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Comparison of the individual benefit of a wireless remote microphone system in the laboratory with the situation in a classroom

Bachelor Thesis

Author:	Sebastian Griepentrog
Student ID:	269414
1st Advisor:	Dr. techn. Hendrik Husstedt
2nd Advisor:	Prof. Dr. rer. nat. Tim Jürgens
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Neubrunnenstraße 3, 55122 Mainz, Germany
Phone +49 (0)6131 28 30-0
Fax +49 (0)6131 28 30-30
E-mail: info@euha.org
Website: www.euha.org

Zusammenfassung

Thema: Vergleich der Messung des individuellen Nutzens einer drahtlosen akustischen Übertragungsanlage (DAÜ) in einer Labor- und Klassenraumsituation

Zusammenfassung: Die Zielsetzung dieser Arbeit ist es, den vereinfachten Messaufbau zur messtechnischen Überprüfung der Anpassung einer DAÜ der EUHA-Leitlinie 04-06 mit einer realen Klassenraumsituation zu vergleichen. Der Messaufbau der Leitlinie simuliert eine Hörsituation ähnlich einer Situation innerhalb eines Klassenraumes. Der Zuhörer wird dabei in einer Entfernung von 4 m vom Sprecher angenommen. Zu diesem Zweck wird eine Studie geplant und durchgeführt, innerhalb welcher das Sprachverstehen der teilnehmenden Probanden sowohl im Messaufbau der Leitlinie als auch in einem Messaufbau in einem Klassenraum gemessen wird.

Basierend auf einer früheren am Deutschen Hörgeräte Institut durchgeführten Studie mit demselben Zweck, werden für diese Studie einige Änderungen im Messaufbau des Klassenraumes vorgenommen. Im Rahmen der Studie wird das Sprachverstehen von 20 Probanden mit symmetrischem Hörverlust vom Typ „N3" (nach IEC 60118-15 Ed.1) in beiden Messaufbauten gemessen. Als Sprachmaterial wird der Freiburger Einsilber Test verwendet. Das Störgeräusch ist ein unkorreliertes CCITT-Rauschen. Verschiedene Messkonditionen werden bei jedem Probanden gemessen. Die Konditionen bestehen aus unterschiedlich lauten Störgeräuschpegeln, mit oder ohne Verwendung einer DAÜ, und verschiedenen Einstellungen in den Mikrofoncharakteristiken der Hörgeräte.

Wie bereits in früheren Studien gezeigt wurde, weisen die Ergebnisse dieser Arbeit signifikante Unterschiede zwischen den Messkonditionen ohne die Verwendung einer DAÜ und den Messkonditionen mit Verwendung einer DAÜ auf. Es zeigen sich keine signifikanten Unterschiede in den Messkonditionen mit Verwendung einer DAÜ innerhalb eines Messaufbaus und im Vergleich der beiden Messaufbauten. Damit ist der Messaufbau der Leitlinie zur Überprüfung der Anpassung einer DAÜ bestätigt. Es zeigt sich jedoch ein signifikanter Unterschied zwischen den beiden Messaufbauten für die Kondition ohne Verwendung einer DAÜ. Der Unterschied wird jedoch als nicht schwerwiegend beurteilt, da die Differenz der Mediane lediglich 7,5% beträgt.

Abstract

Topic: Comparison of the individual benefit of a wireless remote microphone system (WRMS) in the laboratory with the situation in a classroom

Summary: This paper is aimed at comparing a measurement method for measuring the individual benefit of wireless remote microphone systems, suggested by EUHA Guideline 04-06, with a realistic classroom situation. The guideline's measurement setup emulates a listening situation similar to a situation in a classroom where the listener is assumed to be at a distance of 4 m from the speaker. Therefore, a study is designed in which speech intelligibility of the subjects participating is measured in the setup suggested by the EUHA Guideline as well as in a measurement setup in a classroom.

On the basis of a former study conducted at the German Institute of Hearing Aids with the same intention, a few changes in the classroom's setup are made. To this end, speech intelligibility of 20 subjects with symmetrical hearing loss of type „N3" (according to IEC 60118-15 Ed.1) is measured in both measurement setups. As speech test material, the Freiburg monosyllabic word test is used. The noise signal is an uncorrelated CCITT noise. Different conditions are measured with every subject. The conditions include different sound pressure levels of the noise signal, the hearing aids being connected to a WRMS or not, and different settings in the characteristics of the hearing aid microphone.

According to the results of former studies, the results achieved in this study show a significant difference in speech intelligibility between the measurements with a WRMS connected, and the measurements without a WRMS. No significant differences in speech intelligibility occur between or within the measurement setups for all conditions where a WRMS is used. So the simplified setup from the EUHA Guideline is validated. However, a significant difference between the two setups occurs for the measurement condition without the use of a WRMS. As the median difference is only 7.5%, it is rated as not severe.

Contents

1. Introduction

Speech intelligibility in noisy situations is poorer for hearing impaired people than for people with normal hearing [1]. In this context, the so-called "cocktail party situation" is often mentioned where hearing impaired people in particular suffer more from poorer speech intelligibility and higher listening effort.

Hearing aids can help to improve the signal-to-noise ratio (SNR) by preserving and amplifying speech and reducing noise, e.g. using directional microphones. However, hearing aid technology has its limitations in situations where the listener is far away from the signal source, such as in a classroom or in a lecture hall [2, 3]. In such situations, hearing aid features are not able to significantly increase the SNR because the distance is too far and therefore additional technology, e.g. wireless remote microphone systems (WRMS), can be used.

An audiology expert group of the European Union of Hearing Acousticians (EUHA) designed a guideline for the configuration, verification, and measurement of the individual benefit of WRMS by using a simplified setup to simulate a listening situation similar to a classroom or a lecture hall [3]. Furthermore, there are several studies that compare different WRMS, and show considerable speech intelligibility benefits in noisy situations [4, 5, 6, 7]. These studies examined speech intelligibility using different types of transmission [4] and hearing assistance technology [5] in clinical and realistic environments. Moreover, different WRMS were compared within the setup shown in the EUHA Guideline in Christina Fitschen's bachelor thesis [6]. In his bachelor thesis, Hendrick Giesecke compared the results of a speech intelligibility measurement while using WRMS in a classroom with the results from Christina Fitschen's speech intelligibility measurements [7].

However, this comparison has some limitations because the results of two different studies are compared and the setup in the classroom can be improved. This concerns the angle in which the loudspeakers are turned towards the wall, the diffuse sound field's sound pressure level in the classroom, the signal source, and the range of measurements. Therefore, the goal of this thesis is to perform a study that allows to compare the results of the simplified method according to the EUHA Guideline with the results of a realistic classroom situation. To this end, the following three changes compared to the previous work [7] are considered.

First, a uniformly distributed sound pressure level within the classroom is generated by equalising eight loudspeakers at two locations in the room, the subject and the remote microphone. Next, the KEMAR artificial head with a mouth simulator (KEMAR) from G.R.A.S. is used as the signal source instead of a regular loudspeaker. Due to the mouth simulator, the KEMAR is a more realistic signal source because of its facial features. And finally, with the intention to compare data that is actually measured in both rooms with the same subject in the same physical state, speech intelligibility of all subjects is measured in both rooms and on the same date for the same subject.

The structure of this thesis is as follows. Chapter 2 describes the background knowledge concerning WRMS, the distance law in a closed room, the measurement setup as shown in the EUHA Guideline, the guideline's recommendation of measuring the 10 dB FM advantage and two-point equalisation. The equipment used for all measurements, the measurement of sound propagation inside the classroom as well as the study design and study conduct are included in chapter 3. The last two chapters 4 and 5 contain the results and provide a conclusion.

