing one's own voice. The sound production from the vocal cords and oral cavity is shown as "Voice

production” in the model. This sound production causes both airborne sound (leftwards transmission in Figure 1) and BC sound (upwards transmission in Figure 1). The airborne sound outside the mouth is transmitted to the entrance of the ear canal via a mouth-to-ear transmission block and is then transmitted through the outer, middle, and inner ear blocks to become a neural representation causing a sound perception. The BC part of the own voice is modeled similarly but in three different pathways representing the (1) outer, (2) middle, and (3) inner ear parts. The model blocks are here assumed linear and stationary and the changes in AC and BC transmission appears in the source (voice production), i.e. the amount of AC transmitted sound and BC transmitted sound depend on the sound produced, which here is categorized as different phonemes.

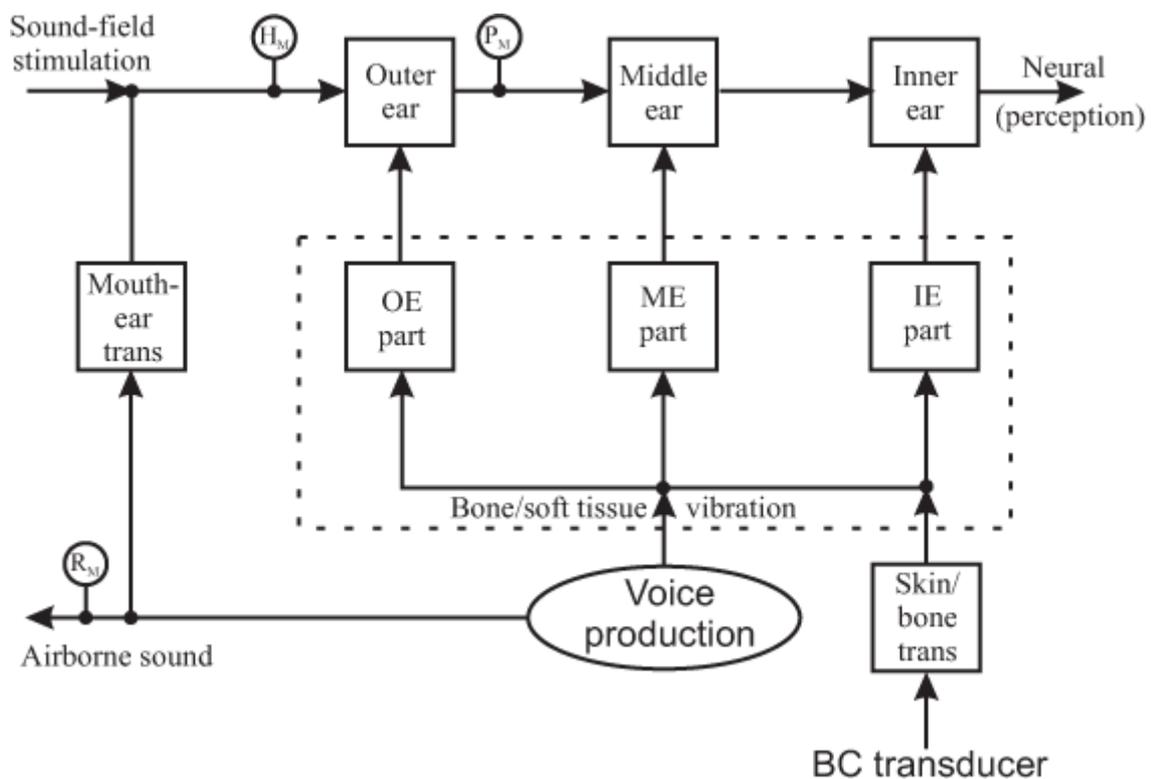


Figure 1: A model of the AC and BC transmission pathways during own vocalization where the voice source is illustrated as an ellipse causing airborne and BC sound. The BC transmission (dashed box) is assumed to give rise to a sound pressure in the ear-canal, motion of the middle ear ossicles, and a sound pressure in the inner ear. The AC transmission is from the airborne sound via a mouth-to-ear pathway transmitted to the outer ear for further transmission to the inner ear via the middle ear. Also indicated in the model is the positioning of the three measurement microphones ( $R_M$ ,  $H_M$ ,  $P_M$ ) and the entrance of AC stimulation (sound field stimulation) and BC stimulation (BC transducer).

The model in Figure 1 incorporates possibilities to stimulate directly by AC (sound field stimulation) and BC (BC transducer). The AC stimulation is a sound field stimulation that enters the outer ear at the ear canal (the effect from head and body is for simplicity included in the sound field) while the BC stimulation is through a BC transducer where a transmission block is included for the transmission through the skin and skull bones. Consequently, the BC stimulation transmission block depends on the stimulation position.

A way to estimate the contribution by AC and BC of one's own voice is to compare the output from the inner ear block for AC and BC transmission separately. Unless subjective measures are used (like masking procedures), this is difficult to accomplish in the human. Therefore, another approach will be used here. The sound pressure in the ear canal during vocalization can easily be measured using a probe-tube microphone. With the assumption that the blocks in Figure 1 are linear and stationary, the relative contribution from AC and BC to the perception of one's own voice can be estimated according to the following:

1. measurement of the ear-canal sound pressure during vocalization from AC alone,
2. measurement of the ear-canal sound pressure during vocalization from BC alone,
3. measurement of the ear-canal sound pressure at AC hearing thresholds, and
4. measurement of the ear-canal sound pressure at BC hearing thresholds.

By relating the ear-canal sound pressure during vocalization to the ear-canal sound pressure at hearing threshold, the audibility of the AC part and BC part during vocalization can be estimated, and later compared for the amount of BC sound that is heard in relation to the AC part of one's own voice. The details of these calculations are presented in section II.C and E.

According to the procedure presented, one prerequisite to estimate the AC and BC part of one's own voice is to be able to measure the AC and BC part of the ear-canal sound pressure

separately. Removing the AC part is most straightforward since it can be attenuated by the use of an ear muff (typical attenuation for an ear-muff range from 15 dB to 40 dB<sup>1</sup>). Hence, an ear-muff would effectively attenuate the ear-canal sound pressure of the AC component of a subject's own voice. If the air volume of the ear-muff is large enough, the occlusion effect from the ear-muff is insignificant (Stenfelt and Reinfeldt, 2007). Therefore, the ear-canal sound pressure from BC alone during own vocalization could be measured by a probe-tube microphone close to the TM while wearing an ear-muff that gives no occlusion effect and attenuates the AC contribution. The BC component cannot be attenuated in a similar way. However, the sound pressure at the open ear-canal entrance would primarily be caused by the AC part from the sound production. This sound pressure at the ear-canal entrance can be transformed to a sound pressure at the TM by measurement of the AC transmission between the ear-canal opening and the TM.

