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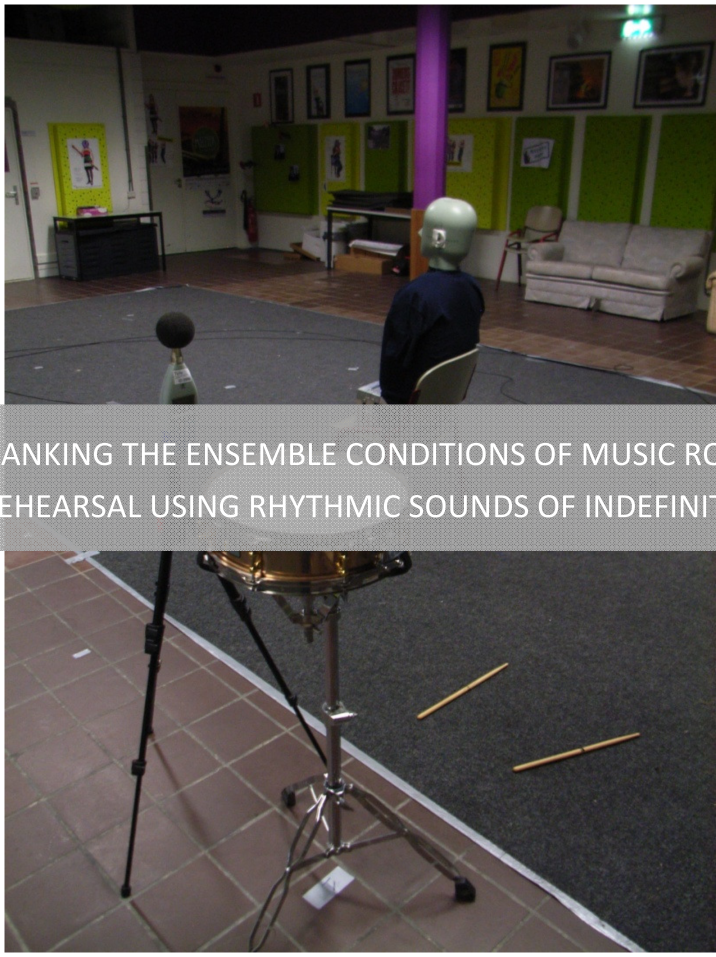
Music Rehearsal Room Acoustics



TU/e

Ranking the ensemble conditions of music rooms intended for rehearsal using rhythmic sounds of indefinite pitch

Master thesis | L.J.W. Schmitz

PROJECT INFORMATION

Music Rehearsal Room Acoustics – Ranking the ensemble conditions of music rooms intended for rehearsal using rhythmic sounds of indefinite pitch.

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SUMMARY

Most music rehearsal spaces are limited in their dimensions because of the limited available budget. This leads to small rooms in comparison to performance spaces. With the same music ensemble size and repertoire, there is a high risk of (too) loud sound levels in rehearsal spaces. This risk can be reduced/controlled with the proper use and amount of sound absorption. However, this increase in sound absorption leads to a decrease of the reverberation time for the same room volume. In the Netherlands, many musicians play in a non-professional wind orchestra. Most of these orchestras have a weekly rehearsal in their local hall. Often, such halls are shared by different music ensembles and with other community activities. All these different users have their specific demands, leading to different acoustical requirements for one room. However, few is known about the acoustic characteristics of these halls and the demands of these orchestras for such halls.

The goal of this research project was to investigate the influence of acoustic parameters (e.g. sound absorption or room volume) on the sound transfer in music rooms intended for rehearsal. Besides objective measurements to assess the stage and room acoustic characteristics of five typical music rehearsal rooms for wind orchestras, a subjective evaluation of the ensemble conditions of these rooms was performed to get some insights in the musicians' preferences. A new methodology was composed for the subjective evaluation by musicians, in an attempt to eliminate prejudices, rising from non-acoustic issues, and let the musicians solely evaluate the acoustics of the room. Recordings, of a musical fragment played on a snare drum, were made in selected music rooms and used to compose a listening test for the subjective evaluation. This led to the research question: Can differences in the values of acoustic parameters, in music rooms intended for rehearsal, be investigated by ranking the ensemble conditions of these rooms, based on recordings of rhythmic sounds of indefinite pitch?

The methods used for the objective measurements are imbedded in guidelines or used before by other researchers. So essentially, this has been a feasibility study for this new methodology for subjective evaluation by musicians. The ranking of the ensemble conditions of the rooms proved to be somewhat difficult for some test persons and some listening positions, but, eventually, they all provided a preferred ranking order. Their ranking order was solely based on these recordings of rhythmic sounds of indefinite pitch, without any prior knowledge about the rooms that were anonymously presented to them.

The objective measurements showed significant differences in the values of the analyzed acoustic parameters for the selected music rooms. The results for the subjective evaluation showed large fluctuations and dispersions (e.g. standard deviation) between and within the different listening conditions. The low significance of these results is not entirely unexpected due to the experimental nature of this methodology. However, some relations were observed between the mean rankings of the test rooms and their architectural and acoustic parameters. These observations emphasize that a good balance of the early reflected sound energy, to satisfy both the intelligibility of musical details and the perception of loudness, seems to be a real challenge. Also, a cautious trend between the total mean ranking of each room and its dispersion among the mean ranking of the six listening conditions can be observed. However, this cannot be predicted by the analyzed architectural and acoustic parameters.

This research showed it is possible to have musicians evaluate music rooms intended for rehearsal, solely based on played back recordings of rhythmic sounds of indefinite pitch. By ranking these music rooms, preferences can be observed and differences in the values of acoustic parameters of these rooms can be investigated. However, apart from some minor trends, no clear relations have yet been found, that could enable a prediction of the preferred sound transfer by determining the objective parameters. Also, as a result of the use of only one snare drum, it has to be seen if these preferences remain valid for a whole (wind) orchestra.

PREFACE

This master thesis was written on account of a my graduation project for the Master track Physics of the Built Environment, part of the Master Architecture, Building and Planning at Eindhoven University of Technology (TU/e). This graduation project titled “Music Rehearsal Room Acoustics – Ranking the ensemble conditions of music rooms intended for rehearsal using rhythmic sound of indefinite pitch” is the last step to obtain the degree Master of Science. The project was done within the chair Building Acoustics, part of the unit Building Physics and Services (BPS) at the Department of the Built Environment at Eindhoven University of Technology. The chair resides at the *Laboratorium voor Akoestiek* on the TU/e campus together with the company Level Acoustics. They collaborate on research, education and consultancy in the field of Acoustics of the Built Environment.

The choice for this research topic is a combination of previous research on the “difference in sound level between the two ears of an orchestra musician using in-ear microphones”, own experiences and the ongoing research at the *Laboratorium voor Akoestiek*. During my spare time, I am playing in (wind) orchestras as a percussionist. This influenced the selection of the test rooms and the use of a snare drum as a sound source for the recordings.

I would like to thank some people that contributed to the research described in this thesis. Constant, Remy, Lieke, Thomas, Marcel and my parents for helping with the measurements. The facility managers of the five test rooms for making their rooms available for scientific research. All the test persons for undergoing the listening test patiently and seriously, and Karen for helping me with contacting and entertaining them. All the staff at the *Laboratorium voor Akoestiek* for the pleasant environment and inspiring discussions. Albert Straten from Adams Musical Instruments for providing the snare drum for this research. And Sandra van Dongen from the Education and Student Service Centre (STU) at TU/e for the enlightening meetings.

Lennart Schmitz
Eindhoven, October 2014

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1. Introduction

In the field of architectural acoustics, much research is done on the room acoustics of performance spaces such as concert halls, theaters and other auditoria. This research is often done from the listeners' point of view. However, from the musicians' point of view, the specific acoustical conditions on stage are important. The research field of stage acoustics became more interesting with the introduction of the EU directive 2003/10/EC (European Union, 2003). This directive aims to protect workers in the music and entertainment sector from noise exposure, by compelling the EU member states to adopt legislation on this matter. This legislation includes limit and action values for noise exposure. The exposure limit values are $L_{EX,8h}$ = 87 dB(A) and $L_{C,peak}$ = 140 dB(C), the upper exposure action values are $L_{EX,8h}$ = 85 dB(A) and $L_{C,peak}$ = 137 dB(C), and the lower exposure action values are $L_{EX,8h}$ = 80 dB(A) and $L_{C,peak}$ = 135 dB(C) (European Union, 2003). The last decade, a research shift from the general acoustics of music rooms towards the sound exposure of (professional) musicians, both on stage (performance conditions) and in small spaces (most rehearsal conditions), could be observed. To create a pleasant acoustical working environment, (too) high sound levels have to be limited, without hindering conditions needed for playing ensemble and to provide a critical analysis of the music and musicians.

