EUROREGIO BNAM2022
Joint Acoustics Conference
9th-11th of May, Aalborg, Denmark

Free-field correction values for RadioEar DD65 v2 Circumaural Audiometric Earphones

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Abstract

Speech audiometry with earphones requires frequency dependent calibration based on free-field correction values for the particular earphone used. The free-field correction values are derived from a loudness matching experiment between free-field frontal incidence third-octave-band noise signals from a loudspeaker and the required earphone levels as measured on an IEC 60318-1:2009 acoustic coupler. This paper describes the determination and results of free-field correction values for RadioEar DD65 v2 circumaural audiometric earphones for all third-octave band frequencies from 125 Hz to 8 kHz, following the procedure described in the IEC 60268-7:2010 standard using 23 test subjects who also participated in the determination on Equivalent Threshold Sound Pressure Levels for the same earphones. The standard contains details on setting up the loudness comparison to have a controlled sound field and great care was taken to conform with this in the experimental setup. The standard also contains practical details on approximate stimulus and pause durations, and on presentation order; first loudspeaker then earphones. However, when it comes to the choice of psychometric method for obtaining loudness match i.e. how the level of the earphones is varied between presentations and how the final loudness match level is obtained it is just generally stating that the level of the earphones is varied until equal loudness is obtained. As this choice is up to the experimenter, care was taken to eliminate potential biases and a two-alternative forced choice paradigm was chosen. The results are compared to data from another laboratory and a similar type of earphones and possible explanations for minor differences are discussed.

Keywords: earphones, audiometry, equal loudness, calibration.

1 Introduction

Speech audiometric assessment with earphones requires frequency dependent calibration based on free-field correction values for the particular earphone used. The free-field correction values are derived from a loudness matching experiment between free-field frontal incidence third-octave-band noise signals from a loudspeaker and the required earphone levels as measured on an IEC 60318-1:2009 [1] acoustic coupler. When free-field correction values are available for a specific earphone it is possible to determine an overall calibration value for speech audiometers using spectral levels of a simulated speech signal with an overall level of 0 dB. The procedure is described in [2] and involves adding the free-field correction values to the spectral values of the simulated speech signal and calculating the total level of the combined third-octave bands.

Free-field correction values are reported in the literature for different audiometric earphones, for example [2, 9, 11] and following the tradition in the field, this paper describes the determination and results of free-field correction values for the RadioEar DD65 v2 circum-aural audiometric earphone. The free-field correction values are determined for all third-octave band frequencies from 125 Hz to 8 kHz, following the procedure described in the IEC 60268-7:2010 [3] standard, section 'Free-field comparison frequency response', using 23 test subjects who also participated in the Equivalent Threshold Sound Pressure Levels (ETSPL) study by [4]. The IEC 60268-7:2010 [3] standard contains details on setting up the loudness comparison to have a controlled sound field (e.g. minimum distance from loudspeaker is 2 m) and maximum permissible level variations and great care was taken to conform with this in the experimental setup. The standard also contain practical details on approx. stimulus and pause durations, and on presentation order; first loudspeaker then earphone. However, when it comes to choice of psychometric method for obtaining loudness match i.e. how the level of the earphone is varied between presentations and how the final loudness match level is obtained it is just generally stating that the level of the earphone is varied until equal loudness is obtained, and *”The adjustment may be performed by the test person or the test supervisor, or automatically under computer control”* (IEC 60268-7:2010 [3] page 25). As this choice is up to the experimenter, care was taken to eliminate potential biases and a two-alternative forced choice paradigm was chosen. The results are compared to data from another laboratory and a similar type of earphone, possible explanations for differences are discussed.