In what follows, the ratio between the BC part of the ear-canal sound pressure and the AC part of the ear-canal sound pressure during vocalization is termed the BC relative to AC ear-canal sound pressure of one's own voice and abbreviated as  $BC_{reAC_{OV\_ECSP}}$  (OV = own voice; ECSP = ear-canal sound pressure). The ratio between the BC and AC parts of one's *perceived* own voice, derived as described above, is referred to as the BC relative to AC sensitivity of one's own voice and abbreviated  $BC_{reAC_{OV\_Sens}}$  (Sens = sensitivity). Moreover, Békésy (1949) indicated that the BC relative to AC sensitivity of one's own voice ( $BC_{reAC_{OV\_Sens}}$ ) depend on the sound produced. Therefore, in total, ten different phonemes from five different phoneme groups are investigated for their relative AC and BC contribution to hearing one's own voice ( $BC_{reAC_{OV\_Sens}}$ ).

The aim of this study is to determine the BC relative to AC sensitivity of one's own voice for ten different phonemes.

## **II. MATERIALS AND METHODS**

### **A. Subjects**

All measurements were conducted on twenty voluntary subjects (10 male and 10 female, age between 23 and 34 years with an average of 29.5 years) with otologically normal ears (ISO 226, 2003). Their hearing thresholds were no worse than 20 dB HL in the frequency range 125 to 8000 Hz and the interaural difference was no more than 15 dB at any frequency measured. These baseline hearing thresholds were obtained with a digital audiometer (Interacoustics AC40) using the Hughson-Westlake procedure in accordance with ISO 8253-1 (1989).

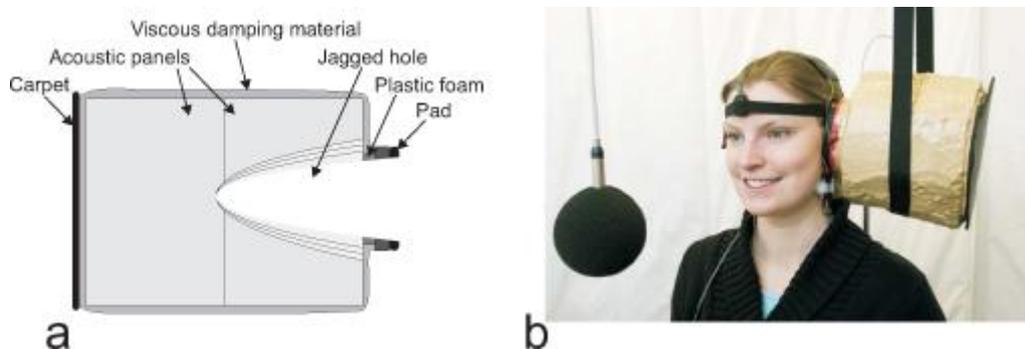
### **B. Materials**

A sound insulated room of 16 m<sup>3</sup> was used for all measurements and the test subject was placed in a chair with a neck support. All measurement equipment are listed in Table 1 and the measurement procedures, explaining the usage of the equipment, are described in Section II.C.

#### **B1. Custom-made large ear-muff**

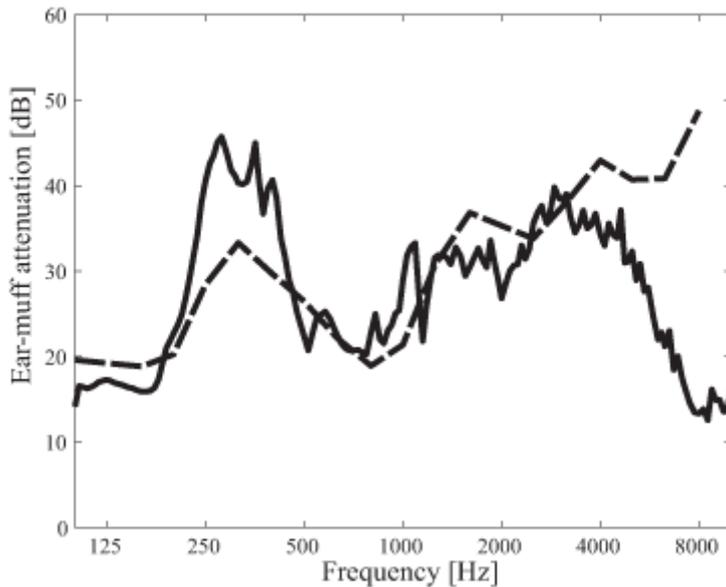
To attenuate the AC sound transmitted to the ear canal without causing an occlusion effect, a large ear-muff, shown in Figure 2, was developed. A Peltor Optime III was used as a base, where the muffs were removed and only the pads and the headband remained. Two approximately round pieces of sound insulating acoustic panel with a diameter of 20 cm and a thickness of 8 cm were attached to each other using glue (Loctite IS 480), sound absorbing

plastic foam, and damping tape (3M™ VHB™). In the acoustic panel closest to the head, a hole was made resulting in volume of approximately 245 cm<sup>3</sup>(see Figure 2). This hollow portion was jagged to minimize influence from standing waves. An approximately 5 mm thick layer of viscous damping material (Swedac DG-U1, ratio 7:1, Swedac Acoustic) was added on the outside of the acoustic panel to increase AC sound attenuation. Finally, a piece of a sound insulating carpet made of bitumen was attached to the end of the ear-muff to further improve the AC sound attenuation. Because of its weight (1.2 kg), it was suspended by bands attached to the ceiling.



*Figure 2: The design of the large ear-muff. Two acoustic panels were glued together and covered by viscous damping material on the outside. One end was covered by a bitumen carpet and the other end was opened creating a hollow portion of 245 cm<sup>3</sup>. This space was large enough to minimize the occlusion effect.*

The goal was an AC sound attenuation by a minimum of 20 dB at frequencies between 0.1 and 10 kHz without causing an occlusion effect; that was almost accomplished. Figure 3 shows the insertion loss of the ear-muff measured with an acoustic test fixture (ISO 4869-3, 2007), and the average of the attenuation from the 20 test subjects, measured as the difference between the ear-canal sound pressure level with and without the ear-muff.



*Figure 3: Attenuation obtained with the large ear-muff. The solid line shows the average ear-canal sound pressure attenuation among the test subjects in this study. The dashed line shows the insertion loss measured on an acoustic test fixture.*

### **C. Measurements**

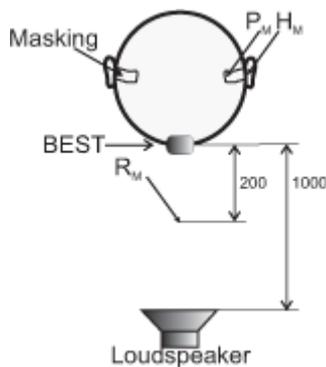
Measurements were done for three conditions: (1) open ear-canal, (2) occluded ear-canal, and (3) closed ear-canal without occlusion effect. The order of the measurements was altered between the test subjects to avoid order errors. However, all measurements for the same condition were obtained in a single sequence to ensure exact same situation for all measurements in that condition.

#### **C1. Hearing thresholds**

To estimate the BC and AC components of one's own voice, measurements of AC and BC hearing thresholds with higher level and frequency resolution than normally obtained using standard audiometry were required. Therefore, hearing thresholds for BC and AC stimulation were obtained with a Békésy procedure using pulsed and frequency modulated tones; this was

implemented in MATLAB<sup>®</sup> on a regular PC equipped with a sound card. The hearing thresholds were obtained at 1/3-octave band frequencies between 160 Hz and 8 kHz; higher frequency resolution was deemed too time consuming. Hearing thresholds for BC stimulation at 125 Hz are known to be insecure. At this frequency, some subjects' response may be tactile rather than auditory. Therefore, hearing thresholds at this frequency were not used and the hearing thresholds started at 160 Hz.