To a very large extend, existing research covers the working environment of professional musicians. However, besides these professional musicians, a lot of people in the Netherlands are playing music for recreation. According to a factsheet from 2012, by the Dutch governmental institute for culture education and recreational art forms (Landelijke Kennisinstituut Cultuureducatie en Amateurkunst, 2012), there were approximately 3.1 million inhabitants, aged 6 or older, in the Netherlands involved in some form of recreational music, both singing and instrumental, and individual and in groups. Many of these non-professional musicians are member of a music ensemble such as a marching or concert band, symphony orchestra, chamber music ensemble or choir. The Dutch national music association for wind and percussion ensembles (Koninklijke Nederlands Muziek Organisatie, 2013) states they represent 2,400 associations with 170,000 members in the Netherlands. The federation of amateur symphony and string orchestras (Federatie van Amateur Symfonie- en Strijorkesten, 2014) states they represent 245 orchestras with 9,000 members in both the Netherlands and Belgium. The national association for choirs (Vereniging van Nederlandse Korenorganisaties, 2014) states they represent thousands of choirs with approximately 180,000 members in the Netherlands.

Most of these music ensembles rehearse on a regular basis (e.g. weekly) to work towards one or more performances per year. In contrast, professional orchestral musicians rehearse almost daily to work towards more performances per week. The rehearsals of professional orchestras take place at the stage of their home concert hall (e.g. *Het Concertgebouw Amsterdam* or *Muziekgebouw Frits Philips Eindhoven*), in large music studios (e.g. *Muziekcentrum van de Omroep* in *Hilversum*) or in dedicated orchestral rehearsal rooms (e.g. the rehearsal room of the *Marinierskapel der Koninklijke Marine* in *Rotterdam*). On the other hand, the rehearsals of non-professional music ensembles often take place in buildings like (cultural) community centers, (music) schools, small theaters or even canteens or sports halls. When lucky, the room used for rehearsal is fitted for this purposes and sometimes even especially designed for it. However, many times costs and floor area are the only factors used to find an available accommodation. Some provisional measures may be taken afterwards to make the room more suitable. Also, with newly built facilities, most rehearsal spaces are limited in their dimensions because of the limited available budget. In both cases, new or re-development, this leads to small rooms in comparison to performances spaces. With the same music ensemble (e.g. an orchestra) size and repertoire, there is a risk of (even) higher sound levels in rehearsal spaces than in performance spaces. Mapping these risks and deriving guidelines to reduce/control these risks is still ongoing research.

This thesis focuses on rehearsal rooms for non-professional (wind) orchestras, because of (1) the large variety of rehearsal rooms within this group, (2) the amount of time spent rehearsing versus giving concerts and (3) personal interest. The first motive indicates the complexity of the subject: for the same function, very different types of rooms are used; there is no consensus about the preferred environment. The second motive clarifies the importance of the subject for non-professional musicians: on a yearly basis they (usually) spend only a few hours playing music in performance spaces, but they spend a lot of hours in rehearsal spaces. Final, the third motive explains the personal involvement with the subject: as a non-professional musicians himself, the author spends a lot of time in a variety of rehearsal rooms; this has awaken a lot of curiosity about the acoustical environment of these rooms.

The goal of this research project was to investigate the influence of acoustic parameters (e.g. sound absorption or room volume) on the sound transfer in music rooms intended for rehearsal. This influence has been studied both through objective room and stage acoustic measurements and subjective evaluation by non-professional musicians, who are used to playing in music ensembles.

The room acoustic measurements were based on ISO 3382-1 (ISO, 2009) and the stage acoustic measurements were based on previous research by Wenmaekers et al. (2012) and Wenmaekers & Hak (2013). The methodology for the subjective evaluation by musicians was newly composed for this research. When using subjective evaluation of the acoustical environment by musicians, interviews or questionnaires are often used. In this sort of inquiries the musicians are, or were at least once, present in the actual room. As a result, these evaluations tend to include (conscious and unconscious) prejudices of the musicians about the studied rehearsal rooms; like the appearance of the room, appreciation of the music, quality of the music ensemble, sympathy for the conductor and even their own temper. In a study by Dammerud (2009) among 180 professional symphony orchestra musicians using questionnaires, the musicians were also asked for non-acoustic issues that have a significant influence on their preferences for certain concert halls. About two thirds of the musicians mentioned that temperature, air quality and lighting are important; not only for comfort reasons, but also for instrument conditions. Followed by visibility and space, which was mentioned by about one third of the musicians. Other issues mentioned were: stage conditions (chairs, stand, risers etc.), accessibility, backstage facilities, quality of nearby restaurants and contact with the audience. These same non-acoustic issues could apply for other music venues (like rehearsal rooms) and other music ensembles (like wind orchestras).

All these non-acoustic judgments could interfere with a critical evaluation of the ensemble conditions in a room. In an attempt to eliminate these prejudices and let the musicians solely evaluate the acoustics of the room, recordings were made in selected music rooms and used to compose a listening test for the subjective evaluation. The audio signal that was recorded was real music played in the actual room. For practical reasons and simplicity, a snare drum was used to produce the music, thus being rhythmic sounds of indefinite pitch. Later on, the recordings were used in the listening test, by requesting the listener to evaluate the ensemble conditions of the room, based on the playback of the recordings, by ranking the anonymous rooms. Thus, the research question became: Can differences in the values of acoustic parameters, in music rooms intended for rehearsal, be investigated by ranking the ensemble conditions of these rooms, based on recordings of rhythmic sounds of indefinite pitch?

The structure of this report is the following. First some background information on this research topic, as gathered through a literature study, is discussed. Then the used methodology is presented. Afterwards, the relevant results are presented and discussed. Then conclusions are drawn and last, some recommendations for further research are given.

2. LITERATURE STUDY

Preliminary to the research described in this thesis, a literature study on the acoustical environment of rooms used by (groups of) musicians to rehearse was performed. This literature study provided background information and served as a starting point to the research described in this thesis. The complete literature study can be found in Appendix A. Below, the concluding section of the literature study is given.

The last decade, the research topic of music rehearsal room acoustics is still present in journals and proceedings. So far, this research has led to some guidelines and rules of thumb from acoustical consultants and manufacturers of music room equipment, for room dimensions and amount of sound absorption, but not to legislation (e.g. building codes or standards) on the architectural properties of rehearsal rooms. In contrary, legislation on sound exposure, intended to protect workers from risks "arising from noise owing to its effects on the health and safety of workers, in particular damage to hearing" (EU, 2003), was introduced in the member states of the European Union. This led to a research shift from the general acoustics of music rooms towards the sound exposure of (professional) musicians in small spaces. Most rehearsal spaces are limited in their dimensions because of the limited available budget. This leads to small rooms in comparison to performance spaces. With the same music ensemble (e.g. an orchestra) size and repertoire, there is a high risk of (too) loud sound levels in rehearsal spaces. This risk can be reduced/controlled with the proper use and amount of sound absorption. However, this increase in sound absorption leads to a decrease of the reverberation time for the same room volume.

Another aspect of rehearsal rooms is the large variety of users, not unusual for these rooms. Often, a rehearsal room is shared by different music ensembles, all with their own number of musicians, combination of instruments, musical style and corresponding repertoire. All these different users have their specific desires for the acoustical environment, leading to different acoustical requirements for one room. To some extent, compromises can be reached with the use of variable acoustics, but each room has its physical limitations and each building owner/user his budget limitations. One last challenging aspect is the communication about the desires, requirements, opportunities and limitations between all the stakeholders, because often each group uses their own terminology.

The research described in this thesis focused on a group of music ensembles that is a typical user of music rehearsal rooms in the Netherlands: wind orchestras. Most wind orchestras consist of non-professional musicians, depend on volunteers and have a small budget to provide their accommodation. Besides objective measurements to assess the stage and room acoustic characteristics of five typical music rehearsal rooms for wind orchestras, subjective evaluation of the ensemble conditions of these rooms was performed to get some insights in the preferences of the main stakeholder (musicians).

Just recently, in Norway, a new standard (NS 8178) on acoustic criteria for rooms and spaces for music rehearsal (and performance) was introduced. A conference paper by Rindel (2014) addressed this standard. At this same conference, a paper by Wenmaekers et al. (2014) was presented, which used measurement data from this thesis, combined with measurement data from similar music rooms, focusing on Early and Late Support over various distances.

3. METHODOLOGY

Can differences in the values of acoustic parameters, in music rooms intended for rehearsal, be investigated by ranking the ensemble conditions of these rooms, based on recordings of rhythmic sounds of indefinite pitch? In order to get an answer to this research question a combination of research methods has been chosen. The object of interest are music rooms intended for rehearsal, with a focus on relatively small rooms used by non-professional music ensembles. These rooms often lack a tailor-made acoustic design for this purpose or are multipurpose. On the one hand, objective measurements to assess the stage and room acoustic characteristics, with a focus on ensemble conditions, of these rooms had to be performed. On the other hand, a new research method has been developed to provide a subjective evaluation of these ensemble conditions. Firstly, the used test rooms and the measurement grid will be described. Secondly, the method for the stage and room acoustic measurements will be described and thirdly, the method for the subjective evaluation will be explained.

3.1 TEST ROOMS

For this research, five music rooms intended for rehearsal were selected. In this section, an overview of the rooms and their architectural properties is given. Also the measurement grid used in all these rooms is defined.

3.1.1 ROOM SELECTION

The test rooms were selected based on experience of the author, connections and availability. An attempt was made to get a good representation of the variety of rooms typically used for rehearsals by non-professional music ensembles. In this research, the following five rooms were used:

- Grote zaal, Multifunctioneel Centrum, Berg aan de Maas [**BM**]
- Blauwe Zaal, Auditorium TU/e, Eindhoven [**BZ**]
- Grote Muziekzaal, Studentencentrum de Bunker, Eindhoven [**BK**]
- Theaterzaal, Activiteitencentrum 't Hazzo, Aalst-Waalre [**HZ**]
- Grote zaal, 't Aad Raodhoes, Melick [**ML**]

The abbreviations for each room, that will be used throughout this thesis, are given in square brackets.