2 Method and material

2.1. Psychometric method for loudness matching

The point of subjective equality (PSE) corresponds to the earphone sound pressure level (SPL) (as measured in an IEC 60318-1:2009 [1] acoustic coupler) needed in order to be perceived equally loud as the free-field frontal incidence 70 dB SPL signal from the loudspeaker (as measured in the listening position with the subject absent). When performing loudness matching there is a level range around the PSE where the test subject may not be completely certain which sound is the louder, as described by the psychometric function. In this range around the PSE a test subject may, for the same presentation levels, at one time judge the earphone signal louder, but at another time the loudspeaker signal louder. The PSE is defined as the SPL of the earphone at the 50 % point on the psychometric function i.e. the SPL, where either earphone or loudspeaker signal is judged louder 50 % of the time.

Numerous methods for finding the PSE exist (see e.g. [5]), ranging from classical methods like constant stimuli method and method of adjustment, to adaptive methods like staircase method or sequential maximum likelihood estimation. For this study the PSE is found using an adaptive up/down staircase method ([6], [7]), which according to [5] is one of the most used methods of loudness matching. The method uses a two-alternative forced choice paradigm (2AFC), where the test subject must choose whether the earphone signal is softer or louder than the loudspeaker signal. This deals with potential bias from the test subject’s internal criterion on how certain they are of ”equal loudness”, which would be a concern if the test procedure was simply to adjust the level until the subject reports that the earphone is equally loud as the loudspeaker signal.

As specified in IEC 60268-7:2010 [3] standard the level of the loudspeaker signal is fixed at 70 dB SPL while the earphone level is varied in steps, and as such the reference signal is always that from the loudspeaker. The loudness of the earphone signal is judged compared the that of the loudspeaker signal. The staircase method specifies that if the earphone signal is judged louder then it will be decreased in level on the next presentation, and if it is judged softer, then it is increased on the next presentation. When the direction in level is changed i.e. a level increase after a level decrease or visa versa, this is called a reversal. Consequently, the method will converge on the 50 % point on the psychometric function i.e. the PSE.

In order to make the method efficient it was chosen to starts with a larger step size of 4 dB in order to quickly reach the level range around the PSE and serve as a familiarization with the new pair of stimuli. After two reversals the stepsize is reduced to 2 dB in order to converge more precisely at the PSE. A stepsize of 1 dB was first considered, but from initial testing it was determined that it makes the task more difficult for the test subject, as it would increase the number of presentations with similar loudness. It would also increase the duration of the experiment without providing more accurate answers.

As specified in the IEC 60268-7:2010 [3] standard a pause of 2.5 s was inserted before the next free-field presentation. This pause functioned as a natural reminder for the test subject that a new loudness comparison had initiated and that they should forget the previous presentation. The start level for the earphone signal was 70 dB ±5 dB by random, i.e. either 65 dB or 75 dB. This was done in order to prevent start levels too far from the expected PSE for efficiency and to minimize potential systematic bias in start point, i.e. always approaching the PSE from below could potentially cause a small bias. The stop criterion is set at 6 reversals. The mean value of the SPL of the last 4 reversal points is used as an estimate of the PSE. Additionally, for additional verification purpose a psychometric function is fitted to the data using maximum likelihood estimation.

2.2. Maximum likelihood estimation

In order to evaluate the robustness of the PSE obtained by using the average of the last four reversal points and the staircase method itself a maximum likelihood estimation (MLE) procedure is used to fit a theoretical curve to the data. As the cumulative normal distribution is often used to describe the shape of the psychometric function (see e.g. [8]) it is used in this study. The MLE procedure estimates parameters of the psychometric function by fitting a cumulative normal function to all the answers given by the subject during a loudness match (excluding the initial answers before two reversals which are considered familiarisation and therefore not included). The MLE procedure fits the cumulative normal distribution through several iterations of varying the two parameters of the cumulative normal distribution, mean μ and standard deviation σ until optimum values for the two parameters are found. The MLE of the mean is the 50 % point on the psychometric function i.e. the PSE.