2. Basic knowledge

2.1 Wireless remote microphone systems

Technologies that wirelessly transfer a signal from a remotely positioned microphone to a listener work e. g. via infrared, electromagnetic induction or frequency modulation. Hearing aids can be connected to such WRMS by using a direct audio input (DAI) adaptor. WRMS traditionally transmit the signal via electromagnetic waves using frequency modulation. These systems are also commonly known as "FM systems", but in this thesis, the term WRMS is consistently used. WRMS can be helpful in everyday situations, but show their value in noisy environments in particular. Hearing aid technology reaches its limitations in wider areas or crowded places where the distance to a signal source is too great. Also, the acoustic characteristics of the room reduce listening comfort. To make use of a WRMS, it is connected with the hearing impaired person's hearing aids. Then, the remote microphone is placed near a signal source. In this way, the signal is received with a high SNR and is then transmitted over the distance to the receiving hearing aids (see fig. 2.1). The hearing aids provide the signal to the listener with an individually adjusted loudness [2]. This not only increases the SNR for the listener, but also reduces reverberation effects.

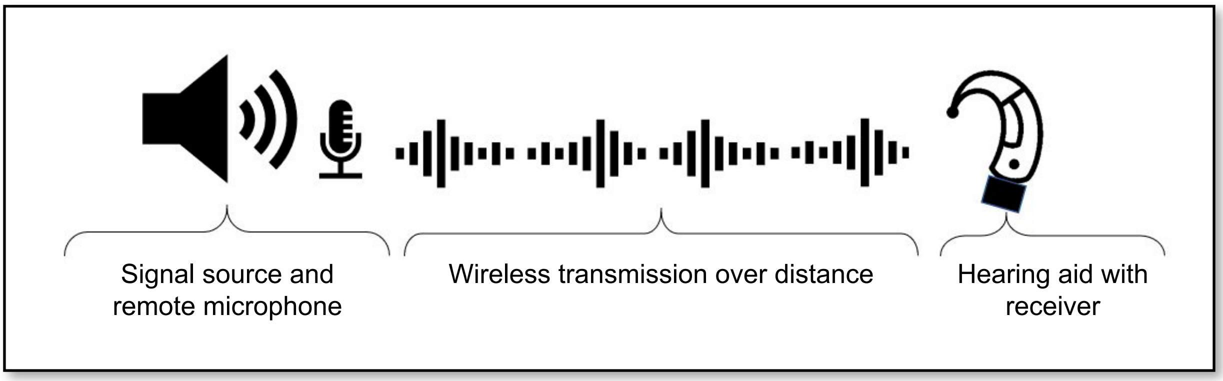

Figure 2.1: Schematic illustration of the functional principle of a WRMS

2.2 Hopkins-Stryker equation (distance law in a closed room)

In a free field, sound propagation is spheric and no reflections need to be considered. Inside closed rooms, reflections that occur affect sound propagation. Primary reflections can be helpful for understanding a signal as they contribute to the signal's loudness. Secondary reflections with a delay of more than 50 ms disturb the signal, however, as they overlay each other and overflow into reverberation [8]. When the reflections reach the critical distance, the acoustic characteristics inside the room will not change any further. That means the sound pressure level will not decrease anymore, but stay on the same level and form a diffuse sound field.

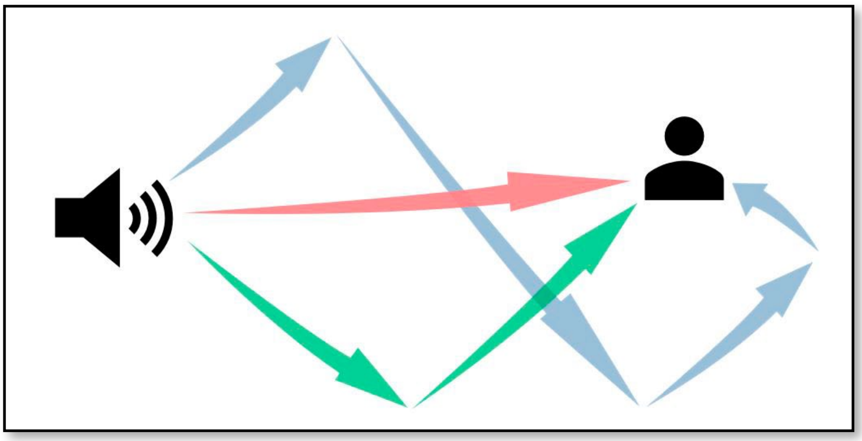

Figure 2.2: Schematic illustration of sound propagation within a closed room. The illustration shows direct sound (red arrow), primary reflections (green arrows) and secondary reflections (blue arrows).

Direct sound signals are not affected by reflections and can be treated as sound propagation in a free field. Thus, the direct sound pressure level L_D decreases by 6 dB per doubled distance. This can be described using the formula

$$L_{\mathrm{D}} = 10\,\mathrm{dB}\ \lg\left(k_1\,\frac{1\,\mathrm{m}^2}{r^2}\right) \tag{2.1}$$

with $k_1 = 10^{\frac{65\,\mathrm{dB}}{10\,\mathrm{dB}}}$ and r = distance in m.

The diffuse sound field's sound pressure level L_R in a closed room, or the reflections that occur, can be calculated using

$$L_{\mathrm{R}} = 10\,\mathrm{dB}\ \lg\left(k_2\,\frac{T}{V}\,\frac{1\,\mathrm{m}^3}{1\,\mathrm{s}}\right) \tag{2.2}$$

with $k_2 = 10^{\frac{93.3\,\mathrm{dB}}{10\,\mathrm{dB}}}$, T = reverberation time in s and V = volume of the room in m^3.

The combination of the formulas (2.1) and (2.2) results in the following equation by Hopkins and Stryker, describing the distance law in a closed room [9]

$$L_{\mathrm{T}} = 10\,\mathrm{dB}\ \lg\left(k_1\,\frac{1\,\mathrm{m}^2}{r^2} + k_2\,\frac{T}{V}\,\frac{1\,\mathrm{m}^3}{1\,\mathrm{s}}\right). \tag{2.3}$$

2.2.1 Approximated sound propagation in the classroom considered

Reverberation time and volume in the classroom considered have been measured in the context of Hendrick Giesecke's thesis [7] and will be adapted for this paper. Using the equation from chapter 2.2 and the data from table 2.1, sound propagation in the closed room is approximated as shown in figure 2.3.

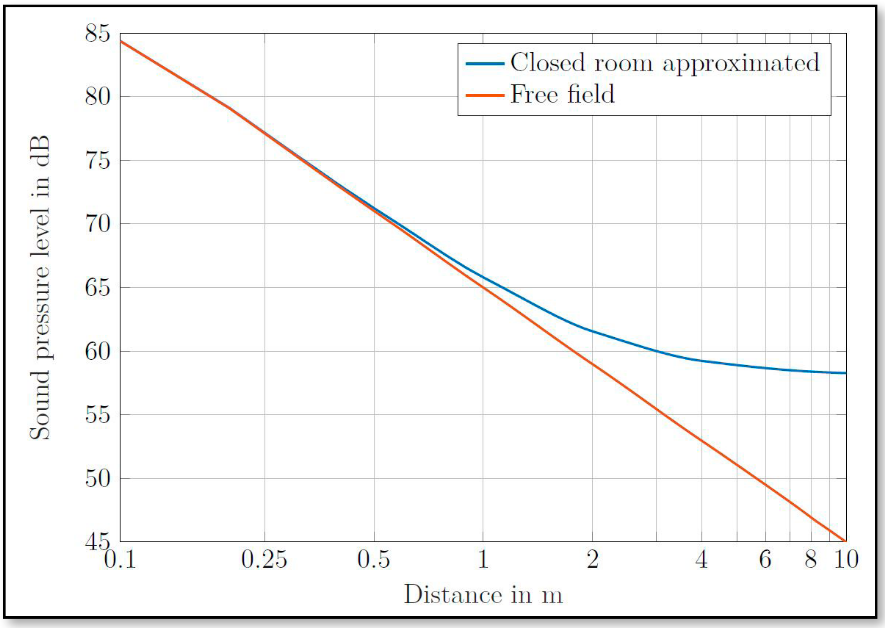

Figure 2.3: Approximated sound propagation inside the classroom considered. The x-axis is assigned logarithmically to the distance in m, the y-axis is assigned to the sound pressure level in dB. The blue graph shows the approximated sound pressure level in the closed room. The red graph shows sound propagation in a free field.