3.1.2 ARCHITECTURAL PROPERTIES

An inventory of the architectural properties of the five selected rooms was made by measuring dimensions, taking notes, drawing sketches and taking photographs. These properties included room dimensions, wall, floor and ceiling finishes, but also relevant objects or elements present in the rooms like sound absorbers, sound reflectors, HVAC systems and furniture. Table 1 gives the average room dimensions of the five test rooms.

TABLE 1: AVERAGE ROOM DIMENSIONS OF THE FIVE TEST ROOMS

Room	Width	Depth	Height	Floor area	Room Volume
	[m]	[m]	[m]	[m²]	[m³]
BM	12.0	30.0	3.0 – 6.7	360	1920
BZ	15.0 – 20.5	24.0	2.1 – 7.0	430	2500
BK	14.5	11.5	3.0 – 4.0	165	650
HZ	11.5 – 16.5	29.0	5.5 – 5.9	400	2250
ML	12.5	18.0	4.0	225	900

On the following pages each test room will be described briefly. An impression of the interior of each room and a simplified 3D model will be shown. Also some relevant architectural characteristics will be pointed out.

3.1.2.1 MFC, BERG AAN DE MAAS [BM]

The *Grote Zaal* is situated on the ground floor in the *Multifunctioneel Centrum (MFC)* in *Berg aan de Maas*. This room is a multi-purpose room, with a small stage of approximately 100 m² at the far end of the room (on the right in the 3D model in Figure 1) and a bar counter on the main entrance side of the room (on the left in the 3D model in Figure 1). Above the bar counter a small balcony is situated.

The room has a curved ceiling finished with wooden laths on a cavity. The lowest floor to ceiling height (3.0 m) is situated at the back of the stage. The highest floor to ceiling height (6.7 m) is situated at about two meter in front of the stage. The stage and the rest of the room can be separated from each other by a mobile wall. When opened, the elements of this mobile wall are split up between the two sides of the stage and 'folded up'. The rail to move and fasten the mobile wall elements is integrated in a kind of proscenium arch, dividing the stage and the rest of the room.

On one side of the room, the wall partly consists of (outdoor) windows. The rest of the walls is finished with plaster and wooden laths on cloth. At the walls surrounding the stage, the wooden laths have a zigzag shape. The floor is finished with a synthetic layer. On stage, there are three thin carpets (4.0 x 2.0 m²) placed on the floor, meant to absorb some of the (high frequency) ground reflections produced by the musicians' instruments. There is also a metal cargo lift positioned in one corner of the stage. Furthermore, some chairs were stacked at two sides of the stage. In the rest of the room, there were some tables and chairs present during the measurements.

In this room, the local music society, consisting of a (youth) wind orchestra and percussion group, rehearses and gives concerts. Not only during the concerts, but also during rehearsal, the musicians are seated/standing on stage. Figure 1 gives an impression of the stage and a simplified model of the room.

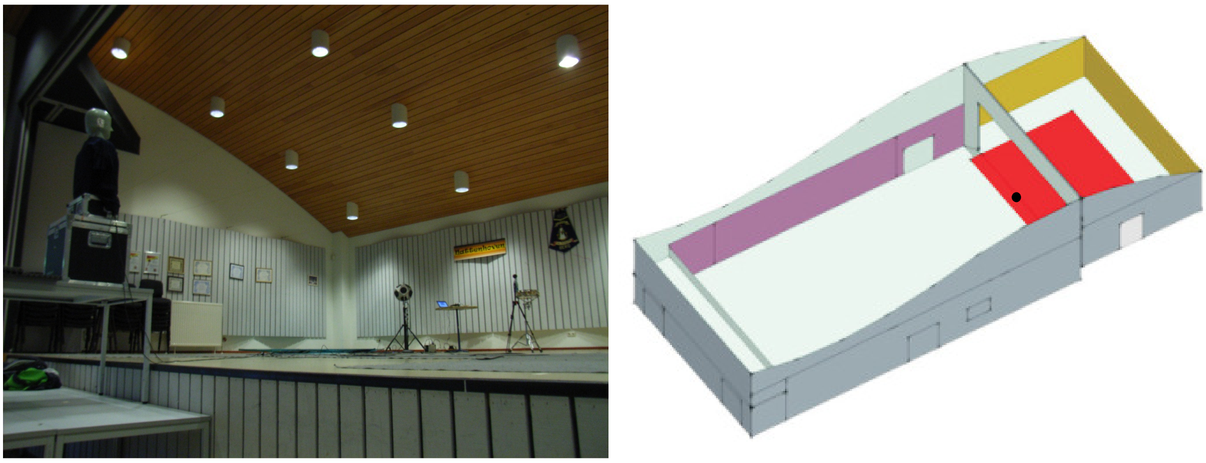

FIGURE 1: BM – PHOTO IMPRESSION (LEFT) AND 3D MODEL (RIGHT); MEASUREMENT GRID (RED) WITH CONDUCTOR POSITION (BLACK DOT), MODERATELY ABSORBING SIDE WALLS (PURPLE), DIFFUSING STAGE WALLS (YELLOW), PROSCENIUM ARCH AND MODERATELY SOUND ABSORBING CURVED CEILING.

3.1.2.2 BUNKER, EINDHOVEN [BK]

The *Grote Muziekzaal* is situated on the first floor in *Studentencentrum de Bunker* in *Eindhoven*. This building is part of the campus of Eindhoven University of Technology. A large part of this building was renovated in 2006/2007 to accommodate multiple student (culture) associations. The *Grote Muziekzaal*, now used as a rehearsal room by *Eindhovens Studenten Muziek Gezelschap Quadrivium* and *Bigband Studentproof*, used to be the kitchen for the former Mensa. The tile floor has not been replaced. This resulted in very strong ground reflections, especially from the percussion and brass instruments. To reduce these ground reflections, two floor carpets of 4.0 x 9.0 m² permanently lay on top of the tile floor.

For about half of the wall length, the walls have plasterboard side sheeting, from the floor to a height of approximately 2.8 m and with an average depth of 0.12 m. Above this side sheeting, the wall consists of painted bricks. The other half of the wall length, consist of plasterboard from floor to ceiling and wall openings; two double doors (2.0 x 2.3 m²), two small doors and two metal roll down shutters (2.8 x 2.5 m² and 2.1 x 2.3 m²). To provide extra sound absorption, 28 acoustical panels (10 large and 18 small) are fixed to the walls. These panels are made up of a perforated plasterboard on a cavity filled with mineral wool, fixed to a fiberboard back plate. The large panels measure 1.25 x 1.20 m² and the small panels 0.62 x 1.20 m². Above the acoustical panels, 37 posters in frames are hung. These frames measure 0.50 x 0.70 m²; some consist of a plastic edge and cover and some of only a glass cover.

The rooms interior floor to ceiling height measures 4.0 m. This ceiling consists of concrete slabs and four large plasterboard squares, that seal of four light domes. This was done to improve the sound insulation to the outdoor environment. However, the effective floor to ceiling height is for large parts of the room just 3.0 m. This due to all the air ducts, light boxes and reflectors that hanging below the fixed ceiling. There are two large air ducts (one inlet and one outlet) with nine smaller side-branches connecting the air vents (0.6 x 0.6 m²). These air ducts consist of reflective materials like aluminum sheets and foil. There are twelve light boxes, measuring 1.25 x 0.3 m², containing two fluorescent light tubes each. There are 21 sound reflectors with a visible surface of 1.20 x 1.10 m². These reflectors consist of a curved plywood board (8 mm thick) with mineral wool (70 mm thick) on top of it.

During the measurements, six stacks with chairs, three couches, four tables, a pushcart, a projection screen and some smaller furniture were stored along the walls. The room also contains two structural concrete columns, with wooden paneling at the bottom, and a (small sized) grand piano (1.70 m long) with a protective sleeve. Figure 2 gives an impression and a simplified model of the room.

FIGURE 2: BK – PHOTO IMPRESSION (LEFT) AND 3D MODEL (RIGHT); MEASUREMENT GRID (RED) WITH CONDUCTOR POSITION (BLACK DOT), ABSORBING WALL PANELS (PURPLE) AND REFLECTIVE CEILING PANELS.

3.1.2.3 AUDITORIUM, EINDHOVEN [BZ]

The *Blauwe Zaal* is situated between the first and second floor of the *Auditorium* in *Eindhoven*. This building is part of the campus of Eindhoven University of Technology. This hall is designed for lectures, presentations and ceremonies, so mainly for speech. However, the hall is also often used for small concerts and rehearsals by music ensembles.

It has a small stage (approximately 70 m^2) and an inclined audience area with fixed seats. The large floor area (approximately 230 m^2) between de stage and audience area can be filled with additional seats. In most rehearsal situations, this floor area is used by the music ensemble. In most concert situations, the stage is used by the music ensemble, with extensions if necessary. All floor areas within in the hall are wooden floors.