2.3. Test setup

The system used for loudness matching consisted of: a Lenovo notebook running a custom made Matlab test program (Matlab 2018a with Audio System Toolbox using ASIO drivers), an external USB 24 bit sound card (RME Fireface UFC), a power amplifier (ROTEL RB-976 MKII, modified to give a constant 0 dB gain and lower noise), an active loudspeaker (Genelec 1031A), and the RadioEar DD65 v2 earphones.

2.4. Transducers

One pair of RadioEar DD65 v2 earphones were included in the tests. According to the IEC 60268-7:2010 [3] standard the left and right transducer should have a similar frequency response within 2 dB. This was fulfilled for the earphones and additionally each transducer was calibrated to give the same level in each ear (as measured on the IEC 60318-1:2009 [1] acoustic coupler - see section 2.8). The free-field sound is reproduced using an active loudspeaker, Genelec 1031A, that has a quite flat frequency response in the frequency range used. This is a requirement in the IEC 60268-7:2010 [3] standard, as it states in Annex C: *"The frequency response of the loudspeaker, measured with sinusoidal signals, should be free from sharp peaks and dips, so as to avoid errors due to colouration"*. Also the harmonic distortion of the loudspeaker at the playback levels of 70 dB SPL used in this study is measured to be well below the limits of 2 % stated in the standard.

2.5. Signals

Third-octave-band filtered pink noise were created in Matlab at the center frequencies from 125 Hz to 8 kHz (48 kHz sampling frequency) and stored as 32 bit wave-files. The duration of each signal was 2.7 s and start and stop shaping was made with half a Blackman-Harris window of 100 ms in duration which was sufficient to prevent clicks at the onset and offset of the signal. Thus, each tone had onset and offset ramps of 50 ms, giving a 2.6 second duration with constant amplitude. The signal level was controlled by digitally attenuating the signals before sending them to the output of the sound card. This was deemed sufficient and free of influence of quantization errors as only a small range of levels were required for the loudness matching and the lowest level needed was in the order of 50 dB from full scale leaving more than 15 bit for the lowest earphone levels on the 24-bit soundcard. The order of frequency was the same for all subjects (see Table 1 for the order in each session 1-4). The order followed the guidelines from the IEC 60268-7:2010 [3] standard, by starting at 1 kHz and progressing up in frequency to the highest frequency (8 kHz), going down in frequency to the lowest frequency (125 Hz) and then increasing the frequency up to the 1 kHz band. The familiarization was done with 1 kHz and not included in the data.

Session 1	1000 Hz	1600 Hz	2000 Hz	5000 Hz	8000 Hz
Session 2	6300 Hz	4000 Hz	3150 Hz	2500 Hz	1250 Hz
Session 3	800 Hz	500 Hz	315 Hz	200 Hz	125 Hz
Session 4	160 Hz	250 Hz	400 Hz	630 Hz	1000 Hz

Table 1: The four sessions and the order of the frequency bands. The familiarisation round before session 1 used 1 kHz, and is not included in the data.

2.6. Response System

In typical loudness matching experiments the test subject would push a button corresponding to which sound was the loudest. However, in this experiment both hands of the subject are occupied with taking earphones on and off repeatedly. Therefore, it would be impractical to use a button test interface. Instead the test subject responded to the presentation by saying out loud whether the earphone sound was ”softer” or ”louder” than the loudspeaker sound. The experimenter would then click the corresponding button on the graphical user interface of the custom made Matlab test program that was also used to supervise the experiment. The Matlab test program loads the stimuli wave-files, adjust levels, presents the stimuli, collects user responses, plots the data in a figure and saves data to files. The signals are send through the sound card to the power amplifier (for earphone signals) or to the active loudspeaker.

2.7. Sound field calibration and verification

All measurements were carried out in the anechoic room of the Acoustics Laboratory of Aalborg University, which is anechoic down to approx. 63 Hz and has a very low background noise level (typically below 0 dB A-weighted SPL).