All testing was done in the left ear while the right ear was masked with noise for monaural hearing thresholds with both AC and BC stimulation (see Figure 4). The masking noise was broadband spectrally designed to be at equal level above the normal hearing thresholds (0 dB HL) for all 1/3-octave frequency bands. The masking noise was fed from a CD player via a power amplifier (Sony) to an insert earphone. The foam part of the insert earphone was modified to avoid occlusion effect (Stenfelt and Reinfeldt, 2007).



*Figure 4: Measurement setup with positions of microphones, loudspeaker, BC transducer (BEST), and masking device. The distances between the subject and the positions of the reference microphone [ $R_M$ ] and the loudspeaker are given in millimeters (200 and 1000, respectively).*

The hearing threshold testing with AC stimulation was done in a sound field and frequency modulated tones were used to minimize the influence from standing waves in the test room.

Although not necessary with BC threshold testing, the same modulated tones were used enabling comparisons of the results with AC and BC hearing thresholds. Moreover, modulated tones were chosen over narrow-band noise for threshold testing as tones are easy for the test subject to distinguish from the masking noise. For the frequency modulation, a frequency deviation of  $1/24$  times the center frequency and a modulation frequency of 8 Hz were used. Furthermore, to ease the task of detecting the target signal, a pulsed sequence was used with  $3/8$  of a second on and  $1/8$  of a second of silence (two tones per second) and with ramped onset and offset of  $9/64$  of a second.

The threshold software was implemented in MATLAB<sup>®</sup> and used at a sampling frequency of 48 kHz. The setup was tested and found linear for the frequencies and levels used here. The subject indicated hearing the tone by pressing the left button of a regular PC mouse; when the subject no longer heard the tone, the button was released. The rate of intensity change was set to 2.5 dB/s and the threshold was determined as the average of four sequential reversals (two maxima and two minima). If the difference between the two maxima or between the two minima exceeded 5 dB at a frequency, an extra run was made and the threshold was calculated from six reversals (three maxima and three minima) as the average of the median of the three maxima and the median of the three minima.

## **C2. Sound pressure at hearing threshold**

The sound pressure was always measured at three positions even if not all sound pressure measurements were used in the analysis. As indicated in Figures 1 and 4, the three measurement positions were (1) 20 cm in front of the mouth (reference microphone, position called  $R_M$ ), (2) at the ear-canal entrance (probe-tube microphone, position called  $H_M$ ), and (3)

in the ear-canal approximately 3 mm from the TM (probe-tube microphone, position called  $P_M$ ). The neck support that was used for all measurements gave a well defined distance between the mouth and the reference microphone as well as between the head and the loudspeaker (Figure 4).

The positioning method for the ear-canal probe-tube microphone (position  $P_M$ ) depended on the measurement condition. For an open ear-canal, the tube opening of the probe-tube microphone was placed at the  $P_M$  position by inserting it until it touched the TM, and then retracting it 3 mm. In the occluded condition, the ear-canal was occluded by a foam ear-plug. The plug was inserted so that the distance between the ear-plug and the TM was approximately 14 mm for all test subjects. Although there are individual differences in ear-canal length, the occlusion effect for the subjects should be comparable (Stenfelt and Reinfeldt, 2007). To avoid leakage when measuring at the  $P_M$  position, the probe-tube penetrated the ear-plug. To close the entrance of the ear-canal to significantly reduce the AC component without altering the ear-canal sound pressure during BC stimulation (avoiding an occlusion effect), the custom-made large ear-muff described previously was used.

For BC stimulation, a BC transducer was attached to the center of the forehead by a softband with a static pressure between 2.5 and 3.0 N (average 2.9 N). The BC transducer was custom made using BEST technology (Håkansson, 2003) that enabled stimulation at low frequencies without non-linear distortion that affected the measurements. For AC stimulation, a loudspeaker was positioned one meter in front of the subjects face and in level with the head. The positioning of the microphones, loudspeaker, and BC transducer are illustrated in Figure 4 and the reference microphone and positioning of the BC transducer is visible in Figure 2b.

The sound pressures during AC and BC stimulation were measured with a signal analyzer (Pulse<sup>®</sup>). During the measurements, the output of the system was fed via a power amplifier (Rotel) to the BC transducer or the loudspeaker, and the sound pressure was measured according to a steady state response procedure (SSR in Pulse<sup>®</sup>) at frequencies between 100 Hz and 10 kHz with a frequency resolution of 1/24 octave (logarithmically spaced). The sound pressures at the three microphones (at R<sub>M</sub>, H<sub>M</sub>, and P<sub>M</sub>) were measured simultaneously by the signal analyzer. The stimulation level during both AC and BC testing were set high enough for the measurement of sound pressures at the microphones to be well above the noise floor. The measured sound pressures were later related to the hearing thresholds to give the sound pressure at threshold; this procedure is described in section II.E

### **C3. Sound pressure from vocalization**

The same microphones in the same positions as described above measured the sound pressure during vocalization. Also, the measurements were obtained with the signal analyzer (Pulse<sup>®</sup>) but as time recordings at a sampling frequency of 65536 Hz. All vocalizations were in Swedish and a set of ten phonemes were used for this stimulation. Phonemes from five of the most common groups were represented: front vowels, back vowels, plosives, nasals, and fricatives. Two phonemes from each group were recorded. Front vowels: /e/ (e:) and /i/ (i:), back vowels: /a/ (ɑ:) and /o/ (o:), plosives: /k/ (k) and /t/ (t), nasals: /m/ (m) and /n/ (n), and fricatives: /s/ (s) and /tj/ (tj). To avoid order errors, lists with the phonemes in different orders were generated. For each condition (open, ear-plug, and large ear-muff), vocalization of each phoneme was conducted three times. Each vocalization was 2-3 seconds long, except for /k/ and /t/, which were repeated at least five times at each vocalization. The test subjects were

instructed to talk at a high enough level to obtain a signal above the noise floor for the microphone recordings. However, this was not achieved at all frequencies for all test subjects, and values at low SNRs were removed from the data set (see section II.F).

#### **D. Calibrations**

Except for the baseline audiograms, the results in this study are based on relative measures, i.e. differences in sound pressure levels. Consequently, the results are not affected by calibration errors. However, all equipment used was calibrated and validated enabling control of measurements to be at a reasonable level. More importantly, the linearity of the soundcard, used for the hearing threshold measurements, was investigated in-depth ensuring linear behavior for the levels and frequencies used.

#### **E. Calculations**

The estimate of the BC relative to AC sensitivity of one's own voice ( $BC_{reAC_{OV\_Sens}}$ ) was calculated from the sound pressure and hearing threshold measurements described above. The following is a description of the calculation steps. Unless otherwise stated, the calculations are done in the frequency domain. The measurements and equations are presented in the format where the first text indicates the microphone position, the first subscript indicates the stimulation type, and the second subscript indicates condition or transmission type. Accordingly,  $ECSP_{OV\_Muff}$  mean the ear-canal sound pressure (microphone at TM), during own vocalization (OV) and with the ear-muff on.