The wall at the back of the stage is almost entirely covered by a projection screen. This screen is acoustical transparent, but behind the screen there is a heavy curtain that provides sound absorption. Within the wall behind the audience area, there is a central control room protruding out of the wall above the last row of seats. The rest of the back wall and the side walls consist of plasterboard with a rough finish.

To the ceiling and top part of the walls, suspended square panels (1.25 x 1.25 m^2) have been mounted, making the top of the hall egg-shaped. These panels provide sound reflection and scattering. Furthermore, lighting and air ducts are hanging from the ceiling. There are also two floor to ceiling heavy curtains on tracks hanging from the ceiling. These curtains were opened to both sides during the measurements. Some tables, two lecterns and some artificial plants were standing along the walls during the measurements. Besides the fixed seats at the audience area, thirteen additional chairs were standing on each side in front of the seating area. Figure 3 gives an impression and a simplified model of the room.

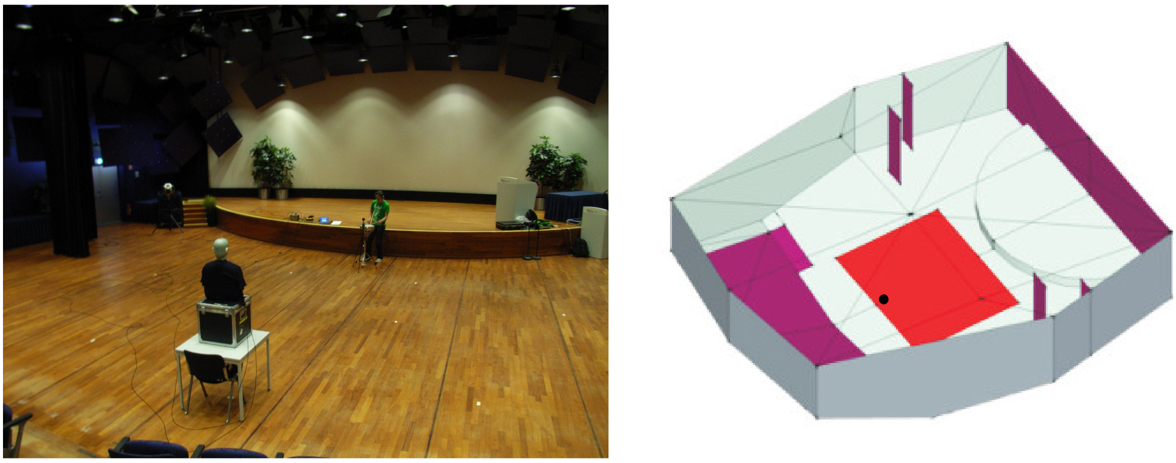

FIGURE 3: BZ – PHOTO IMPRESSION (LEFT) AND 3D MODEL (RIGHT); MEASUREMENT GRID (RED) WITH CONDUCTOR POSITION (BLACK DOT), ABSORBING AUDIENCE AREA, CURTAINS AND ABSORPTION BEHIND PROJECTION SCREEN (PURPLE) AND CURVED STAGE.

3.1.2.4 Hazzo, Aalst-Waalre [HZ]

The *Theaterzaal* is situated on the ground floor in *Activiteitencentrum 't Hazzo* in *Aalst-Waalre*. This building consists of multiple rooms of different size and for different purposes, like a sports hall, meeting rooms and this theater/events hall. This multifunctional hall has a theater like stage (approximately 120 m²), but most music ensembles prefer to rehearse in the lower section of the hall (approximately 280 m²). The stage has a wooden floor, but the lower section of the hall has a synthetic (parquet imitation) floor.

At first sight, the hall looks like a shoebox shape, but the two side walls do not run parallel. The width of the wall at the back of the stage is smaller than the width of the wall at the other end of the hall, thus, in the horizontal section, the hall is slightly funnel-shaped. The walls and ceiling at the stage area are fully reflective and there are some theater accessories installed, like coulisse (four panels on each side), curtains and lighting (racks). During the measurements, all curtains were withdrawn and at the back of the stage stacked chairs were stored.

The walls in the lower section of the hall consist of a plasterboard finish. From approximately a height of 1.5 to 3 meter and above, large wall panels with a wood-wool cement slab cover are fixed to the walls to provide sound absorption. This combination roughly makes the walls reflective at ear level and absorptive above. In the middle of the lower section, a mobile wall is situated to divide the hall in two almost equal parts. This mobile wall was withdrawn during the measurements.

The ceiling in the lower section is finished with wooden panels. At the outer edge, the ceiling is flat, but at the large middle section it is zigzag shaped alternating in two directions. The ceiling panels are reflective and the zigzag shape is to provide sound diffusion. Integrated within the ceiling are light boxes and air in- and outlets. At one position, a rack with lighting in hanging from the ceiling.

At the far end of the hall opposite the stage is a bar counter. During the measurements, stacked chairs and tables were stored behind and in the corners next to this bar counter. Figure 4 gives an impression and a simplified model of the room.

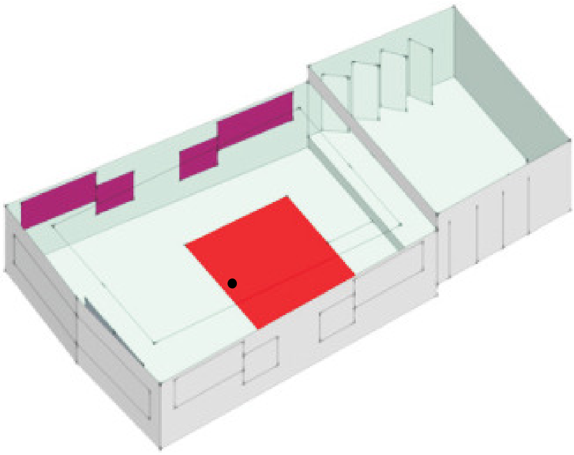

FIGURE 4: HZ – PHOTO IMPRESSION (LEFT) AND 3D MODEL (RIGHT); MEASUREMENT GRID (RED) WITH CONDUCTOR POSITION (BLACK DOT), ABSORBING WALL PANELS ABOVE 1.5-3 M (PURPLE), FULLY REFLECTIVE STAGE AND REFLECTIVE AND ZIGZAG SHAPED MIDDLE CEILING PART.

3.1.2.5 AAD RAODHOES, MELICK [ML]

The *Grote Zaal* is situated on the ground floor in *'t Aad Raodhoes* in *Melick*. This building is the home of the local music society *Harmonie Concordia Melick*. This room was added to the main building in the nineteen-nineties to accommodate rehearsals of the local (youth) wind orchestra and percussion ensemble, but also to accommodate small concerts with comparable music ensembles and choirs.

The room has a shoebox shape with at one corner a small entrance platform, due to the height difference with the adjacent main building. Two large stair steps and a slope provide access to the floor. Next to the entrance platform, a storage room is situated. This cove has a straight side, an arched side and an open side to the room. Here, chairs, tables, a grand piano and percussion instruments were stored during the measurements. In this cove, the floor to ceiling height is 2.7 m. The floor to ceiling height within the rest of the room is 4.0 m. The floor consists of linoleum, creating a reflective surface.

Three of the four walls consist of brickwork, with integrated structural steel columns and five floor to ceiling plastic door- and window-frames. These frames were largely covered by plastic vertical blinds during the measurements. The fourth wall consists of plaster with wooden paneling for the lowest 1.25 m. In the corner of the room with the entrance platform, the wall partly consists of a mobile wall (4.25 x 3.25 m²), facilitating a coupling with the main building. This mobile wall was closed during the measurements and during rehearsals.

The ceiling consists of a suspended ceiling with both absorbing and reflective elements (estimated sound absorption coefficient of 0.5). The light boxes and air vents are integrated in this suspended ceiling. Along the walls, 21 framed paintings were hanging. These frames had metal edges and glass covers and varied in size from 0.6 x 0.5 m2 to 1.0 x 0.7 m². The room contains six radiators along the walls measuring 1.65 x 0.9 x 0.10 m³. During the measurements, the following furniture was present in the room: four pushcarts with stacked wooden chairs (1.5 x 1.3 x 0.75 m³) and three tables (1.26 x 0.70 x 0.74 m³). Figure 5 gives an impression and a simplified model of the room.

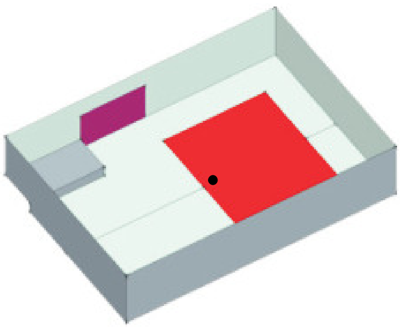

FIGURE 5: ML – PHOTO IMPRESSION (LEFT) AND 3D MODEL (RIGHT); MEASUREMENT GRID (RED) WITH CONDUCTOR POSITION (BLACK DOT), ABSORBING AREA (PURPLE) AND SMALL ENTRANCE PLATFORM.