The reference sound field was calibrated and verified using a free-field microphone (B&K type 4165) connected to a microphone preamplifier (B&K type 2669) connected to a conditioning amplifier (B&K Nexus type 2690) which was connected to the input of the sound card. A custom made Matlab program was used to reproduce the calibration stimuli and record the signals from the microphone. Before the measurements the entire electroacoustic chain (from microphone to digital value) was calibrated using a 1000 Hz calibrator (B&K 4230). The recorded signals were compensated for the microphone sensitivity and conditioning amplifier gain, obtaining amplitude values in Pascals. The reference point is on axis of the loudspeaker at a distance of 2.48 m. The reference level of 70 dB is measured with the test subject absent. The homogeneity of the sound field was verified and within ± 1 dB at all positions 15 cm front/back/left/right/up/down from the reference listening position (see Fig 1). The reference level of 70 dB in the reference listening position was regularly verified by measurement during the days of the experiment.

2.8. Earphone calibration and verification

The SPL from the DD65 v2 (both left and right ear) were determined using an IEC 60318-1:2009 [1] acoustic coupler (B&K type 4153), mounted on the side of a cube so that the distance between each earphone cushion was 135 mm and the measured side was placed centred on the circum-aural earphone adapter plate of the coupler. The headband length was set to give 130 mm from the centre-line between cushion midpoints and the inside top of the headband, giving a coupling force of 10.3 ± 0.7 N. A pressure field microphone (B&K type 4134),

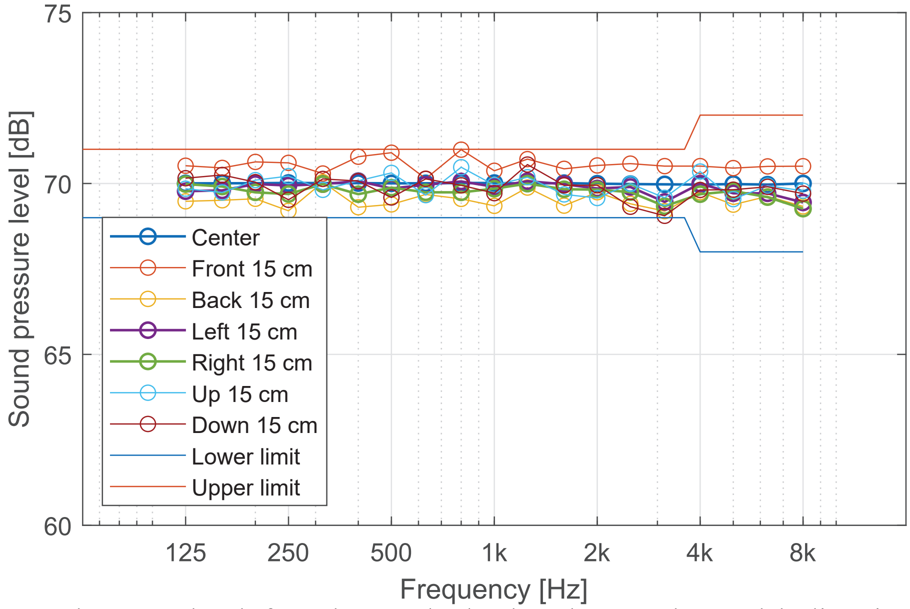

Figure 1: Sound pressure levels from the Genelec loudspeaker at and around the listening positions

microphone preamplifier (B&K type 2669) and conditioning amplifier (B&K Nexus type 2690), were connected to one of the analog inputs of the sound card. A Matlab program was used to reproduce the calibration stimuli and record the sound pressure level produced by the earphone in the acoustic coupler. Before the measurements the entire electroacoustic chain (from microphone to digital value) was calibrated using a 1000 Hz calibrator, B&K 4230. Measurement were made by reproducing different levels from the Matlab program and verifying the levels. The recorded signals were compensated for the microphone sensitivity and measurement amplifier gain, obtaining amplitude valued in Pascals. The earphone calibration for both left and right was regularly verified by measurement during the days of the experiment.