The sound pressures were measured using three different types of sound stimulations (AC sound field, BC transducer at the forehead and, own vocalization) and three conditions (open

ear-canal, ear-plug, large ear-muff). For the two stimulations that were generated by the signal analyzer system, AC sound field and BC transducer at the forehead, the stimulation level could be set equal for all three measurement conditions. However, the source level could not be controlled during vocalization where voice strength and duration differed slightly between measurements. Therefore, the vocalization data was always normalized to the reference microphone ( $R_M$ ) in front of the test subjects' mouth to give comparable data between vocalizations. This means that all ear-canal sound pressure measurements during vocalization are obtained as relative sound pressures

$$ECSP_{OV} = \frac{[P_M]}{[R_M]}, \quad (1)$$

and similarly for sound pressure measures at the ear-canal entrance

$$EntranceSP_{OV} = \frac{[H_M]}{[R_M]}. \quad (2)$$

### **E1. BC relative to AC ear-canal sound pressure of one's own voice**

As illustrated in Figure 1, the  $BCreAC_{OV\_Sens}$  is calculated from the relation between the BC and AC contribution to the ear-canal sound pressure during vocalization, the BC relative to AC ear-canal sound pressure of one's own voice ( $BCreAC_{OV\_ECSP}$ ). The latter is derived as the ratio between the BC part of ear-canal sound pressure during vocalization ( $ECSP_{OV\_BC}$ ) and the AC part of ear-canal sound pressure during vocalization ( $ECSP_{OV\_AC}$ ) as

$$BCreAC_{OV\_ECSP} = \frac{ECSP_{OV\_BC}}{ECSP_{OV\_AC}} \quad (3)$$

The BC contribution to the ear-canal sound pressure during vocalization is measured as the ear-canal sound pressure with the large ear-muff, i.e.

$$ECSP_{OV\_BC} = ECSP_{OV\_Muff} \cdot H \quad (4)$$

Since the BC component is difficult to remove from the ear-canal sound pressure, the AC part of the ear-canal sound pressure during vocalization ( $ECSP_{OV\_AC}$ ) is estimated from the sound pressure at the ear-canal entrance during vocalization ( $EntranceSP_{OV\_Open}$ ) and corrected for the sound transmission between the ear-canal entrance and the TM ( $H = \text{entrance to TM}$ ).

$$ECSP_{OV\_AC} = EntranceSP_{OV\_Open} \cdot H \quad (5)$$

$$H = \frac{ECSP_{AC\_Open}}{EntranceSP_{AC\_Open}} \quad (6)$$

The above calculations assume that the open ear-canal entrance sound pressure during vocalization ( $EntranceSP_{OV\_Open}$ ) is dominated by AC transmitted sound and that the influence from BC sound radiated in the ear-canal is insignificant. This assumption was verified by comparing the sound pressure at the ear-canal entrance for open and plug in the ear-canal ( $EntranceSP_{OV\_Open}$  vs.  $EntranceSP_{OV\_Plug}$ ): the measured sound pressures for the two conditions were approximately equal.

## **E2. BC relative to AC sensitivity of one's own voice**

The relative difference between the BC and AC sensitivity of one's own voice ( $BCreAC_{OV\_Sens}$ ) can be estimated from the  $BCreAC_{OV\_ECSP}$  derived above (Equation 3) using the sound pressures at hearing thresholds. In principle,  $BCreAC_{OV\_Sens}$  is a measure of the audibility of one's own voice transmitted by BC relative to AC. Therefore, the audibility of the vocalization transmitted by BC and AC is determined as the sound pressure in the ear-canal above the hearing thresholds. To achieve that, the ear-canal sound pressures at thresholds are determined from the hearing threshold measurements and the ear-canal sound

pressure measurements with either AC sound field stimulation (for AC data) or stimulation by the BC transducer (for BC data). Consequently, the ear-canal sound pressure at threshold for AC stimulation is calculated as

$$ECSP_{AC@Threshold} = ECSP_{AC\_Open} \square \frac{AC \text{ threshold amplitude}_{Open}}{AC \text{ stimulation amplitude}_{Open}} . \quad (7)$$

Equation (7) is given in amplitudes even if hearing thresholds are usually measured in decibels; the thresholds are converted to the amplitude domain before the calculation.

However, the interpretation of equation (7) is rather straightforward: if the ear-canal sound pressure for the 1 kHz frequency band is measured at a sound field stimulation level of 60 dB SPL (20 mPa) and the hearing threshold for 1 kHz as measured by the Békésy procedure is 20 dB SPL (0.2 mPa), the  $ECSP_{AC\_Open}$  needs to be adjusted 100 times (40 dB) to give the ear-canal sound pressure at threshold for AC stimulation ( $ECSP_{AC@Threshold}$ ). In a similar way, the ear-canal sound pressure at threshold for BC stimulation is calculated from measurements with the BC transducer at the forehead and with the large ear-muff.

$$ECSP_{BC@Threshold} = ECSP_{BC\_Muff} \square \frac{BC \text{ threshold amplitude}_{Muff}}{BC \text{ stimulation amplitude}_{Muff}} . \quad (8)$$

Now, the ear-canal sound pressures during own vocalization can be related to the ear-canal sound pressures at hearing threshold giving an estimate of the audibility of one's own voice as transmitted by BC and AC according to

$$BCreAC_{OV\_Sens} = BCreAC_{OV\_ECSP} \square \frac{ECSP_{AC@Threshold}}{ECSP_{BC@Threshold}} . \quad (9)$$

## **F. Analysis**

The above described calculations were done for all three vocalization repetitions of the ten phonemes. Each phoneme vocalization was manually cut out from the time recording in the time domain using a window with a cosine ramp of 0.01 second at the start and end, and with a flat plateau between. The normalized phoneme was transformed to the spectral domain using Fourier transform. Next, to enable comparison with the sound pressure data obtained with AC sound field and BC transducer stimulation, the spectrum of the phoneme vocalization was recalculated to a frequency resolution of 1/24-octave by averaging the values within 1/3-octave surrounding each 1/24-octave frequency.

Then, all estimates were converted to decibels and for each subject the level of each frequency band was the average of the three repetitions of each phoneme. All vocalization data were compared in the spectral domain to the recorded noise (recording without stimulation); if the value at any of the frequencies (1/24-octave) was lower than 6 dB above the noise floor, that datum was removed from the data set. Sound pressure data from BC stimulation was often below the set SNR limit below 160 Hz and above 6.3 kHz.

Consequently, such data were removed. Most of the bad data at low and high frequencies with BC stimulation were obtained with an open ear-canal or when wearing the large ear-muff; with the ear-canal occluded by an ear-plug, the occlusion effect increased the ear-canal sound pressure above the noise floor at low frequencies and these BC data could be used.