Reverberation time T at 2000 Hz (s)	Volume V (m3)
0.812	304.01

Table 2.1: Reverberation time and volume taken from Hendrik Giesecke's thesis [7]

2.3 Simplified measurement setup from the EUHA Guideline

EUHA Guideline 04-06 suggests a simplified setup to measure the individual benefit of WRMS [3, 10]. This method emulates a listening situation inside a classroom or lecture hall. Here, the speaker is assumed to be at a distance of 4 m from the listener. Figure 2.4 shows a schematic illustration of the setup.

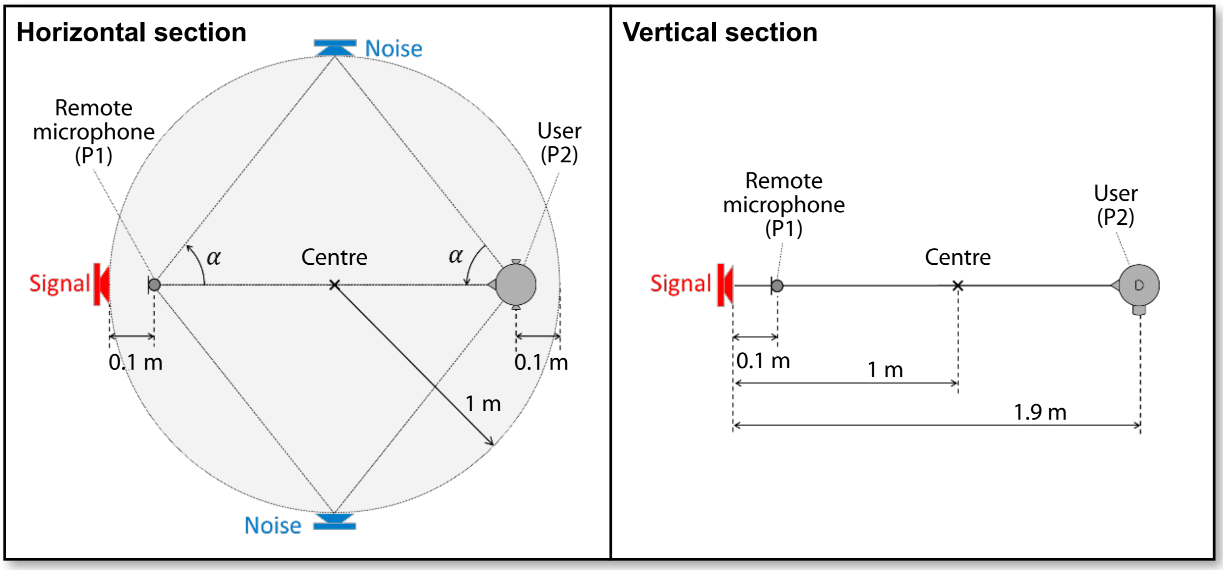

Figure 2.4: Schematic illustration of the measurement setup shown in the EUHA Guideline [3]

The loudspeakers for noise and speech signals are set up at a radial distance of 1 m from a reference point (centre). The user (P2) is placed opposite the signal speaker at 0.9 m distance from the reference point. The remote microphone (P1) of the WRMS is placed at 0.1 m distance from the signal speaker and the angle α is 45 °. The *Freiburger Einsilbertest* (FET), a monosyllabic speech test, is used as the speech signal. For measurements without a WRMS, the sound pressure level of the speech signal is 58 dB at the location of the subject, which would be the equivalent speech level at 4 m distance in a typical classroom. For measurements with WRMS, the sound pressure level of the signal is 80 dB, or 85 dB at the remote microphone, depending on whether the remote microphone is carried around the neck or placed in front of the mouth. The noise sound pressure level is 60 dB at the subject's location, as well as at the location of the remote microphone. To ensure the accuracy of all sound pressure levels, they are adjusted with correction factors [3].

2.4 Configuration and verification of the transfer characteristic (10 dB FM advantage)

The configuration and verification of the transfer characteristic is validated via the transparency measurement. This measurement is important because it confirms the assumption of the 10 dB FM advantage. This means that the wirelessly transmitted signal is 10 dB louder than noise in the listener's immediate environment [3, 11].

The EUHA Guideline says that "the transfer characteristic of the WRM system is transparent if the International Speech Test Signal (ISTS), provided with 65 dB SPL at the remote microphone, generates an equal output signal for the user to an ISTS with 65 dB SPL without WRMS. In this context, 'equal' means that in both cases, the signal recognised by the user differs by not more than ±5 dB in the frequency range from 800 Hz to 3.5 kHz" [3]. The transparency measurement is performed using an acoustic test box, and split into three measurement steps. First, the hearing aid is placed inside the box without a connection to the WRMS (see fig. 2.5). Next, the hearing aid is placed inside the box with a connection to the WRMS (see fig. 2.6). Last, the hearing aid is placed outside the box and the remote microphone of the WRMS is placed inside the box (see fig. 2.7). For all three measurements, the output characteristic is measured using an ISTS at 65 dB SPL. Transparency is confirmed when the measured output characteristics from step two and step three are equal to the characteristic measured in step one, ±5 dB within the frequency range from 800 Hz to 3.5 kHz. To verify the measurement setup, both the hearing aid and the connected remote microphone can be placed outside the box. If an output characteristic is now measured in the same way as described for the measurement steps above, it needs to be at least 10 dB below the characteristic of step one, as in this measurement the damping characteristics of the test box limit the sound pressure level [3].

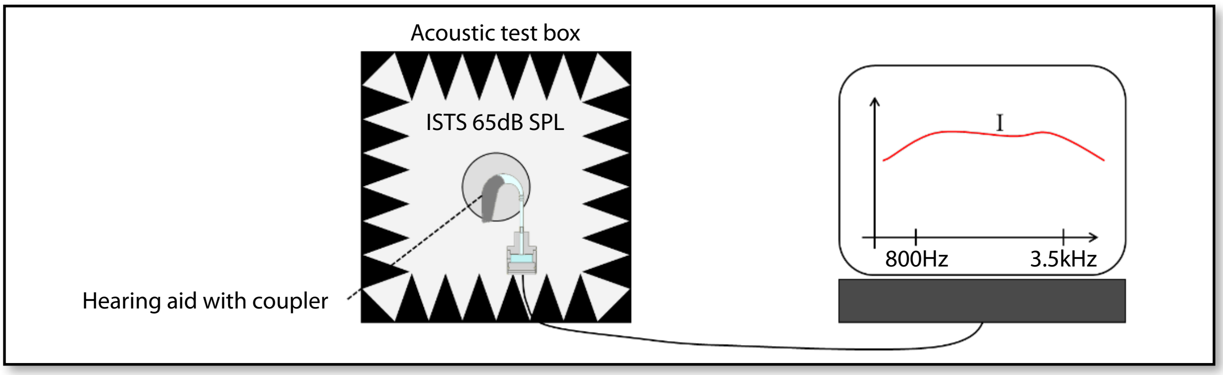

Figure 2.5: Step 1 of the transparency measurement, as recommended in the EUHA Guideline [3]