2.9. Fitting of the earphones

Spectacles and earrings were removed and hair-style was rearranged if it might influence the position of the earphones as described in the IEC 60268-7:2010 [3] standard. The earphones were fitted by the test subjects themselves under the supervision of the experimenter. They were instructed to make certain that the earphones rested properly and comfortably around the ears. The experimenter was in control of starting the sound reproduction in the earphones, and would not initiate this before the test subject's hands had left the earphones, which signalled that the earphones were sitting comfortably on the ears. While listening to the loudspeaker in the free field the test subjects held the earphones in their lap.

2.10. Subjects

The 25 normal-hearing and otologically normal test subjects from the ETSPL study [4] were invited to participate. Two test subjects withdrew giving a total of 23 subjects (12 male and 11 female). They were between 18 and 25 years of age. All subjects were students at Aalborg University and received remuneration for their participation.

2.11. Procedure

All subjects were given written instructions outside the anechoic room supported by oral instructions inside the anechoic room. The subject was positioned on the chair and the height was adjusted to get the entrance of the right ear canal in the reference position (marked by a red laser cross) and facing the loudspeaker (marked with red vertical laser on nose). The vertical loudspeaker laser was turned off during the experiment as to not disturb the eyes of the test subject, but the laser cross at the ear was on during the test and the test subject position was continuously monitored and if necessary corrected during the experiment.

Test subjects were instructed to look at the loudspeaker and keep the head position during the experiment. When not listening to the earphones they would hold them in their lap. Following the instructions, a familiarization trial with one frequency band (1000 Hz) was made, before data collection began with session 1.

The experimenter was sitting inside the room at a considerable distance (3.7 m from reference position off-axis) as to not disturb the test subject or the sound field. From this position the experimenter had a good view of the earphones and the laser cross placed at the reference position which should hit the subject right ear canal entrance during free-field exposure from the loudspeaker.

During the experiment, the investigator could monitor the test progress from the Matlab controlled system. Four sessions of five center frequencies were used (see Table 1). Between sessions the subject had a break before proceeding with the next session. The whole test including familiarization and breaks lasted approx. 1 hour per subject.

3 Results

3.1. Free-field correction values

Table 2 shows the earphone level that gives equal loudness to a free-field level of 70 dB (frontal incidence), and Table 3 shows the corresponding free-field correction values. These are shown in Figure 2 and Figure 3 together with maximum likelihood estimates based on the individual answers after the two initial reversals.

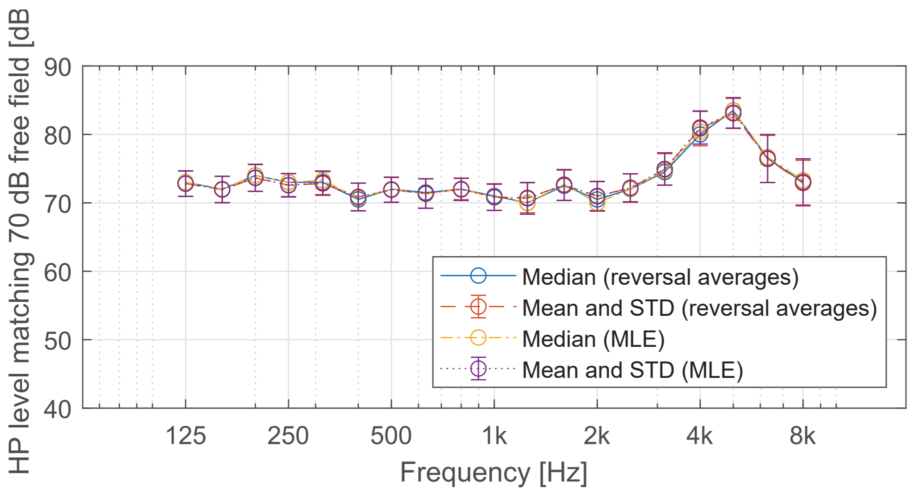

Figure 2: RadioEar DD65 v2 SPL needed to match the loudness of a 70 dB free field third-octave-band noise. Error bars show the standard deviation.