3.1.3 MEASUREMENT GRID

For the stage and room acoustic measurements and for the subjective evaluation method the same measurement grid was used. The used measurement grid was based on research on stage acoustic parameters on concert halls stages (Wenmaekers et al., 2012). The measurement grid described by Wenmaekers et al. (2012), however, was used for measurements at the stages of concert halls and based on a symphony orchestra. Because this research focuses on wind orchestras and rehearsal rooms, the measurement grid had to be modified. The picture on the left in Figure 6 shows the measurement grid as described by Wenmaekers et al. (2012) and the picture on the right in Figure 6 shows the measurement grid used in this research. Measurement positions 11 and 12 have been omitted due to the smaller width of the measured rooms relative to the stages of concert halls and the smaller width of a wind orchestra relative to a symphony orchestra. The musicians within a wind orchestra also tend to be seated more closely packed together relative to those within a symphony orchestra, so the dimensions of the whole grid were scaled down to 80% of the original size, thus decreasing the distances between the nodes of the grid lines from 1.5 by 1.8 m² to 1.2 by 1.4 m². What did not change was the symmetry of the measurement grid, thus one half of the measurement positions were both source and receiver position and the other half only receiver positions. Measurement position 10 represents the conductor of the orchestra and faces the other measurement positions. Measurement positions 1 to 9 represent musicians and are orientated towards the conductor (measurement position 10). Measurement position 1 represent the percussion section of a wind orchestra, measurement positions 2,3,5 and 6 represent the brass sections and measurement positions 4,7,8 and 9 the woodwind sections.

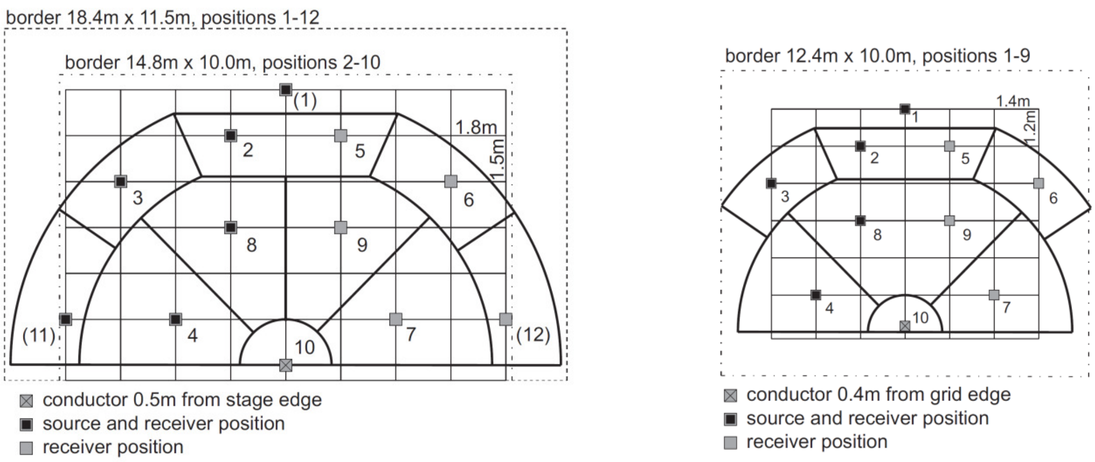

FIGURE 6: MEASUREMENT GRID WITH MEASUREMENT POSITIONS. LEFT: SYMPHONY ORCHESTRA - RIGHT: WIND ORCHESTRA

3.2 Stage and room acoustic measurements

In this section the methodology used for the objective stage and room acoustic measurements is described along with the measurement set-up, used equipment and performance of the measurements. Stage acoustics measurements were performed to obtain objective parameters related to the ensemble conditions in the different rooms. Room acoustic measurements were performed to obtain objective parameters to described the acoustic environment within the different rooms. During all measurements, the indoor temperature and relative humidity were measured and registered at four moments.

3.2.1 Extended support parameters

The stage acoustic parameters used to describe the ensemble conditions within the test rooms are the extended support parameters as shown in Equation 1 and 2.

$$ST_{early;d} = 10\lg\left(\frac{\int_{10}^{103-delay} p_d^{\,2}\,dt}{\int_{0}^{10} p_{1m}^2\,dt}\right) \qquad (1)$$

$$ST_{late;d} = 10\lg\left(\frac{\int_{103-delay}^{\infty} p_d^{\,2}\,dt}{\int_{0}^{10} p_{1m}^2\,dt}\right) \qquad (2)$$

where, p_d is the sound pressure measured at distance d; p_{1m} is the sound pressure measured at 1 meter distance; and *delay* is the source to receiver distance divided by the speed of sound; time to infinity is defined as the time of the cross point between the decay curve and the noise floor of the impulse response.

These extended support parameters, introduced by Wenmaekers et al. (2012), were adapted from the 'normal' support parameters Early Support (ST_{early}) and Late Support (ST_{late}), based on research by Gade (1989 & 2010) and included in the annex of the standard ISO 3382-1. These extended support parameters provide the possibility to measure the Early and Late Support at various source to receiver (S-R) distances. This added functionality should make it possible to study not only the support for sound from the own instrument (1 meter S-R distance) but also for sound from the other players in the ensemble (S-R distances > 1 meter). A variable time point '103-delay' is introduced that takes into account the delay of direct sound by increased distance. This way, the parameters can be measured at S-R distances up to 25 m, considering a time interval width of 30 ms as an acceptable minimum. The time interval of early reflected sound starts at 10 ms, instead of 20 ms in the 'normal' support parameters, to be able to measure closer to the stage/room boundaries up to 2 m. The reference level at 1 meter distance is measured separately at only one position free from reflective walls or ceilings, in this case measurement position 8 from Figure 6. See Wenmaekers et al. (2012) for more background information and literature on these extended support parameters.

3.2.1.1 Measurement set-up

The measurement set-up used for these stage acoustic measurements was based on previous research from Wenmaekers & Hak (2013) and consisted of an omnidirectional sound source and two omnidirectional microphones as receiver; the latter was to minimize the time needed for the measurements. The omnidirectional sound source used was a dodecahedron loudspeaker and as receiver two prepolarized free field microphones ½" were used. Measurement positions 1,2,3,4 and 8 from Figure 6 were used as source positions and measurement positions 1 to 10 as receiver positions. The loudspeaker was placed at one of the five source positions and each microphone at one of the 9 receiver positions or at 1 meter distance from the sound source. At this 1 meter distance position the microphone was placed behind the loudspeaker as seen from the conductor (measurement position 10). This is done according to the analogy that the source represent a music instrument and the receiver a musician. Only at measurement position 1 this 1 meter distance was not at the back but at the left as seen from the conductor (measurement position 10) due to the close proximity to a back wall in most of the test rooms. Because measurement position 1 represents the percussion section and percussionists often also have instruments around them instead of only in front of the, the analogy between instrument (source) and musician (receiver) is still (partly) intact. The used source height was 1.35 meter and the receiver height 1.2 meter, except for receiver position 10 where the receiver height was 1.95 meter. Position 10 represents a conductor standing on a platform, therefore, this position has an increased receiver height. The loudspeaker was rotated in five steps of 72 degrees and for each rotation the Room Impulse Response (RIR) (see picture on the left in Figure 7) was measured using an e-Sweep signal. This signal was produced and recorded using the acoustic measurement software Dirac installed on a netbook. The used measurement time was 5.46 seconds. The measurement equipment that was used for these stage acoustic measurements is shown in Appendix B.

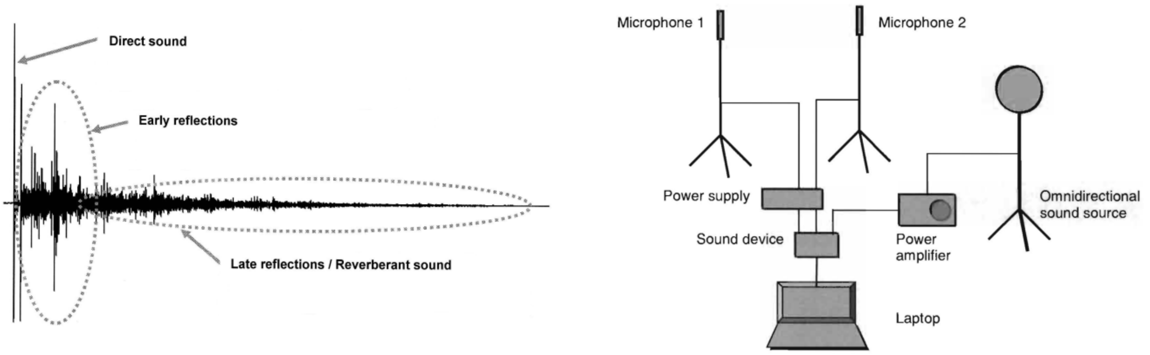

FIGURE 7: ROOM IMPULSE RESPONSE (LEFT) AND SCHEMATIC MEASUREMENT SET-UP (RIGHT)

3.2.1.2 Source-receiver distances

The use of five source positions, nine receiver positions and 1 meter distance measurements at each source position, leads to 50 source-receiver combinations. These combinations can be found in Appendix B, along with the source to receiver distances (as a result of the measurement grid) and the corresponding delays (ms), leading to the limit values used in the extended support parameters from Equation 1 and 2. The S-R distances vary from 1.00 to 8.40 m, leading to a delay range from 3 to 25 ms with a corresponding limit value range from 100 to 78 ms.