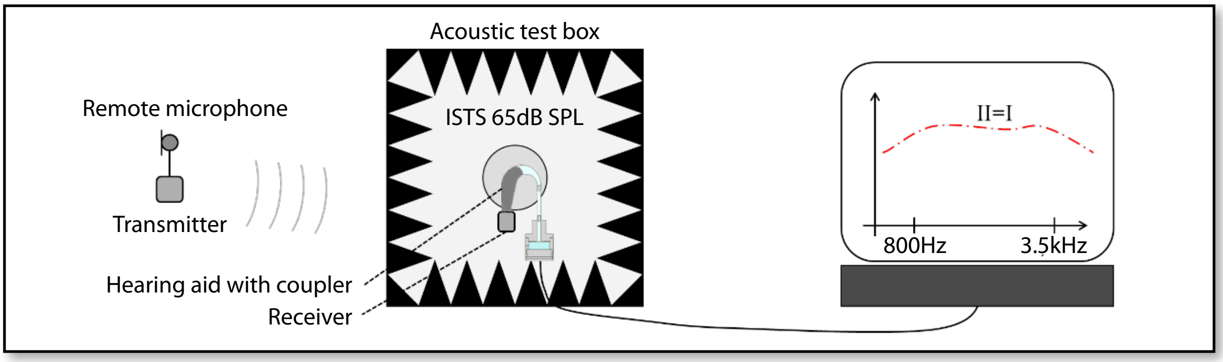

Figure 2.6: Step 2 of the transparency measurement, as recommended in the EUHA Guideline [3]

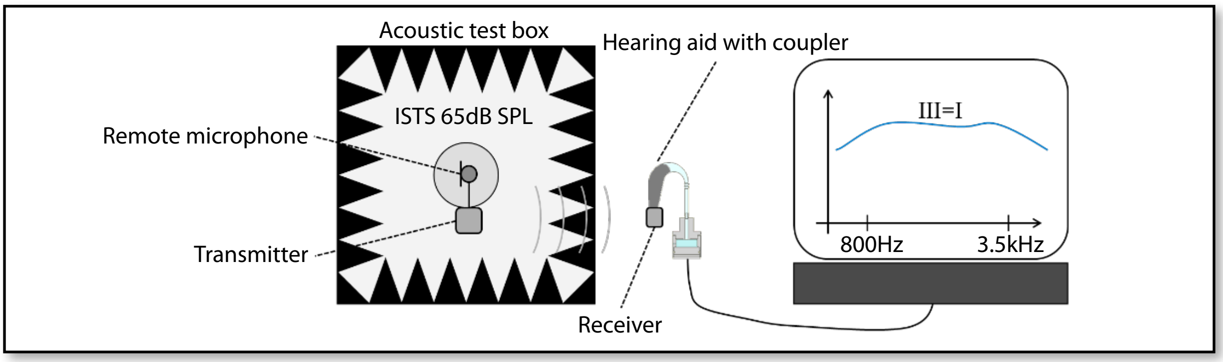

Figure 2.7: Step 3 of the transparency measurement, as recommended in the EUHA Guideline [3]

2.5 Two-point equalisation

The equalisation of eight speakers at two locations is realised using a Matlab tool provided by the German Institute of Hearing Aids. In short, the functional principle is as follows. For each frequency, a system is defined using the following equation

$$\mathrm{x} = \mathrm{As}, \tag{2.4}$$

where x represents the desired loudness at the two equalisation points and s represents the weighting factor of all eight loudspeakers. The system matrix A includes the loudness of each loudspeaker at both equalisation points. In this case, A is an asymmetrical

2x8 matrix. To calculate the necessary loudness x, the weighting defined in s is calculated using

$$A^{-1}x = s. \tag{2.5}$$

As A is not symmetrical, the matrix inverse does not exist and therefore the Moore-Penrose pseudoinverse[1] is used.

1 The Moore-Penrose pseudoinverse replaces the matrix inverse in cases where it does not exist. It is frequently used to solve a system of linear equations with more than one unique solution.

3. Methods

3.1 Equipment

All measurements and setups described in this paper are realised using the following equipment: two notebooks with Matlab R2017b software installed, from which all measurements are programmed, started, and controlled. The KEMAR artificial head with a mouth simulator from G.R.A.S. is used as the signal speaker inside the classroom. The noise signal is distributed from eight bi-amplified loudspeakers by Genelec (4x 8020C and 4x 8020A). For sound propagation over distance, the equalisation of the KEMAR and the two-point equalisation, up to two type 4190 microphones are used in combination with a 4-channel microphone power supply type 2829, all from Brüel & Kjær. For microphone calibration, a type 4228 pistonphone is used, also from Brüel & Kjær. The measurements in the laboratory are conducted with the use of an audiometer and an acoustic test box from Acousticon GmbH. The adjusted sound pressure levels in the laboratory are verified via a handheld type 2250 analyser from Brüel & Kjær. To connect the hardware with each notebook, the soundcards Fireface 802 and Fireface UC from RME are used.

3.2 Preliminary measurements in the classroom considered

3.2.1 Sound propagation over distance

3.2.1.1 Setup

Before starting the study, sound propagation over distance inside the classroom is measured. The aim is to compare the measured results, especially at distances of 1 m and 4 m, with the approximated sound propagation using the equation from chapter 2.2. For this measurement, the ISTS is used as a signal and the KEMAR as the loudspeaker. A microphone records the emitted signal at the designated distances (0.1 m, 0.25 m, 0.5 m, 1 m, 2 m, 3 m, 4 m, 5 m, 6 m, 7 m, 8 m, 9 m, and 10 m) (see fig. 3.1).

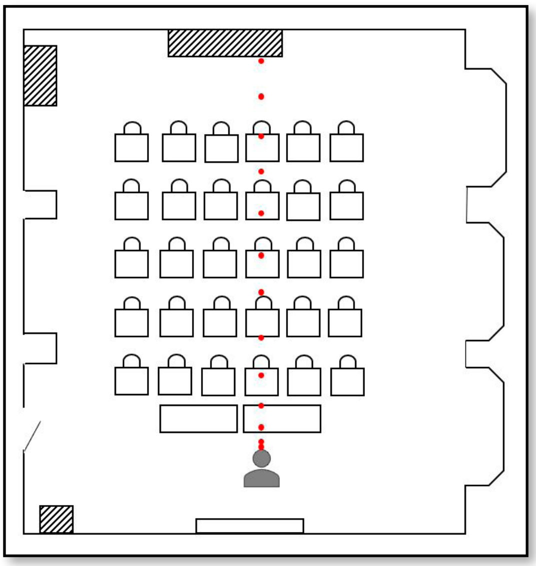

Figure 3.1: Schematic illustration of the measurement distances for the sound propagation measurement in the classroom. The red dots show the measurement points.

3.2.1.2 Measurement

The ISTS is played via the KEMAR for one minute and simultaneously the signal is recorded at one measurement point. Figure 3.2 shows an example of the measurement setup for one distance (e.g. 0.1 m). The complete measurement is repeated three times to avoid measurement variations because of non-exact microphone placement. This results in three measured sound pressure level (SPL) values per distance, which are averaged afterwards.