3.2. Determination of SPL of speech presented via earphones

Overall calibration of speech audiometers can be determined for the specific earphone using the free-field correction values and spectral levels of a simulated speech signal with an overall level of 0 dB. The procedure is described in [2] and involves adding the free-field correction values to the spectral values of the simulated speech signal and calculating the total level of the combined third-octave bands. The calculations are based on Impulse time weighting and a fast time weighting reduces the level by 0.5 dB as described by [9]. For the free-field correction values (median) in Table 3 this gives a level of 1.8 dB for impulsive and 1.3 dB for fast time weighting.

Freq. [Hz]	Median [dB]	Mean [dB]	STD [dB]	95% CI [dB]
125	73.0	72.8	1.9	0.8
160	72.0	71.9	1.9	0.8
200	74.0	73.6	2.0	0.8
250	73.0	72.6	1.7	0.7
315	73.0	72.8	1.7	0.8
400	70.5	70.8	2.0	0.9
500	72.0	71.9	1.9	0.8
630	71.5	71.4	2.2	0.9
800	72.0	72.0	1.6	0.7
1000	71.0	70.8	1.9	0.8
1250	70.0	70.7	2.2	0.9
1600	72.5	72.6	2.2	1.0
2000	70.5	71.0	2.1	0.9
2500	72.0	72.2	2.1	0.9
3150	74.5	74.9	2.3	1.0
4000	80.0	80.8	2.5	1.1
5000	83.5	83.1	2.2	1.0
6300	76.5	76.4	3.4	1.5
8000	73.0	72.9	3.3	1.4

Table 2: Earphone levels in coupler in order to loudness match a free-field frontal incidence level of 70 dB SPL reported as median, mean, standard deviation (STD) and 95% confidence interval (CI) for all frequencies

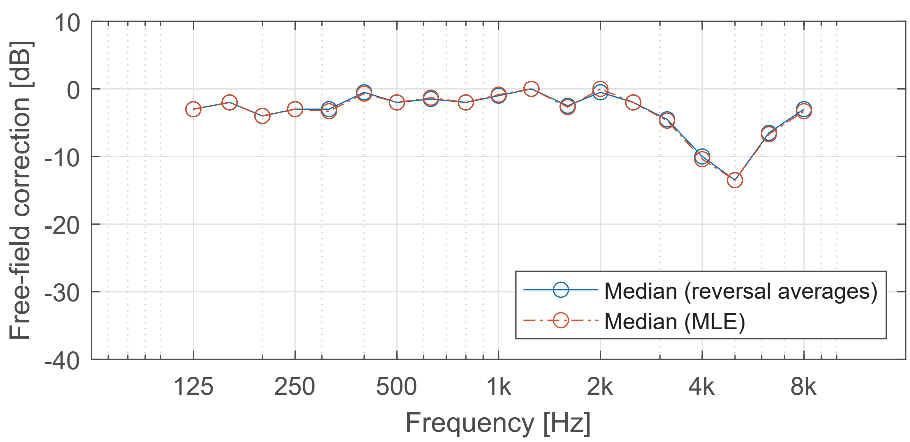

Figure 3: Free-field correction values for RadioEar DD65 v2.