### III. RESULTS

#### A. Ear-canal sound pressure during vocalization

The ear-canal sound pressure (as measured by the microphone  $P_M$ ) relative to the reference sound pressure ( $R_M$ ) (Equation 1) during vocalization of the phonemes /e/ and /s/ is shown in Figure 5 for three measurement conditions: (1) the ear-canal open, (2) with the large ear-muff, and (3) with an ear-plug. The results are the averages from all test subjects and the standard error of the mean (SEM) is given. When the ear-canal is open, the ear-canal sound pressure contains both AC and BC transmitted sound while the ear-canal sound pressure is dominated by BC sound for the ear-muff and the ear-plug conditions. The difference in ear-canal sound pressure between the ear-plug and the ear-muff is caused by the occlusion effect. It is clear that the AC sound contributes significantly to the ear-canal sound pressure for these two phonemes; the differences between the open and the two occluded situations are the greatest at the higher frequencies. Occluding the ear-canal changes the resonance properties of the ear-canal, and the high-frequency difference between the open and the two occluded situations is influenced by this effect; the ear-plug measurements more so than the ear-muff measurements. At those frequencies where no data are shown, less than five subjects reached the set SNR limit of 6 dB. This occurred mostly at high frequencies when the AC sound was attenuated.

The two phonemes in Figure 5 show differences in the ear-canal sound pressure. This was true for all ten phonemes where the relative ear-canal sound pressure varied. However, similarities were seen between the phonemes within the same phoneme groups. When

comparing the relative ear-canal sound pressure for /e/ and /s/, it can be seen that the relative BC component is higher for /e/ than for /s/ around 1 kHz (the relative ear-canal sound pressure for the large ear-muff is higher), while it is the opposite at lower frequencies. It should be remembered that the ear-canal sound pressure data in Figure 5 are related to the sound pressure in front of the mouth; even if the relative ear-canal sound pressure data with open ear-canal were slightly higher for /s/ than for /e/, the absolute ear-canal sound pressure (without normalizing for the vocalization strength) was higher for /e/ than for /s/.

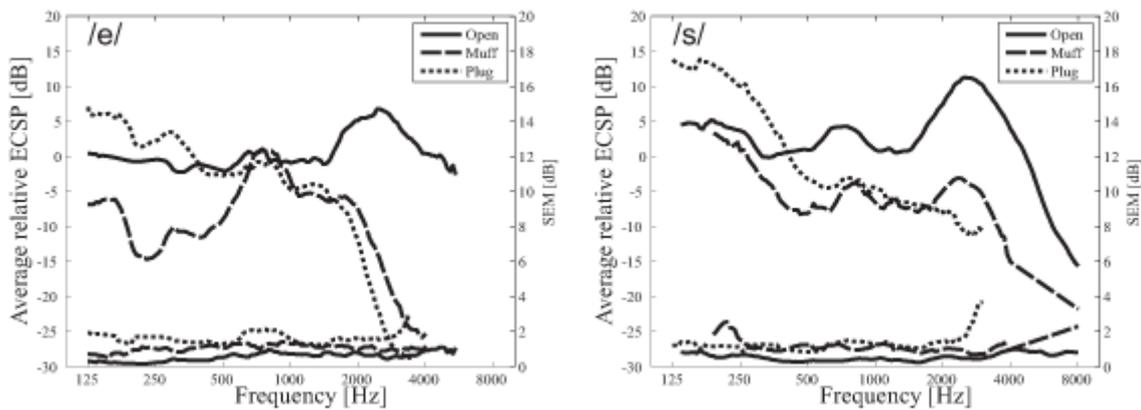


Figure 5: The ear-canal sound pressure  $[P_M]$  relative to the reference sound pressure  $[R_M]$  for open ear-canal, large ear-muff, and ear-plug, all for the phonemes /e/ and /s/. Results are given as averages of the data from all subjects with datum above the 6 dB SNR limit (left ordinate) and standard error of the mean (SEM, right ordinate).

Individual data points and their average are shown in Figure 6 for the two phonemes /e/ and /s/ at the three measurement conditions. The first row shows the relative ear-canal sound pressure (the ear-canal sound pressure  $[P_M]$  relative to the reference microphone  $[R_M]$ , equation 1) with the ear-canal open; the second row shows the relative ear-canal entrance sound pressure (ear-canal entrance sound pressure  $[H_M]$  relative to the reference microphone  $[R_M]$ , equation 2) with the ear-canal open, and the third row shows the relative ear-canal sound pressure when the large ear-muff was applied ( $[P_M]$  re  $[R_M]$ , equation 1). The dots are the data from the subjects that obtained measured data above the 6 dB SNR limit, and the

solid line is the average over those subjects if they were five or more. The difference between the relative ear-canal sound pressures at the TM and the entrance with an open ear-canal (two first rows in Figure 6) is primarily caused by the ear-canal resonance, but the sound pressure at the TM is also influenced by the BC sound while the sound pressure at the entrance is not.