3.2.2 Reverberation time

The reverberation time (T_{30}) of each studied room was determined in Dirac, by using the impulse response measurements from the stage acoustic measurements. The test rooms were unoccupied during the measurements and no chairs or stands were put in the orchestra area (empty 'stage'), in line with ISO-3382-1 (2009). For the reverberation time determination, the impulse response measurements at 1 meter distance from the sound source were left out. This was done because the 1 meter distance position lay within the critical distance (range 1.5 to 2.5 m) in each room.

3.2.3 Background noise

Besides the measurements described above, other measurements were performed to determine the background noise of the empty test rooms. The level calibrated measurement set-up and equipment used for the background noise measurements was identical to the measurement set-up described above. For background noise measurements no impulse response was measured, but the sound pressure level present in the room: the sound that came from building systems and other indoor and outdoor environmental noises.

3.3 Subjective evaluation

In this section the methodology used for the subjective evaluation is described. Recordings were made of a musical fragment played inside each test room. These recordings were used to comprise a listening test. This listening test was presented to test persons, in an attempt to obtain their preferences on the ensemble conditions in the studied rooms.

A musical fragment was played in all music rooms intended for rehearsal, with various source to receiver distances. The instrument used to play the musical fragment, was a snare drum. This instrument was chosen for practical reasons: it is easy to move, it could be played by the author, it is identifiable for wind orchestra musicians and it produces no melodic sounds, but rhythmic sounds of indefinite pitch. The latter excludes extra variables like tuning and melody, so the main focus is on rhythm and tempo. The musical fragment was played at three different musical dynamics (loudness): p (*piano*), mf (*mezzo forte*) and ff (*fortissimo*). This was done to study the (possible) changing perception and preference with changing loudness.

3.3.1 Recordings

The musical fragment was recorded binaurally, using a head and torso simulator (HATS), so it could be played back using headphones. By using these recordings, exactly the same musical fragment could be used throughout the whole subjective evaluation process, providing reproducibility of the sound source. By playing it back using headphones, the listener perceives the recordings as they would be perceived in the recording room itself, without interference of the room acoustics of the playback room.

3.3.1.1 Musical fragment

A musical fragment to be played on snare drum was selected. The used musical fragment, are the first 14 bars from the snare drum part from the third movement (Alborada) from Capriccio Espagnole by Nicolai Rimsky-Korsakov. This fragment was chosen for several reasons: (1) it consists of multiple rhythmic patterns (like rolls and loose strokes) and note values, (2) it is a complete but relative short musical phrase and (3) it is a combination of repetition and variation of rhythms. These reasons make it a representative musical fragment for a snare drum part within an orchestral piece of music. The sheet music from this part is shown in Figure 8. The used tempo is 120 beats per minute (beat is quarter note).

FIGURE 8: MUSICAL FRAGMENT – FROM CAPRICCIO ESPAGNOLE BY NICOLAI RIMSKY-KORSAKOV (SHEET MUSIC FROM IMSLP.ORG)

3.3.1.2 Measurement set-up

For the measurement set-up, used for the recording of the musical fragment, the same measurement grid as for the stage and room acoustic measurements was used. The measurement grid and positions can be found in Figure 6. Measurement position 1 was used as source position for the snare drum and measurement positions 2,3,4,8 and 10 as receiver positions for the head and torso simulator (HATS). Position 10 represented the position of the conductor within an orchestra. At this position, the HATS was orientated with its back to the wall facing the room (orchestra). Positions 1,2,3,4 and 8 represented musicians. Here, the HATS was orientated towards position 10, thus facing the conductor.

The snare drum was mounted on a drum stand and placed at measurement position 1. The HATS was placed on a chair at one of the receiver positions. The casing of the measurement amplifier was used to raise the ears of the HATS to a sitting height of approximately 1.20 meter. At receiver position 10, the HATS was placed on a table (available in each test room) and the casing of the dodecahedron loudspeaker was used to raise the ears of the HATS to a standing height of approximately 1.80 meter.

The HATS was connected to a netbook via a power supply and USB audio interface. The acoustics measurement software Dirac was used to record the musical fragment, played by the author on the snare drum, and converted the recording to wave-files. A sound level meter was placed in front of the snare drum, at a distance of 0.19 m from the edge of the snare drum, and with the microphone at a height of 1.17 m. The three used dynamics (p, mf and ff) were calibrated with the use of the sound level meter in front of the snare drum. Before the recordings, the sound level meter was calibrated with a calibrator at an SPL of 93,8 dB at a frequency of 1000 Hz. During the recordings, a target $L_{p,eq}$ (as measured by the sound level meter) was used to maintain the correct musical dynamic. The target $L_{p,eq}$ over the played musical fragment was 75 dB for *piano*; 90 dB for *mezzo forte* and 105 dB for *fortissimo*. These target values were determined by an empirical experiment in one of the measurements rooms of the Acoustical Laboratory at Eindhoven University of Technology.

The used tempo was 120 bpm (beat is quarter note). This tempo was maintained throughout all the recordings with the use of a (digital) metronome played back via headphones. The measurement sequence was as following:

Start Dirac (4 beats) – Start RION (4 beats) – musical fragment (27 beats) – Stop RION (4 beats)

The selected measurement time in Dirac was 21.8 seconds. At all five receiver positions, the musical fragment was recorded for the three musical dynamics. Figure 9 shows the source (snare drum), receiver (HATS) and 'musical dynamic calibrator' (sound level meter) used during the recordings of the musical fragments.

FIGURE 9: SOUND SOURCE (SNARE DRUM), RECEIVER (HATS) AND SOUND LEVEL METER

The measurement equipment, that was used for these recordings of the musical fragment played on the snare drum, can be found in Appendix B.

3.3.2 Listening test

A listening test was created, using a selection of the recordings made with the snare drum and HATS. An accompanying question form was compiled, containing questions to obtain general information about the musical background of the test persons and to obtain their preferences on the ensemble conditions in the studied rooms. The selected recordings were played back through high-quality headphones for a good reproducibility and fidelity.

The general information about the musical background of the test persons included: age and gender, musical instrument and years of experience, quantity and type of music ensembles, and quantity of used rehearsal rooms in a year.

The test person had to base their preferences, on the ensemble conditions in the five test rooms, on the playback of the recordings of the musical fragment in these rooms. They had to rank the five rooms from 1 (best) to 5 (worst). The rooms were anonymous and shuffled for each set recordings. The played back recordings lasted 15 seconds each. There were six sets of recordings, each set consisting of five recordings, one for each of the test rooms. There were two sets of recordings for each musical dynamic: one for a receiver position close to the sound source and another for a receiver position distant to the sound source. For the receiver position nearby position 2 was chosen; thus resulting in a source-receiver pair S1R2, with a source-receiver distance of 1.84 meter. For the receiver position far away position 4 was chosen; thus resulting in a source-receiver pair S1R4, with a source-receiver distance of 6.62 meter. There were only two S-R pairs used for the listening test, to avoid the test from becoming too time consuming. When looking at the analogy of the measurement grid and the source-receiver relation with an (wind) orchestra, S1R2 can be seen as sound originating in the musician's own instrument section or neighbors and S1R4 can be seen as sound originating from the other side of the orchestra.

3.3.2.1 Test persons

Test persons were used to evaluate the recordings with the use of the listening test. The test persons had to be non-professional musicians, with experience of playing music in a wind orchestra. All test persons were in the age of 18 to 36 years old, see Figure 10 for an age distribution plot. This was deliberate to get a homogenous test group in age and exclude age as an extra variable. Eventually, the listening test was presented to 24 test persons, 14 males and 10 females. It was no requirement for the test persons to have a 'live' experience with the studied rooms, but due to the connections of the author with both test rooms and test persons, each test person did have 'live' experience with at least one of the studied rooms.

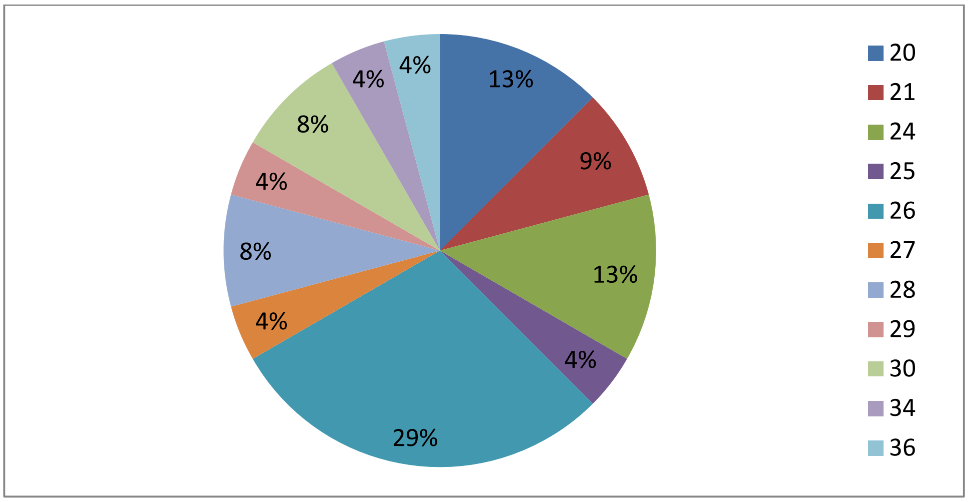

FIGURE 10: PLOT FOR THE AGE DISTRIBUTION FOR THE TEST PERSONS

3.3.2.2 Test set-up

The set-up used for the listening test consisted of a notebook, with audio playback software installed on it, and headphones. Furthermore, the test persons had the question form in front of them and they had scrap paper at their disposal. The latter was to make notes while they were listening to the recordings. The playback equipment used during the listening test can be found in Appendix B.