4 Discussion

The median PSE based on the average of the last four reversals and the median PSE based on maximum likelihood estimates from individual answers after the two initial reversals agree with each other. This serves as a confirmation that the reversal averages from the stair-case method give a good estimate of the PSE and the

Freq. [Hz]	Median [dB]	Mean [dB]	STD [dB]	95% CI [dB]
125	-3.0	-2.8	1.9	0.8
160	-2.0	-1.9	1.9	0.8
200	-4.0	-3.6	2.0	0.8
250	-3.0	-2.6	1.7	0.7
315	-3.0	-2.8	1.7	0.8
400	-0.5	-0.8	2.0	0.9
500	-2.0	-1.9	1.9	0.8
630	-1.5	-1.4	2.2	0.9
800	-2.0	-2.0	1.6	0.7
1000	-1.0	-0.8	1.9	0.8
1250	0.0	-0.7	2.2	0.9
1600	-2.5	-2.6	2.2	1.0
2000	-0.5	-1.0	2.1	0.9
2500	-2.0	-2.2	2.1	0.9
3150	-4.5	-4.9	2.3	1.0
4000	-10.0	-10.8	2.5	1.1
5000	-13.5	-13.1	2.2	1.0
6300	-6.5	-6.4	3.4	1.5
8000	-3.0	-2.9	3.3	1.4

Table 3: Free field correction values reported as median, mean, standard deviation (STD) and 95% confidence interval (CI) for all frequencies

free-field correction values.

The free-field correction shows a frequency dependent correction, which is relatively close to 0 dB at the low-to medium frequencies. The difference in this frequency region can possibly be explained by the physical difference between real subject's head and ear and the artificial ear with plate of the IEC 60318-1:2009 [1] acoustic coupler. For example is it expected that there are differences between fit and internal volume, where leakages is mostly influencing the lowest frequencies. In addition, there is a perceptual difference between listening to an external frontal incidence plane wave from a visible loudspeaker and a diotic earphone presentation that will give an auditory event located in the center of the head. It can be hypothesized that this could potentially affect the perceived loudness. At the higher frequencies the pinna will amplify the frontal incidence plane wave, thereby requiring substantial higher levels from the earphone to obtain equal loudness. This is clearly seen in Figure 2 and the free-field correction values where the largest correction is at 5000 Hz, where a median of 13.5 dB increase in level of the earphone signal is required. The standard deviation is generally largest at the highest frequencies 6300 Hz and 8000 Hz, where individual differences in head, and pinna shape, and earphone fit is expected to have a significant impact on the levels at the eardrums for the free-field and earphone playback respectively. For the lower frequencies the standard deviation is in the order of 2 dB, which gives good confidence in the estimates and resulting in 95 % confidence intervals for the mean values below ± 1 dB in this frequency range.

The free-field correction for the RadioEar DD65 v2 has also been determined by another group of researchers [10][11] in another laboratory. A comparison between the results from this study and their results can be seen in Figure 4. Several differences in methodology exist, mainly: The loudspeaker level was not kept at 70 dB SPL but at levels of equal loudness was chosen meaning that the level was at a level in the range 61-72 dB depending on frequency (here it should be mentioned that IEC 60268-7:2010 [3] standard suggests keeping it fairly constant ±5 dB and approx. 70 dB). A stimulus duration of 2 s (IEC 60268-7:2010 [3] suggests approx. 2.5 s) and an identical start level for earphone and loudspeaker was used. The psychometric method for finding the equal loudness is different as they used two series of 2 dB steps (up-down, down-up) after an initial 6 dB and 3 dB step size staircase procedure. The subjects indicated their responses using two-foot switches and presentations were repeated if no response was giving. Finally, they used only one mandatory break (as compared to three breaks in this study), which means that the test subjects had to perform during longer time periods. These methodological differences and the use of different equipment, test subjects, laboratory, sound field, etc. can easily explain the relatively small differences (up to 4.9 dB at 6.3 kHz) seen. Similar for all corrections are a dip at 5 kHz which corresponds to the amplification of the loudspeaker signal due to the pinna.