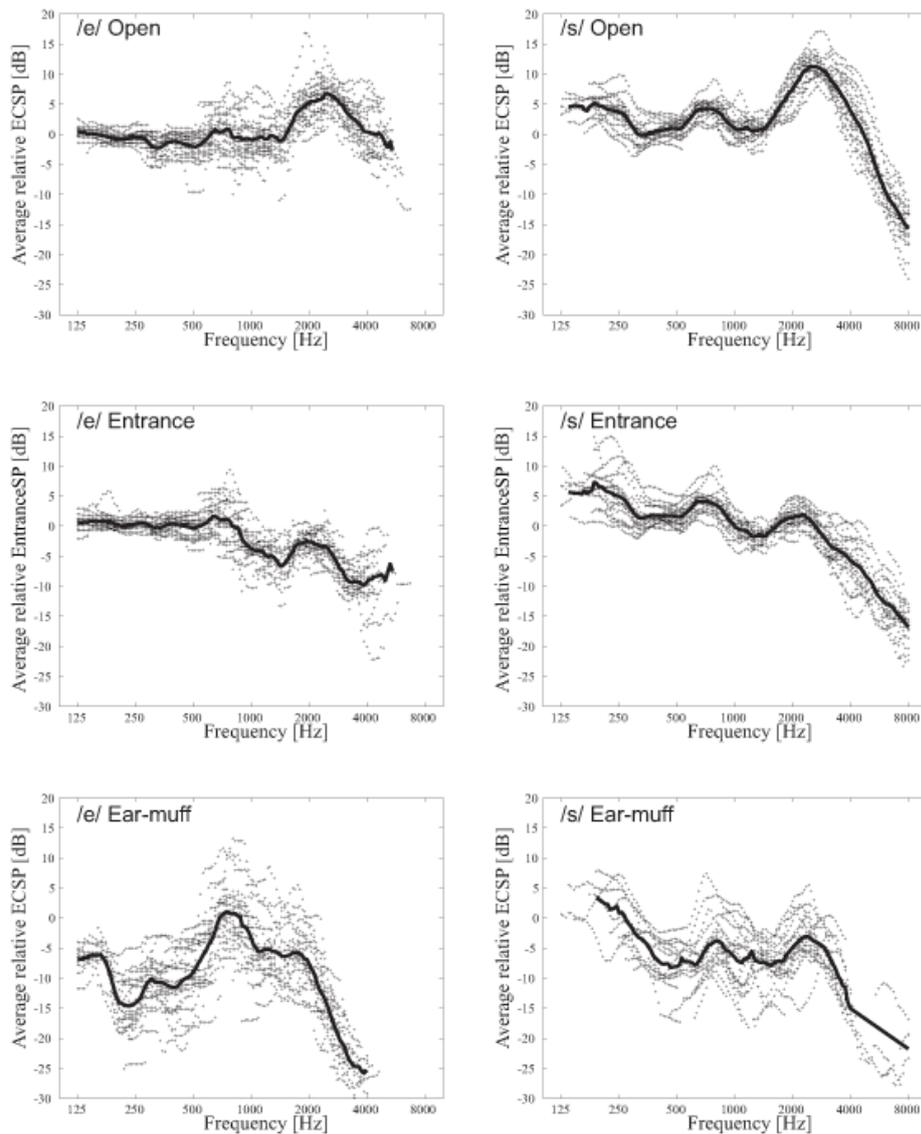


Figure 6: The individual and average relative ear-canal sound pressure with open ear-canal (row 1), individual and average relative sound pressure at the entrance of open ear-canal (row 2), and individual and average relative ear-canal sound pressure for the large ear-muff (row 3) shown for vocalizations of the phonemes /e/ (column 1) and /s/ (column 2). The dots indicate data points above the 6 dB SNR limit from all subjects, and the thick lines are the averages of those data points if they were five or more.

When the relative ear-canal sound pressure was measured with the large ear-muff (row 3 in Figure 6), the intersubject variations were greater than in the two other situations. We offer the following explanation for this finding: when wearing the large ear-muff, the ear-canal sound pressure is dominated by BC sound, and this component of one's own voice is probably more dependent on the anatomy of the skull and the speech production than the AC component is. Since there are large variations of the composition and anatomy of the human skull, the BC component has larger intersubject variations than the AC component has.

### **B. AC and BC components of one's own voice**

In Figure 7, the BC relative to AC ear-canal sound pressure of one's own voice ( $BCreAC_{OV\_ECSP}$ ) and the BC relative to AC sensitivity of one's own voice ( $BCreAC_{OV\_Sens}$ ) are shown for all ten phonemes used in this study. The data are presented as the average from all subjects where five or more data points exceeded the SNR limit. In the first row, the results of the phonemes /e/, /i/, /a/, and /o/ are shown, and in the second row, the results of the phonemes /k/, /t/, /m/, /n/, /s/, and /tj/ are shown. A positive value indicates that the BC component is higher than the AC component. The  $BCreAC_{OV\_ECSP}$  is an objective measure that describes the difference in ear-canal sound pressure for the BC and the AC part of one's own voice. The  $BCreAC_{OV\_Sens}$  is a subjective measure, since it also includes individual hearing thresholds. The difference between the  $BCreAC_{OV\_ECSP}$  and the  $BCreAC_{OV\_Sens}$  equals the difference in ear-canal sound pressure at hearing threshold between AC and BC sound. The AC path to the cochlea is through the ear-canal and the middle ear ossicles, while BC sound has several important pathways, cf. Figure 1. When the  $BCreAC_{OV\_Sens}$  is higher than the  $BCreAC_{OV\_ECSP}$ , the ear-canal sound pressure at the hearing threshold is higher for AC than for BC sound.

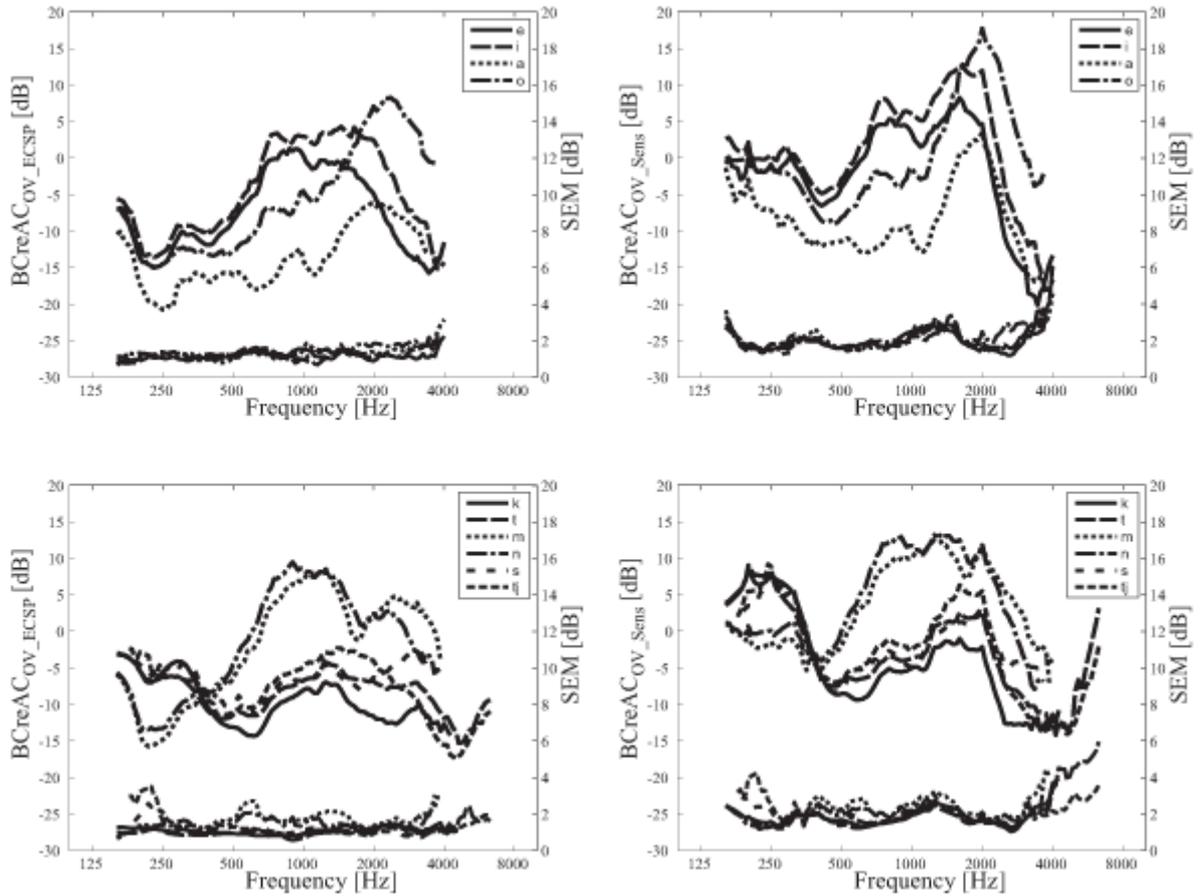


Figure 7: Estimates of the BC relative to AC ear-canal sound pressure of one's own voice ( $B_{CreAC_{OV\_ECSP}}$ , first column) and the BC relative to AC sensitivity of one's own voice ( $B_{CreAC_{OV\_Sens}}$ , second column) are shown for ten vocalizations. The phonemes /e/, /i/, /a/, and /o/ are shown in the first row, while the second row shows the phonemes /k/, /t/, /m/, /n/, /s/, and /tj/. Results are given as averages of data points for all subjects above the 6 dB SNR limit (left ordinate) and standard error of the mean (SEM, right ordinate).