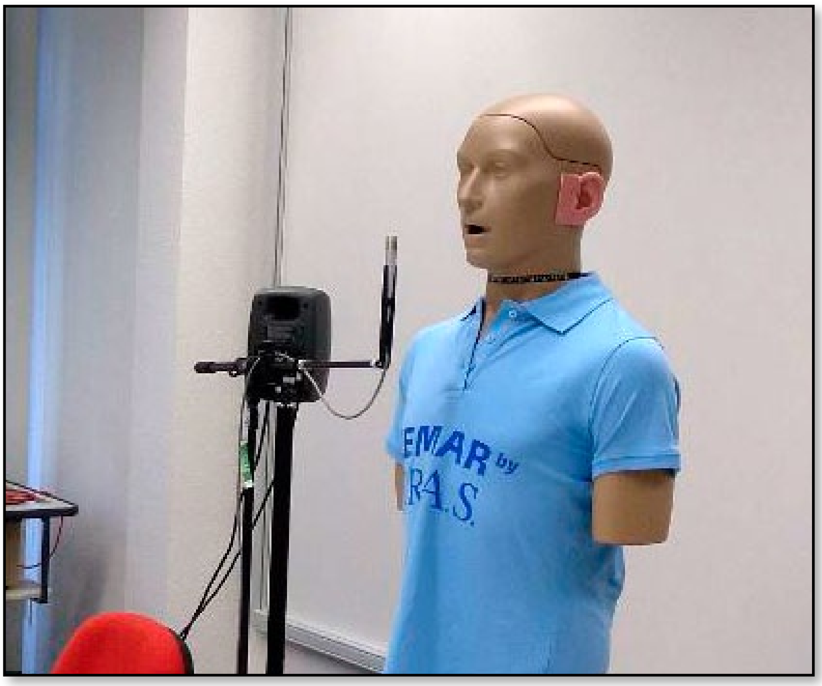

Figure 3.2: Sound propagation measurement with the KEMAR as signal speaker playing the ISTS. The microphone is recording the signal in the designated distance.

3.2.1.3 Results

The results are compared with the data from chapter 2.2.1 and illustrated in figure 3.3.

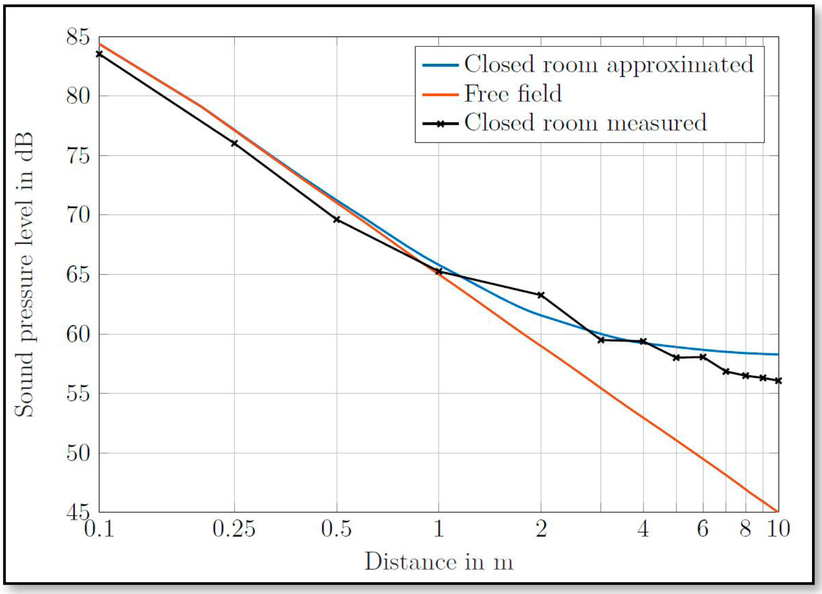

Figure 3.3: Sound propagation in the classroom. The x-axis is assigned logarithmically to the distance in m, the y-axis is assigned to the sound pressure level in dB. The blue graph shows the approximated sound pressure level over distance according to Hopkins and Stryker. The red graph shows sound propagation in a free field. The black graph shows the measured sound propagation inside the classroom.

Figure 3.3 shows that the sound pressure level at 1 m and 4 m matches the approximation inside the classroom. At 1 m, the approximated sound pressure level is 65.8 dB and the measured sound pressure level is 65.26 dB. At 4 m, the approximated sound pressure level is 59.23 dB and the measured sound pressure level is 59.38 dB. However, one finds that the sound pressure level distributed from the KEMAR is below the approximation until a distance of 1.1 m is reached. After this point, the measured graph systematically fluctuates around the approximation in up to ±2 dB. This can be due to the fact that the equation by Hopkins and Stryker is an approximation only.

3.3 Two-point equalisation in the classroom considered

To simulate a homogenous diffuse sound field within the classroom, eight loudspeakers simultaneously play an uncorrelated CCITT noise signal.

The German Institute of Hearing Aids provides a measurement tool described in chapter 2.5 to equalise the eight speakers at two locations in the room. These two points are the positions of the subject and the remote microphone. Figure 3.4 shows the relation of the sound pressure level at those two points before and after the equalisation.

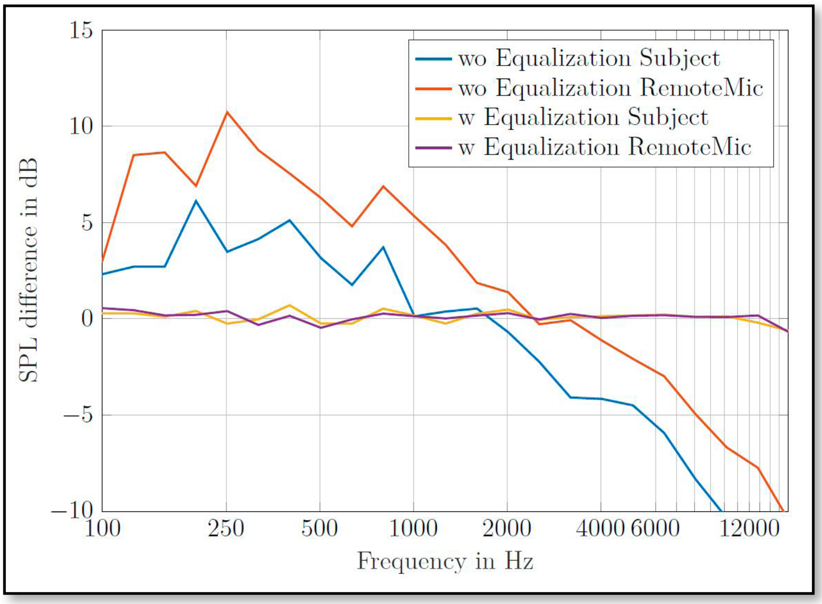

Figure 3.4: Plot after equalising eight loudspeakers at two points. The x-axis is logarithmically assigned to the frequency in Hz, the y-axis is assigned to the SPL difference in dB between the positions of the subject and the remote microphone. The blue and the red lines represent the sound pressure level from all speakers without equalisation at both positions. The orange and the violet lines represent the sound pressure level from all speakers after equalisation at both positions.

3.4 Study design

3.4.1 Theoretical design

The main part of this thesis is to design and perform a study with the purpose of comparing two measurement setups, i.e. the simplified measurement setup of the EUHA Guideline with an actual classroom situation. The measurement setups are located in two separate rooms and each subject will be measured in both situations.

Twenty subjects, ten female and ten male, aged between 52 and 83 years take part in the study, selected according to their hearing threshold. The average binaural hearing loss should be symmetrical for both ears and is oriented towards the hearing loss type "N3", shown in figure 3.5 according to IEC 60118-15 Ed.1 [12]. The subjects are equipped with the same pair of hearing aids and use the same WRMS technology. The speech signal for both setups is the FET and the noise signal is an uncorrelated CCITT noise.