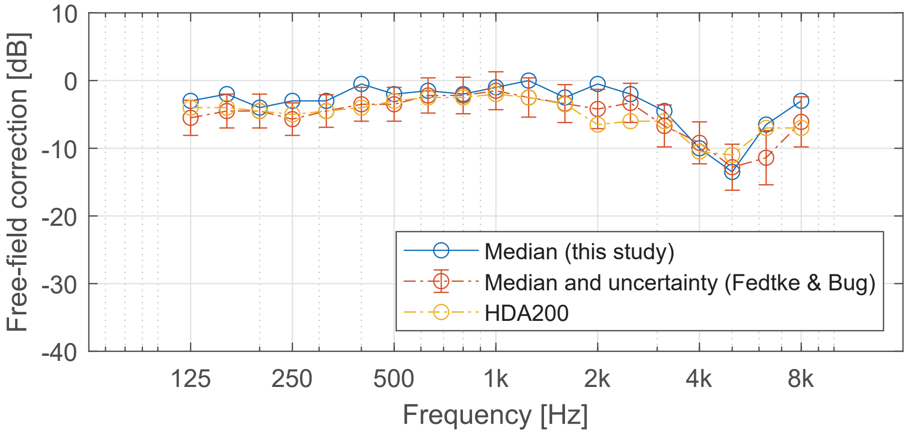

Figure 4: Free-field correction values for RadioEar DD65 v2 compared to values from another study [10][11]. For reference also HDA200 from [2] free-field correction values are plotted.

In the Equivalent Threshold Sound Pressure Levels (ETSPL) study by [4] the RadioEar DD65 v2 performs quite similar to the Sennheiser HDA200, which is also a circumaural audiometric earphone. A similarity trend can also be seen in the free-field correction values for the two earphones as seen in Figure 4.

Using a fixed presentation order with always presenting the loudspeaker signal before the earphone signal may potentially cause a systematic bias to the loudness matches, as there are known time-order effects in loudness judgements (see e.g. [5]). A common way to minimize the influence of these effects is to randomize the presentation order. However, this is not practical for the present study as randomizing whether or not the test subject should wear the earphones first would add a considerable complexity to the task of the test subject and experimenter. This is probably the reason why the presentation order is also fixed in the procedure described in the IEC 60268-7:2010 [3] standard.

Another potential source of bias is using a fixed presentation order of frequencies. It is possible that effects like carry-over effects and fatigue effects could have influenced the results in a systematic way. I.e. in the beginning the test subject is fresh and have full attention to the task, but in the end of the experiment attention may be lower, which could introduce more variation in responses and affect the accuracy of the results in the last session. Breaks between each session was used to minimize this potential effect. Going from a frequency with higher loudness to another frequency where 70 dB SPL has a lower loudness can potentially bias the initial loudness perception. However, this bias is expected be equal to both loudspeaker and earphone presentation, and as such not cause bias on the last number of reversals of a test run. In order to minimize the effect of any carry-over effects and fatigue effects etc. it would have been beneficial to randomize the frequency presentation order. However, this would not follow the guidelines in the IEC 60268-7:2010 [3] standard (see section 2.5).

5 Conclusion

Free-field correction values for the RadioEar DD65 v2 circum-aural audiometric earphones have been determined and the sound pressure level of speech presented via earphones have been determined. For overall calibration of speech audiometers this gives a level of 1.8 dB for impulse and 1.3 dB for fast time weighting. The results are similar to results from another laboratory and the small differences can be explained by methodological differences as well as different physical setups and subjects.

6 Acknowledgement

Funding and collaboration with Interacoustics A/S who also supplied the RadioEar DD65 v2 circum-aural audiometric earphones is gratefully appreciated. The authors would also like to thank all the test subjects for their participation in the present and accompanying study [4]. The authors also thank engineering assistant Claus Vestergaard Skipper for technical support and physical setup in the laboratory, and M. Sc. E. E. Oliver Erik Palmhøj Jokumsen for his assistance with running the experiments.

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