When  $B_{CreAC_{OV\_ECSP}}$  in Figure 7 is positive, the ear-canal sound pressure includes more BC sound than AC sound from one's own voice, meaning that more sound is radiated into the ear-canal from vibrations in the skull bone and soft tissues than is transmitted from the mouth via the surrounding air. For the ear-canal sound pressure of one's own voice, the BC component is highest for the phonemes /m/ and /n/; it is almost 10 dB higher than the AC component around 1 kHz.

A positive  $BCreAC_{OV\_Sens}$  indicates that more BC than AC sound from one's own voice is perceived by the human ear. Hence, during own vocalization, the human ear perceives more BC than AC sound at frequencies where the  $BCreAC_{OV\_Sens}$  is positive. For the sensitivity of one's own voice, /m/ and /n/ have among the highest values of the phonemes used (similar to the result of the  $BCreAC_{OV\_ECSP}$ ), but the BC component for /o/ is even higher; it is about 15 dB higher than the AC component at 2 kHz.

## IV. DISCUSSION

### A. Error analysis

The sound pressure at the entrance of the open ear-canal, transformed to sound pressure at the TM by the transfer function between ear-canal entrance and TM during AC sound field stimulation (equation 6), was used as the AC component of one's own voice. In this calculation, the sound pressure at the entrance of the open ear-canal was assumed to only include AC transmitted sound. However, it could be contaminated by BC sound radiated from the ear-canal. To investigate whether this was the case, the sound pressure at the entrance of the open ear-canal was compared to the sound pressure at the ear-canal entrance occluded with an ear-plug. The latter condition excludes BC radiation from the ear-canal but it also changes the acoustics slightly for the sound pressure at the ear-canal entrance measurement. We found the sound pressure at the entrance of the open ear-canal to differ less than 3 dB at any frequency compared with the sound pressure at the ear-canal entrance when using an ear-plug; this means that the error caused by BC transmission from the ear-canal was bounded by 3 dB. However, the difference is also believed to be caused by the ear-plug itself, since it changes the appearance of the concha and, by that, the acoustics. Hence, the AC sound transmission is changed. Since our measurements could not reveal the cause of the difference,

the sound pressure at the entrance of the open ear-canal was used for the calculation of the AC component.

One source of uncertainty for the BC component was that the BC stimulation was provided at the forehead by the BC transducer, which is at an anatomical different position than the oral cavity and the vocal cords where the vocalization stimulation origin. The BC transmission from the forehead to the ear-canal and the cochlea are most probably different compared with that from the oral cavity and the vocal cords. One may argue that the teeth would be better than the forehead as stimulation point since it is anatomically closer and the BC transmission pathways may be more similar to the BC vocalization pathways. This was investigated in two subjects by comparing the ear-canal sound pressure and hearing thresholds with open ear-canal when BC stimulations were at the teeth and at the forehead. The ear-canal sound pressure and the hearing thresholds were similar for the two stimulation positions (forehead and teeth). This was taken as an indication that using the forehead as stimulation position could be used for deriving an approximate estimation of the BC component of one's own voice. It was also noticed that the BC transmission at the teeth depended on the biting force; the biting force was difficult to control and maintain at a specified level during the entire measurement. This was yet another indication of the forehead as a favourable stimulation position as it provides a stable condition.

All measurements were conducted in a sound insulated room of 16 m<sup>3</sup> that had semi-hard walls. Hence, it is not fully anechoic. Therefore, the room itself may have influenced the AC data. However, additional damping material was placed in the test room and it was arranged

in a non-rectangular order to minimize the possibility of standing waves. We therefore believe that if the room influenced the data its effect was small.

All vocalization data were compared to the noise floor in the spectral domain (in each frequency band), and if the value was below the SNR limit (6 dB above the noise floor), the datum was removed from the data set. The average and the SEM were only calculated for those frequencies where data from at least five subjects remained. Since the noise level was approximately the same for all subjects, this means that low values were discarded while high values (above the SNR limit) were included. Such procedure causes a bias toward higher values when low-level data are removed due to the noise. Since more data points from ear-canal sound pressure measures with the large ear-muff (BC data) were removed than from sound pressure at the entrance of the open ear-canal (AC data),  $BCreAC_{OV\_ECSP}$  and  $BCreAC_{OV\_Sens}$  may be biased towards higher values.

## **B. Calculations of the BC and AC contributions during vocalization**

The estimate of the BC relative to AC sensitivity of one's own voice ( $BCreAC_{OV\_Sens}$ , Figure 7) was, beside the calculation presented in section II.E, also computed with two other methods. All methods estimated the AC component of one's own voice the same, but the estimations of the BC component differed. Since the AC part of the ear-canal sound pressure with an open ear-canal was estimated, the BC part could be estimated from the ear-canal sound pressure with an open ear-canal by removing the AC part. This calculation resulted in a  $BCreAC_{OV\_Sens}$  that was similar to the present one (Figure 7) at low frequencies, but differed at high frequencies. This difference is primarily attributed to the phase calculation; at higher frequencies, the estimation of the sound pressure phase becomes uncertain. Using this type of

computation, the derivation of the BC part is based on subtraction and is therefore sensitive to small errors in the phase estimate. Due to the subtraction, errors originating in AC radiation from the BC transducer at higher frequencies, and/or ear-canal sound radiation at the entrance from BC transmission may also affect the BC estimate.

Another way that the  $BCreAC_{OV\_Sens}$  was calculated was by using the ear-canal sound pressure obtained with the ear-plug. In this case, the ear-canal sound pressure is assumed to contain only BC transmitted sound but is affected by the occlusion effect. However, since the BC hearing thresholds are also affected by the occlusion effect, the changes in BC hearing thresholds and ear canal sound pressure can be assumed to cancel. This calculation approach gave a slightly higher  $BCreAC_{OV\_Sens}$  at low frequencies than the method using the large ear-muff. The low-frequency difference can be explained by the occlusion effect. Even if the occlusion effect influences the ear-canal sound pressure similarly for stimulation by BC transducer at the forehead as the BC part of the vocalization (as measured by the change in ear-canal sound pressure during vocalization with ear-plug and ear-muff), the hearing thresholds are different. An occlusion changes the relative contribution between the outer ear part of BC relative the other contributions (middle and inner ear, see Figure 1). Consequently, the estimation of the BC part of one's own voice is for a different BC transmission system than what is normally perceived with an open ear canal. Therefore, the estimation of the BC part of  $BCreAC_{OV\_Sens}$  using an ear-plug is erroneous at low frequencies. Of the three methods, the one using the large ear-muff provides the best estimate over the largest frequency range. At low frequencies the ear-plug method gives too high estimates due to the occlusion effect and at high frequencies the subtraction method overestimates BC component and thereby the  $BCreAC_{OV\_Sens}$ . However, the ear-muff method gave comparable results to the subtraction method at low frequencies and to the ear-plug method at higher frequencies; this

is an indication that the ear-muff method gave valid estimates of the BC part of the  $BCreAC_{OV\_Sens}$ .