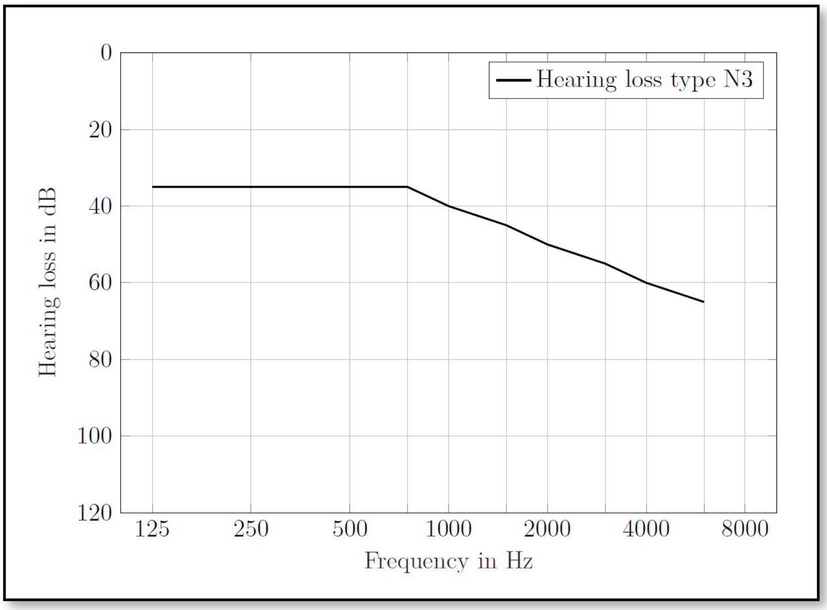

Figure 3.5: "N3" type hearing loss type; the black line shows the "N3" type hearing loss according to IEC 60118-15 Ed.1 in dB. The x-axis is logarithmically assigned to the frequency in Hz and the y-axis is assigned to the hearing loss in dB.

3.4.2 EUHA measurement setup

The simplified measurement setup described in the EUHA Guideline is set up in the laboratory as shown in figure 3.6. The setup is defined according to the EUHA Guideline and as shown in chapter 2.3. It is important to guarantee a fixed position for the subject. There-

Figure 3.6: Measurement setup as described in the EUHA Guideline

fore, a stationary chair is used and the position of its legs is marked on the floor. The loudspeakers are positioned at an equal height of 1.4 m. The remote microphone's characteristic is set on fix-directional and the microphone is placed straight in front of the signal loudspeaker (see fig. 3.7).

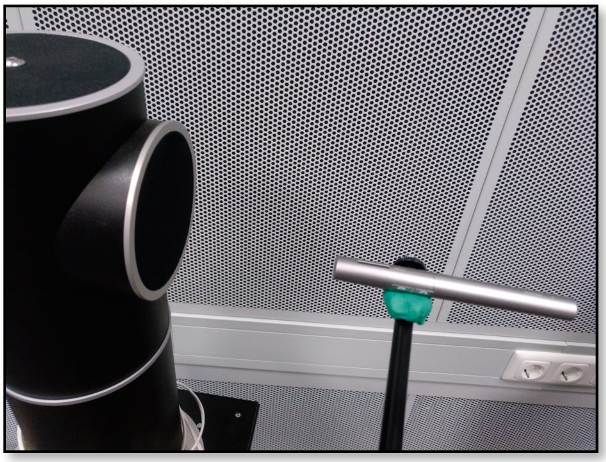

Figure 3.7: Remote microphone placement in front of the signal loudspeaker

3.4.3 Classroom measurement setup

The measurement setup in the classroom consists of eight loudspeakers which are evenly distributed along the edge of the room at a height of 1.65 m. Their distance to the wall is 1 m and all loudspeakers are turned at an angle of 45° towards the wall. The KEMAR stands at 1 m distance to the wall and is turned towards the room. Its head height is at 1.70 m, which is modelled on the arithmetical average height of the average heights of women and men in Germany [13, 14]. The subject is placed in the middle of the room, in a straight line and at 4 m distance to the KEMAR. Figure 3.8 shows a schematic illustration of the setup.

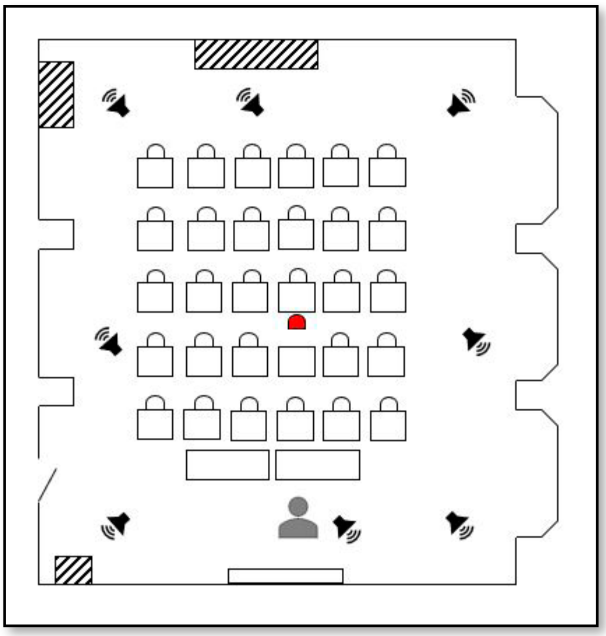

Figure 3.8: Schematic illustration of the measurement setup in the classroom. The position marked in red shows the subject's position, the figure at the front end represents the KEMAR. The speakers are aligned at 1 m distance from the walls and turned at an angle of 45 °.

The measurement setup in the classroom is shown in figures 3.9 and 3.10.

Figure 3.9: Measurement setup in the classroom, front part with the KEMAR

Figure 3.10: Measurement setup in the classroom, back part

3.5 Study conduct

The study is conducted during a period of two weeks, from 05/22/2018 to 06/01/2018. On each day, up to four subjects are measured. Before measurements start, the two-point equalisation of the eight noise loudspeakers is checked as well as the equalisation of the KEMAR. The adjustment sound pressure levels for the laboratory setup are also checked on every day.

For each subject, the hearing loss is measured and hearing aids are fitted. The connection to the subjects' ears is done via individual earmoulds. In cases where no personal earmoulds are available, provisional eartips are used. The hearing aids are adjusted setting them to *First Fit* and the fitting algorithm used is *NAL- NL2*. In the next step, the 10 dB FM advantage is checked as described in chapter 2.4. Finally, speech intelligibility is measured in both rooms. The measurement is conducted in different conditions which include the difference of using or not using a WRMS, a variation in noise levels, and two different settings for the characteristics of the hearing aid microphones (see table 3.1).

Number	WRMS	Noise level (dB)	Hearing aid characteristics
1	without	60	omnidirectional
2	with	60	omnidirectional
3	with	65	omnidirectional
4	with	70	omnidirectional
5	with	70	directional

Table 3.1: Conditions for speech test

The conditions 1, 2 and 4 are specified in the EUHA Guideline, whereas their purpose is to show the benefit of a WRMS. Condition 3 is defined as an intermediate step in the increase of the noise level. Condition 5 is chosen to check on a possible benefit that might be a result of microphone directivity of the hearing aids.

The room to be used first, the conditions for the speech test, the order of the FET word groups as well as the words within the groups are randomised before the study. In the laboratory, the audiometer used provides the FET lists and is used as a measuring tool for the EUHA setup. In the classroom, a FET measurement tool is used which is programmed via Matlab.

4. Results

4.1 Average hearing threshold

The average hearing loss of all subjects matches the specification ±6 dB in the frequency range from 500 Hz to 4000 Hz. Figure 4.1 shows the averaged hearing thresholds of the left and right ears of all subjects compared to the "N3" type hearing loss shown in figure 3.5.