3.3.2.3 Question form

The question form used during the listening test consisted of six general questions and six questions concerning the six sets of recordings. The question form was in Dutch, as all the test persons had the Dutch nationality, and can be found in Appendix C. The six questions concerning the six sets of recordings, were the main questions and were numbered. For each of the three musical dynamics, the corresponding question (for both receiver positions) focused on a certain perception. The *mezzo forte* fragments focused on a general impression of the ensemble conditions in the five test rooms; the *piano* fragments focused on the audibility of musical details; and the *fortissimo* fragments focused on the loudness. This sequence was also the sequence of the set of recordings; beginning with a comfortable mf, than the subtle p and at the end the loud *fortissimo*. The six general questions were put in between the questions about the sets of recordings. This was done to 'clear the ears and head' after each set of recordings, stimulating the test person to consider each set of recordings independent. For each of the three musical dynamics, first the far away receiver position was played back and second the nearby receiver position.

Below, the questions concerning the three musical dynamics and six sets of recordings (two sets per musical dynamic) are translated into English:

- You now hear five *mezzo forte* fragments (again), recorded in five different music rehearsal rooms at an identical position. In which of these rooms would you prefer to rehearse with a music ensemble? Rank the five fragments in order of preference, beginning with the most favorable.
- You now hear five *piano* fragments (again), recorded in five different music rehearsal rooms at an identical position. In which of these rooms can you distinguish the musical details best? Rank the five fragments in order of preference, beginning with the most favorable.
- You now hear five *fortissimo* fragments (again), recorded in five different music rehearsal rooms at an identical position. In which of these rooms the loudness of the *fortissimo* is endured best? Rank the five fragments in order of preference, beginning with the most favorable.

4. RESULTS AND DISCUSSION

In this chapter, the results of both the objective measurements and subjective evaluation are presented and discussed. Also, the relation between these two aspects is discussed. This will be done with the help of graphs and tables with the most relevant data..

4.1 STAGE AND ROOM ACOUSTIC MEASUREMENTS

In this section, the results of the objective stage and room acoustic measurements will be presented and discussed. The following objective parameters were obtained from the stage and room acoustics measurements: (1) extended support parameters $ST_{early,d}$ and $ST_{late,d}$, (2) reverberation times T_{30}, RT_{low}, RT_{mid} and RT_{high}, and (3) background noise levels L_{eq}, L_{Aeq} and L_{Ceq}.

4.1.1 EXTENDED SUPPORT PARAMETERS

The extended support parameters were determined as an average over 5 measurements, while rotating the dodecahedron loudspeaker in steps of 72 degrees. For each room, there were 50 values for both $ST_{early,d}$ and $ST_{late,d}$, corresponding with the 50 source-receiver combinations, including the 1 meter distance measurement at each of the five source positions; which are basically the original support parameters ST_{early} and ST_{late} as described in ISO 3382-1. All values are averages over the 250 to 2000 Hz octave bands.

In Figure 11, a scatter plot for $ST_{early,d}$ over varying source to receiver distance is given for the five test rooms. As mentioned above, there are 50 source-receivers combinations. However, some source-receiver combinations have the same source to receiver distance, resulting in 21 different source to receiver distances. These 21 distances correspond with the vertical lines visible in the scatter plot. This plot shows significant differences among the five rooms; JND = 2.0 dB estimated by A.C. Gade, as mentioned by Hak et al. (2012). At the two longest source to receiver distances, the differences are the smallest, but still provide a range that is larger than the JND. With increasing source to receiver distance $ST_{early,d}$ decreases for all rooms, showing a moderate decay over distance, consistent with (good) concert hall stages (see Figure 13 and accompanying text).

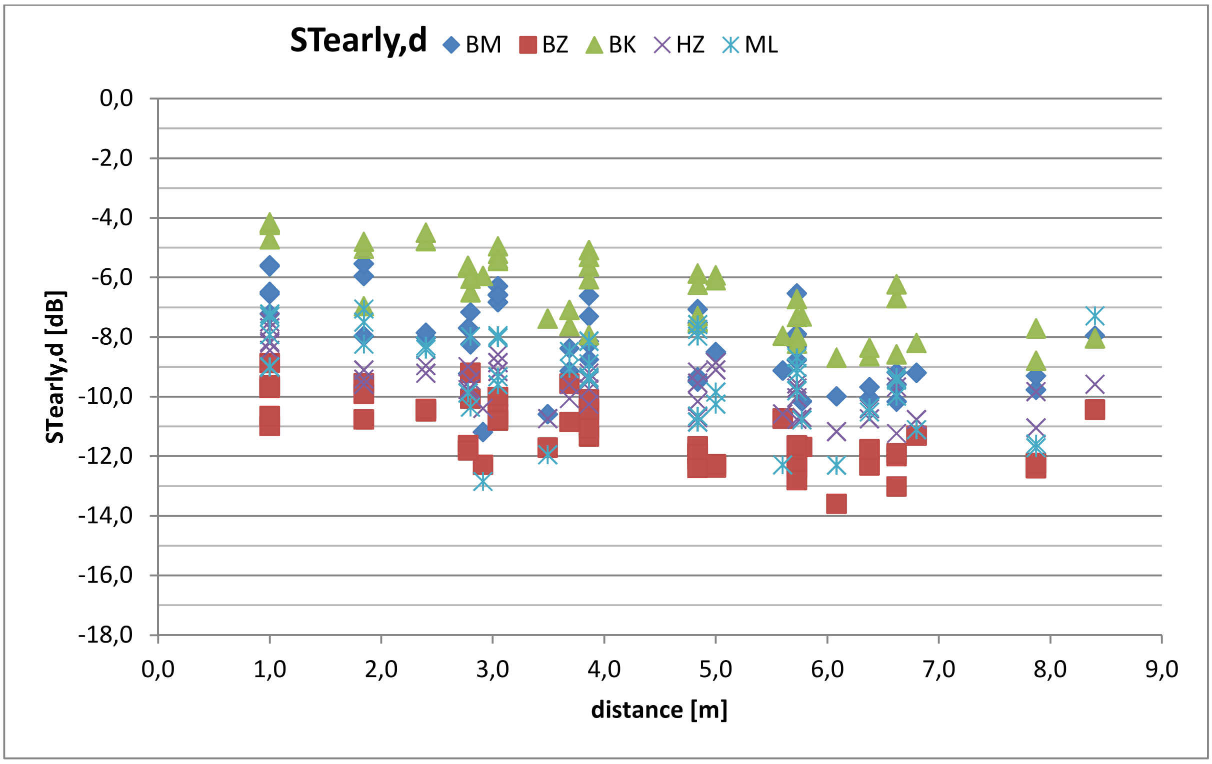

FIGURE 11: SCATTER PLOT FOR EARLY SUPPORT OVER VARYING SOURCE TO RECEIVER DISTANCE FOR THE FIVE ROOMS

In Figure 12, a scatter plot for $ST_{late,d}$ over varying source to receiver distance is given for the five test rooms. This plot also shows significant differences (>JND) among the five rooms. However, the results of the rooms seem to be spread over two groups. With increasing source to receiver distance $ST_{late,d}$ slightly decreases for all rooms, with differences between the values at 1.0 and 8.4 meter distances smaller than JND. The difference between the maximum and minimum value for each room, lies within the range of 2.4 to 2.7 dB, just exceeding the JND. Thus, this decrease is clearly less than the decrease in $ST_{early,d}$ as seen in Figure 11 and essential negligible. This is consistent with trends for concert hall stages.