### **C. The BC relative to AC sensitivity of one's own voice**

The stapedius muscle contracts a short period before vocalizing (Borg and Zakrisson, 1975) and is believed to be elicited throughout the vocalization. It is not clear how this affects BC sound. For example, the sensitivity for BC sound is normally only slightly affected by a middle ear impairment (Katz, 1994) indicating that a contraction of the stapedius muscle should not affect the BC component of one's own voice. However, one study on cats suggests that the effect of the stapedius muscle is similar for AC and BC sound transmission: approximately 10 dB attenuation for frequencies below 1.5 kHz (Irvine, 1976). An attenuation of AC transmission of 5 to 10 dB for frequencies below 1.5 kHz in cats was also reported by Moller (1965) but the effect of the stapedius muscle contraction on AC sound transmission in man have been reported to range from no effect to an attenuation that increases with decreased frequency below 2 kHz reaching 40 dB (Morgan and Dirks, 1975). As far as the authors know, the effect from the stapedius reflex on BC sound in human has never been reported. Since the influence from the stapedius muscle on BC sound transmission is not known in the human, its effect is not included in the calculations of  $BCreAC_{OV\_Sens}$ . If the data from Irvine (1976) holds for humans, the estimates of the AC and BC components are affected equally. However, it is likely that the AC component is attenuated more than the BC component by the action of the stapedius muscle. Consequently, the true  $BCreAC_{OV\_Sens}$  may be slightly higher than our estimates.

In Figure 7, the  $BCreAC_{OV\_ECSP}$  and the  $BCreAC_{OV\_Sens}$  are shown for all ten phonemes used. There are large variations between some of the phonemes, but similarities are seen for phonemes from the same group. A likely reason for these similarities is that phonemes from the same group are produced in approximately the same way, either in the vocal cords, in a part of the oral cavity or as a combination of both. For example, the fricatives (/s/ and /tʃ/) are mostly produced in the oral cavity, while the front vowels (/e/ and /i/) are both produced by the vocal cords and in the frontal part of the oral cavity. Our own perception of the front vowels was dominated by BC sound at frequencies between 700 Hz and 2.1 kHz, while our own perception of the fricatives was dominated by BC sound at frequencies below 350 Hz and between 1.4 and 2.1 kHz. This difference can be explained by the differences in speech production. Fricatives, which have almost no involvement of the vocal cords, seem to give more AC sound than front vowels. Differences were also found between the nasals (/m/ and /n/) and the other phonemes, which could be explained by that the nasal sound is not transmitted through an open mouth as the other phonemes. The strong BC part for /m/ and /n/ in the 0.7 to 1.2 kHz area may be caused by the nasal cavity resonance (Sandberg, 1977). Furthermore, it is highly plausible that closed lips, in comparison to open, provide less AC sound compared to BC sound. This phenomenon could explain the difference between the back vowel phonemes, /a/ and /o/. The lips are more opened for /a/ than for /o/; consequently less BC relative to AC sound was transmitted to the ear-canal and the cochlea for /a/. These findings are in line with the statement by von Békésy (1949) that the BC component is relatively higher for sounds produced by a small opening of the mouth than by a large opening.

Our test group consisted of an equal number of male and female subjects. We therefore analyzed  $BCreAC_{OV\_ECSP}$  and  $BCreAC_{OV\_Sens}$  for the two groups separately and compared the

results. No obvious differences between the sexes were discovered, except for a small difference at low frequencies, where the males had slightly higher  $BCreAC_{OV\_ECSP}$  values. This implies a slightly higher BC part of the ECSP for males than for females at low frequencies. However, the small difference between the sexes was not significant.

Pörschmann (2000), who estimated the AC and BC components of one's own voice for two phonemes (comparable to our  $BCreAC_{OV\_Sens}$ ), also reported differences between phonemes (/s/ and /z/). However, in his results, the BC part of one's own voice dominated for both phonemes between 700 Hz and 1.2 kHz. In our results, the highest contributions of the BC part of one's own vocalization were at frequencies between 1.5 and 2 kHz. Also, the peak of the  $BCreAC_{OV\_Sens}$  was different compared with the peak in Pörschmann's study. A difference between the two studies is that Pörschmann used a masking procedure to estimate the two components of sound transmission whereas we used hearing thresholds and ear-canal sound pressures. Even if both methods should give similar results, the procedural difference may partly explain the difference.

It should be noted that for all phonemes in this study, except for /k/, the BC component was greater than the AC component of the sensitivity of one's own voice in the 1.5 to 2 kHz frequency range. Recently, Homma et al. (2009) showed in a modelling experiment that the ossicular chain has its resonance for BC stimulation in this frequency range; a finding shown experimentally by Stenfelt et al. (2002). One explanation for the higher influence of BC sound for the perception of our own voice at the frequencies between 1.5 and 2 kHz can be the influence of this middle ear resonance. However, this needs to be further investigated.

Von Békésy (1949) showed that for hearing one's own voice, the AC and the BC components are in the same order of magnitude and that the BC component is higher for sounds produced by a small opening of the mouth. According to the results of our study, von Békésy's statements are correct. The AC and the BC components of one's own voice are approximately in the same order of magnitude, but they are highly frequency dependent. At some frequencies, the AC component dominates, while the BC component dominates at others

## **V. CONCLUSIONS**

Similar to results from previous studies (von Békésy, 1949; Pörschmann, 2000), the relative perception of the BC and the AC parts of one's own voice were shown to be of equal importance; however, frequency dependent. The relative perception was further shown to vary largely for different phonemes, but those generated similarly showed similar relations between the BC and the AC components. The nasals (/m/ and /n/) showed high BC relative to AC sound transmission; the BC part was about 12 dB higher than the AC part around 1 – 2 kHz. The front vowels (/e/ and /i/) did also show BC contribution in the same frequency range, as did the back vowel /o/ with a peak of 15 dB at 2 kHz. The phonemes that had the least contribution by BC at 1 to 2 kHz were the plosives (/k/ and /t/); they had larger BC contribution at low frequencies (below 300 Hz).

## **VI. ACKNOWLEDGMENT**

The study was supported in part by the Swedish Hearing Research Foundation (Hörsselforskningsfonden) and Stingerfonden. We are also grateful to Tobias Good at 3M (at that time Peltor AB) for help with measurements of the large ear-muff on an acoustic test fixture.

## FOOTNOTES

1. values taken from product data sheets from various manufacturers and previous studies, e.g. Berger et al. (2003) and Reinfeldt et al. (2007).

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## Tables

Table 1: List of equipment used for the measurements.

<b>Equipment</b>	<b>Manufacturer and model</b>
Sound card	M-AUDIO Delta 44
CD player	Technics SL-PS740A
Power amplifier	Sony TA-N220
Insert earphone	Etymotic Research ER-2
Reference microphone	Brüel & Kjær 4134
Power supply	Brüel & Kjær 2804
Probe tube microphones	Etymotic Research ER-7C
BC transducer	BEST <sup>®</sup> (Håkansson, 2003)
Loudspeaker	HECO <sup>®</sup> Odeon 100
Signal analyzer	Five-channel input, two-channel output Brüel & Kjær IDAe frame type 3560C controlled by Pulse <sup>®</sup> ver. 12.6
Power amplifier	Rotel RB-976MkII