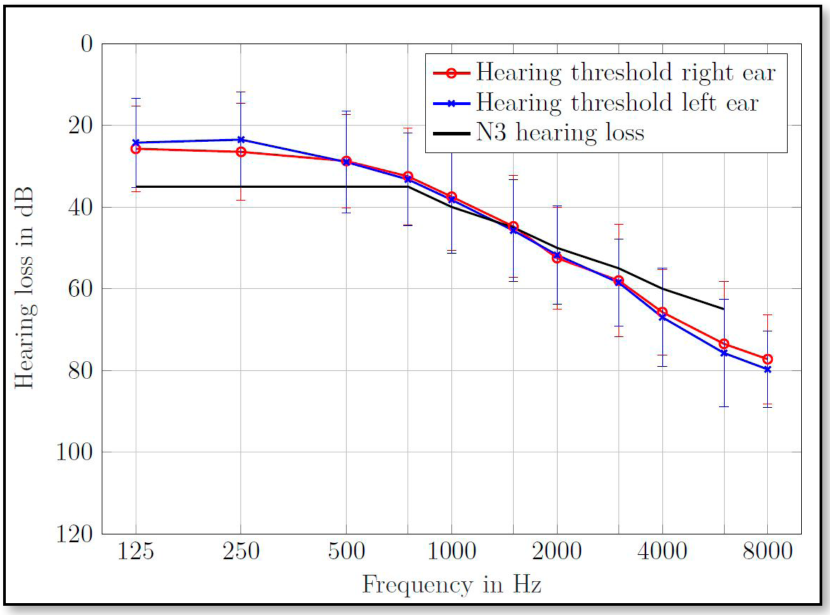

Figure 4.1: Hearing threshold from all subjects displayed with standard deviation compared to "N3" type hearing loss. The red line shows all averaged right ears, and the blue line all averaged left ears. The black line displays the IEC 60118-15 "N3" type hearing loss. The x-axis is logarithmically assigned to the frequency in Hz, the y-axis is assigned to the hearing loss in dB.

4.2 Speech intelligibility in the laboratory and the classroom

Before the statistical evaluation, all conditions measured are checked for normal distribution using the Shapiro-Wilk test. Table 4.1 shows the *p*-values at a significance level of $\alpha = 0.05$ for each measurement condition.

Population	Laboratory	Classroom
Condition 1	0.0128	0.0034
Condition 2	0.0113	0.0094
Condition 3	0.0085	0.0056
Condition 4	0.1197	0.0537
Condition 5	0.1831	0.1349

Table 4.1: p-*values for Shapiro-Wilk test from all conditions ($\alpha = 0.05$)*

As not normally distributed populations occur, non-parametric statistical tests are used for further evaluation. Speech intelligibility values from all conditions measured within the laboratory and the classroom are examined for significant differences. To do so, the Kruskal-Wallis test is used with Bonferroni correction applied. Due to the Bonferroni correction, a new significance level emerges, indicating highly significant differences (***):

$\alpha = 5\ 10^{-5}$. Table 4.2 shows the *p*-values for the laboratory measurement and figure 4.2 shows the related results as boxplots.

	Condition 2	Condition 3	Condition 4	Condition 5
Condition 1	$1.2228\ 10^{-19}$	$2.8866\ 10^{-15}$	$1.5042\ 10^{-8}$	$3.4754\ 10^{-10}$
Condition 2		1	0.0107	0.0715
Condition 3			0.3284	1
Condition 4				1

Table 4.2: p-*values for Kruskal-Wallis test, comparing the measurement conditions within the laboratory*

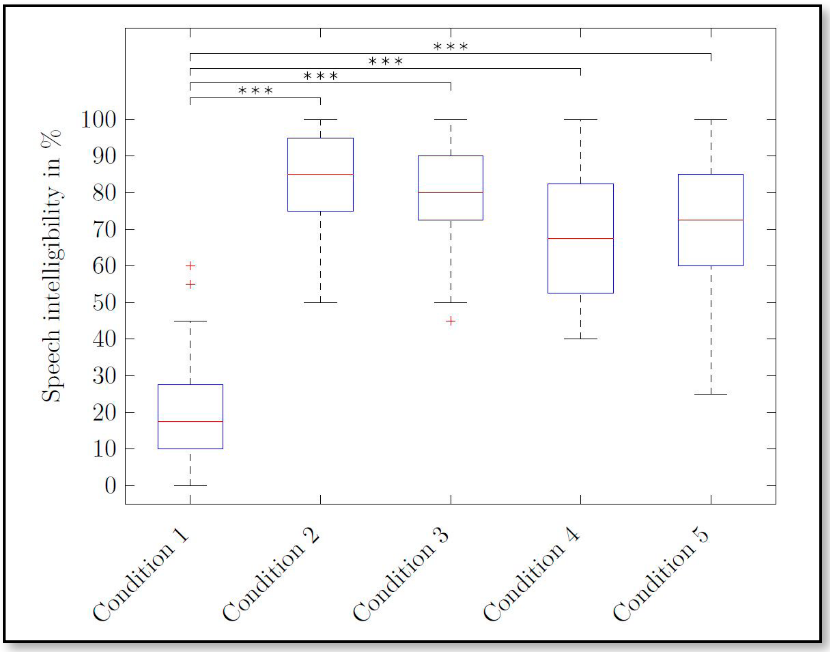

Figure 4.2: Speech intelligibility measured in the ***laboratory*** *with and without the use of a WRMS, illustrated as boxplots. The x-axis shows the measurement conditions from table 3.1 from 1 to 5. The asterisks mark the highly significant difference between condition 1 and all other conditions.*

Within the simplified setup according to the EUHA Guideline, the speech intelligibility measured without using a WRMS shows a clear difference to the results measured with the use of a WRMS. The *p*-values proof that there is a highly significant difference between condition 1 and all other conditions (see boxplot figure 4.2). However, there is no significant difference between the other conditions 2-5. The median for condition 1 is 17.5%. The 25th quartile (10%) and the 75th quartile (27.5%) form the interquartile range (IQR) with 17.5%. For condition 2, the median is 85% and the IQR amounts to 20% (between 75% and 95%). For condition 3, the median is 80% and the IQR amounts to 17.5% (between 72.5% and 90%). For condition 4, the median is 67.5% and the IQR amounts to 30% (between 52.5% and 82.5%). For condition 5, the median is 72.5% and the IQR amounts to 25% (from 60% to 85%).

Table 4.3 shows the *p*-values for the classroom measurement and figure 4.3 shows the related results as boxplots.

	Condition 2	Condition 3	Condition 4	Condition 5
Condition 1	$9.1468\ 10^{-20}$	$6.069\ 10^{-15}$	$5.2068\ 10^{-10}$	$4.2911\ 10^{-11}$
Condition 2		1	0.0543	0.1560
Condition 3			1	1
Condition 4				1

Table 4.3: p-*values for Kruskal-Wallis test, comparing the measurement conditions within the classroom*

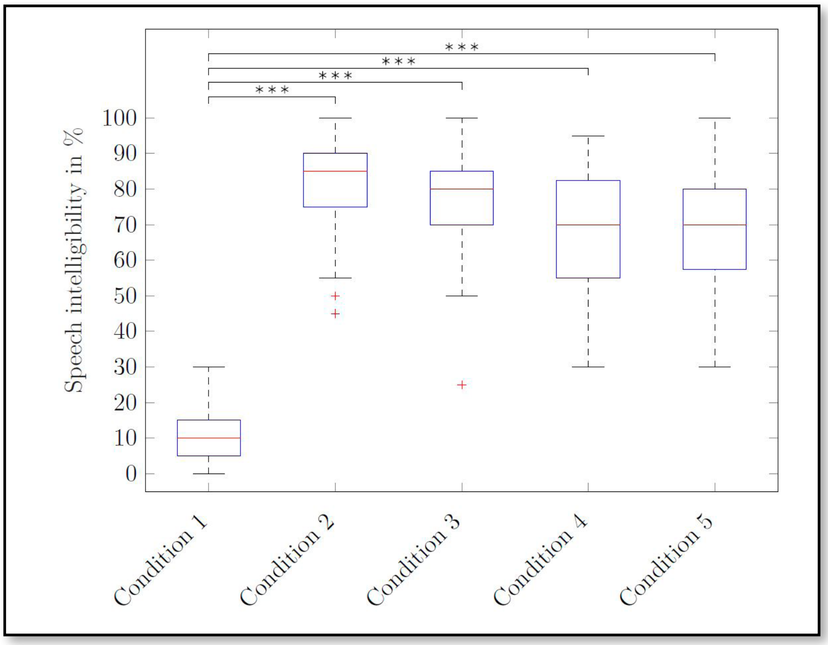

Figure 4.3: Speech intelligibility measured in the ***classroom*** *with and without the use of a WRMS, illustrated as boxplots. The x-axis shows the measurement conditions from table 3.1 from 1 to 5. The asterisks mark the highly significant difference between condition 1 and all other conditions.*

Inside the classroom, the speech intelligibility measured without using a WRMS shows a clear difference to the results measured with the use of a WRMS. The *p*-values also show that there is a highly significant difference between condition 1 and all other conditions (see boxplot figure 4.3). There is no other significant difference between the conditions 2-5. The median for condition 1 is 10% and the IQR amounts to 10% (between 5% and 15%). For condition 2, the median is 85% and the IQR amounts to 15% (between 75% and 90%). For condition 3, the median is 80% and the IQR amounts to 15% (between 70% and 85%). For condition 4, the median is 70% and the IQR amounts to 27.5% (between 55% and 82.5%). For condition 5, the median is 70% and the IQR amounts to 22.5% (from 57.5% to 80%).

Individual benefit in terms of speech intelligibility while using WRMS is validated in both setups because of the significant differences in speech intelligibility between the condition without a WRMS and the conditions with a WRMS. The results are confirmed by former studies that show the same relation [5, 6, 7].

4.3 Comparison of both setups

The next part of the evaluation is to check on differences between the conditions of the different setups. To do so, speech intelligibility values from both rooms are compared pairwise in the corresponding conditions for each measurement setup. This is done using the Wilcoxon rank sum test. Table 4.4 shows the *p*-values and figure 4.4 shows the related results as boxplots.

Conditions	*p*-value
1 EUHA - 1 Classroom	$1.7516\ 10^{-4}$
2 EUHA - 2 Classroom	0.3805
3 EUHA - 3 Classroom	0.4527
4 EUHA - 4 Classroom	0.9153
5 EUHA - 5 Classroom	0.8201

Table 4.4: p-values for Wilcoxon rank sum test, pairwise comparison of the measurement conditions from both rooms*

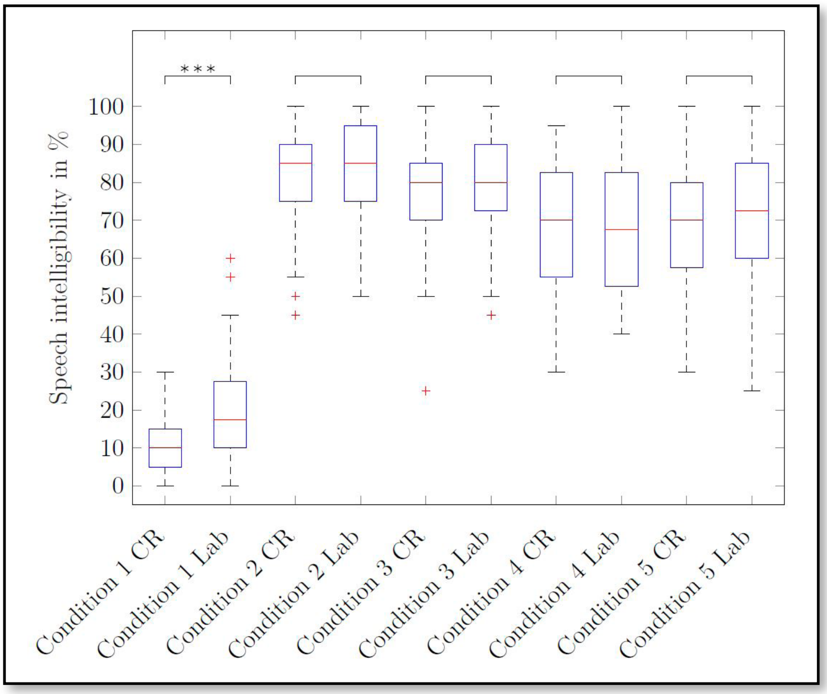

Figure 4.4: Speech intelligibility compared pairwise for each measurement condition from both rooms. The x-axis shows the corresponding measurement conditions from table 3.1 from 1 to 5. The conditions marked 'CR' represent the conditions from the classroom and the conditions marked 'Lab' represent the conditions from the EUHA setup. The asterisks mark the highly significant difference between the rooms in condition 1.

The Wilcoxon rank sum test shows no significant difference between the rooms for the conditions where a WRMS is used, but a highly significant difference between the rooms for the conditions where no WRMS is used.

Both measurement setups show no significant differences in speech intelligibility within and between the two setups while a WRMS is used. So the simplified measurement setup suggested by the EUHA Guideline is confirmed after comparing the results with a realistic classroom situation. The results also show a highly significant difference in speech intelligibility between the two rooms where no WRMS is used. The difference between the medians, however, is 7.5% and therefore rated as not severe. It might be caused by the acoustic characteristics of the classroom as well as the diffuse sound field. In the conditions without a WRMS, the SNR is very low and reverberations do affect speech intelligibility.

5. Conclusion

The intention of this paper was to design a study to measure individual benefit in terms of speech intelligibility while using a WRMS within the EUHA Guideline's simplified measurement setup as well as within a realistic classroom situation. The main goal afterwards was to compare both setups and thus validate the simplified measurement setup as suggested in the EUHA Guideline.

Before the study, the classroom was examined for its acoustic properties. The results of the sound propagation measurement confirmed that the classroom was suitable as they matched the approximated and expected SPL values at the distances of 1 m and 4 m. Thanks to a tool to equalise eight speakers at two points, the sound pressure level of the noise inside the classroom was equally emitted at the locations of the subject and the remote microphone.

The results of the study show that individual benefit in terms of speech intelligibility while using WRMS is validated in both setups with high significance. The results support the findings of former studies. Both measurement setups show no significant differences in speech intelligibility within and between the two setups while a WRMS is used. Thus, the simplified measurement setup suggested by the EUHA Guideline is confirmed by the results of this study.

However, the results also show a highly significant difference in speech intelligibility between the two rooms in the condition where no WRMS is used, most likely due to the acoustic characteristics of the classroom.

As an outlook, the study could be repeated with other types of hearing loss. Moreover, one might consider comparing different other rooms with the setup shown in the EUHA Guideline. Apart from that, different other streaming devices, e. g. mobile phones, could be measured with the setup shown in the Guideline. To take a closer look at the significant difference between the two rooms for the condition without a WRMS, the setup described in the Guideline could be modified by adding more loudspeakers to generate a diffuse sound field in the laboratory.

6. References

6.1 List of abbreviations

DAI	Direct audio input
EUHA	European Union of Hearing Aid Acousticians
FET	*Freiburger Einsilbertest* (Freiburg monosyllabic word test)
IQR	Interquartile range
ISTS	International Speech Test Signal
KEMAR	KEMAR artificial head with a mouth simulator
SNR	Signal-to-noise ratio
SPL	Sound pressure level
WRMS(s)	Wireless remote microphone system(s)

6.2 List of figures

6.3 List of tables

6.4 Bibliography

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