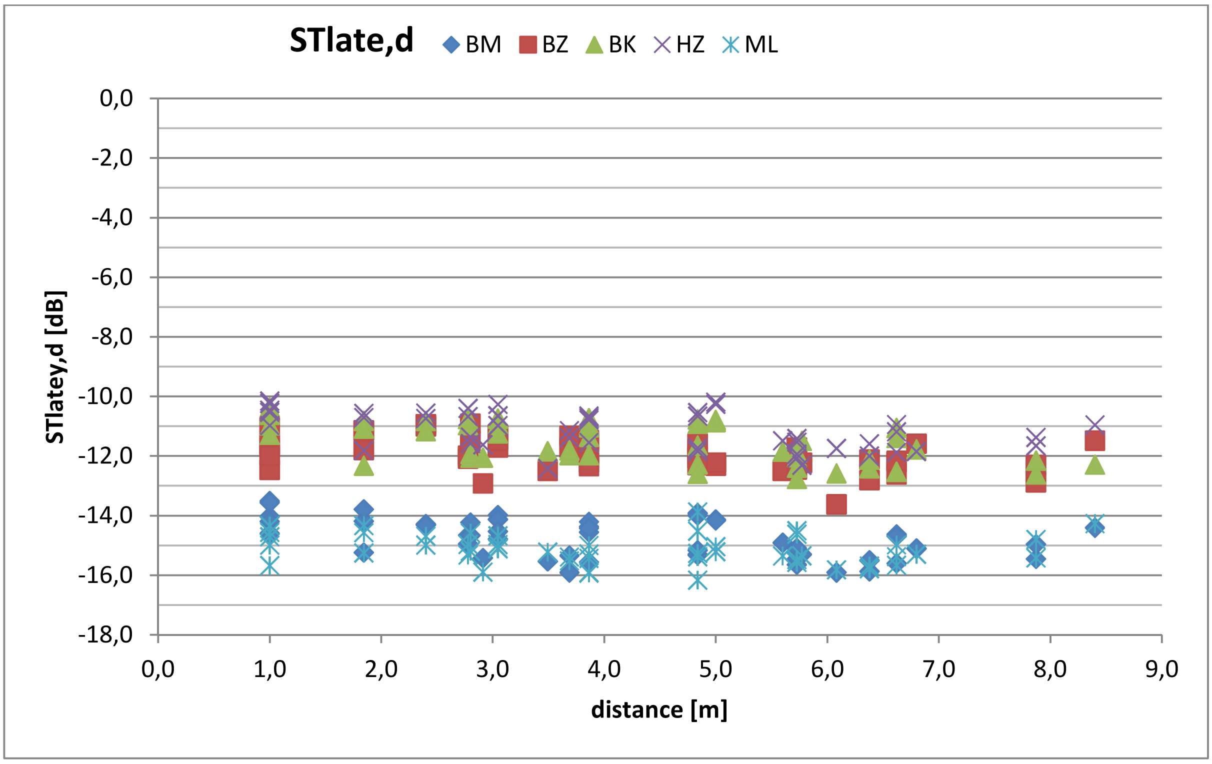

FIGURE 12: SCATTER PLOT FOR LATE SUPPORT OVER VARYING SOURCE TO RECEIVER DISTANCE FOR THE FIVE ROOMS

In Table 2, the coefficient ‘a’ and ‘b’ of the logarithmic trend lines *a lg(d) + b* for $ST_{early,d}$ and the average values for $ST_{late,d}$ are given for the five studied rehearsal rooms and concert hall stage references. These references represent a concert hall with a good reputation in terms of stage acoustics and a concert hall with a poor reputation in terms of stage acoustics. Their values are taken from previous research by Wenmaekers & Hak (2013). The results for $ST_{late,d}$ indicate that for BZ, BK and HZ more late reflected sound energy is present compared to concert halls stages ($ST_{late,d}$ increases 3 to 4 dB). For ML and BM, a similar amount of late reflected sound energy is present compared to concert hall stages.

TABLE 2: CHARATERISTIC NUMBERS FOR $ST_{early,d}$ AND $ST_{late,d}$

	$ST_{early,d}$ = a lg(d) + b [dB]		$ST_{late,d}$ [dB]
Room/Stage	**a**	**b**	**average**
BM	-1.5	-6.2	-14.8
BZ	-1.2	-9.6	-11.9
BK	-1.9	-4.0	-11.5
HZ	-1.1	-8.2	-11.1
ML	-1.2	-7.8	-15.1
Good	-1.6	-11.0	-15.2
Poor	-10.8	-9.8	-14.5

Figure 13 shows the logarithmic trend lines for $ST_{early,d}$ over varying source to receiver distance for the five studied rooms versus the same trend lines for the two concert hall references. The results for $ST_{early,d}$ indicate that (much) more early reflected sound energy is present in the studied rehearsal rooms compared to concert halls stages. The slopes (variable 'a') of the logarithmic trend lines for the five rehearsal rooms have much resemblance to that of a concert hall with a good reputation in terms of stage acoustics.

Furthermore, as could be expected, the trend line of the smallest room (BK) lies on top and the trend line of the largest room (BZ) at the bottom of the five rehearsal rooms. Also, the trend lines of the two concert hall references, which have a much larger room volume (factor 6 to 8), lie below this largest rehearsal room. However, the trend lines of the three other rehearsal rooms do not follow this trend of lower $ST_{early,d}$ with increasing room volume. The logarithmic trend line for ML and HZ are even close to similar, while HZ has more than 2 times the room volume of ML. So, the Early Support over varying source to receiver distance seems not (solely) dependant on the room volume.

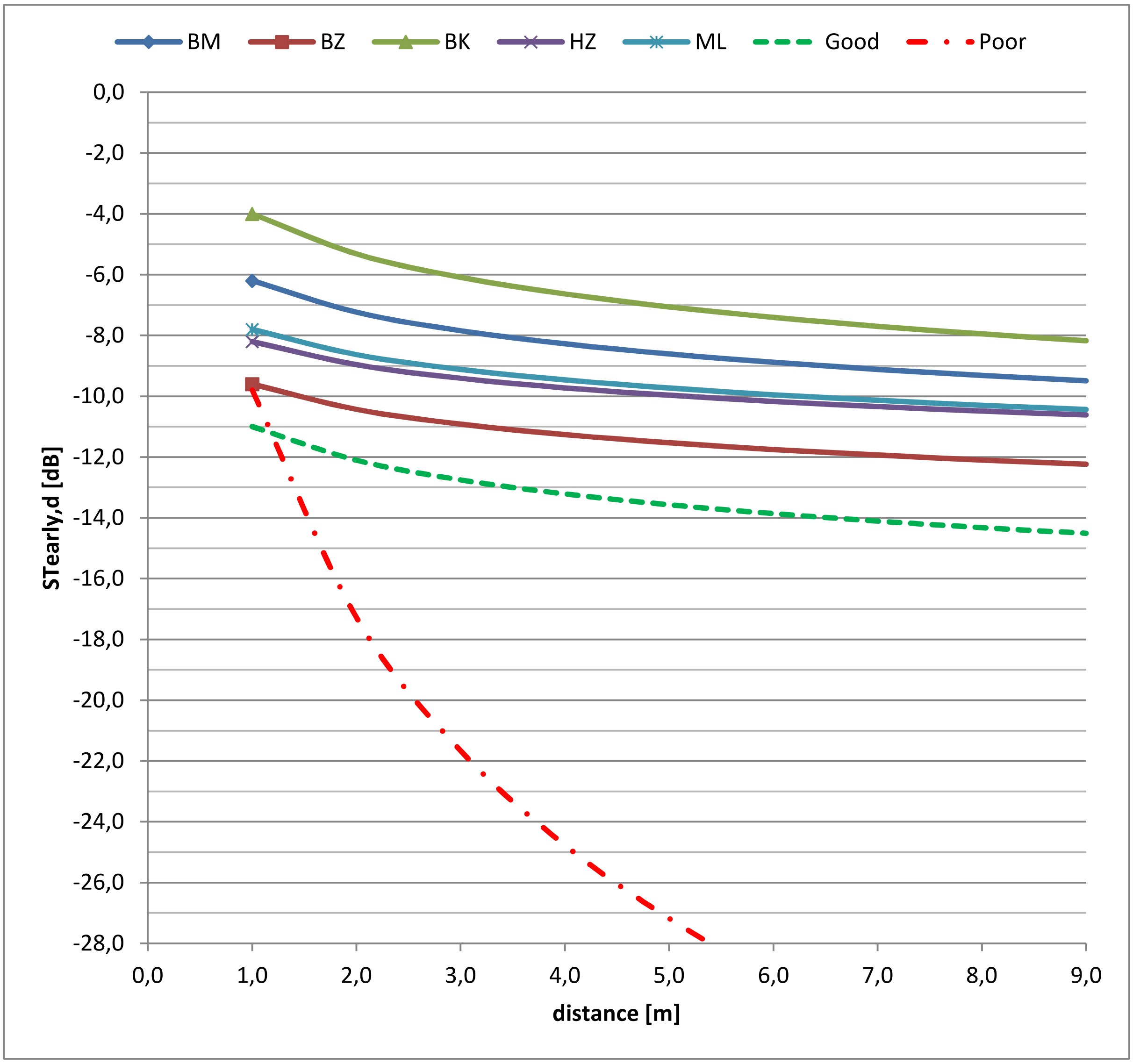

FIGURE 13: LOGARITHMIC TREND LINES FOR EARLY SUPPORT OVER VARYING SOURCE TO RECEIVER DISTANCE FOR THE FIVE ROOMS VERSUS CONCERT HALL REFERENCES

In Appendix D more detailed graphs for each test room can be found along with tables of all the calculated extended support parameter values.

4.1.2 Reverberation time

The reverberation time T_{30} [s] was determined with Dirac for all impulse responses from source-receiver combinations with a source to receiver distance of more than 1 meter. This was done for the octave bands from 63 to 8000 Hz. For each octave band, all values were averaged for each room. These averages are shown in Figure 14. The graphs show a clearly higher T_{30} over all octave bands for the two largest rooms (BZ and HZ) and the lowest T_{30} for the smallest room (BK). ML, which is 1.5 times the room volume of BK, has comparable values to BK for the lower octave bands (63 - 500 Hz). However, for the higher octave bands (1000 - 8000 Hz), its values are comparable to that of the three other rooms, which are at least 2 times the room volume of ML. Though, the room with the most alternating values is BM. Most of its values are comparable with the two largest rooms (BZ and HZ), but its values for the 250 and 500 Hz octave band are comparable with the two smallest rooms (BK and ML). All rooms show a decrease in T_{30} above 2000 Hz of about 0.2 to 0.3 seconds. The values for 63 Hz show the largest differences between the five rooms, with a difference of over 1 second between the lowest and highest value.

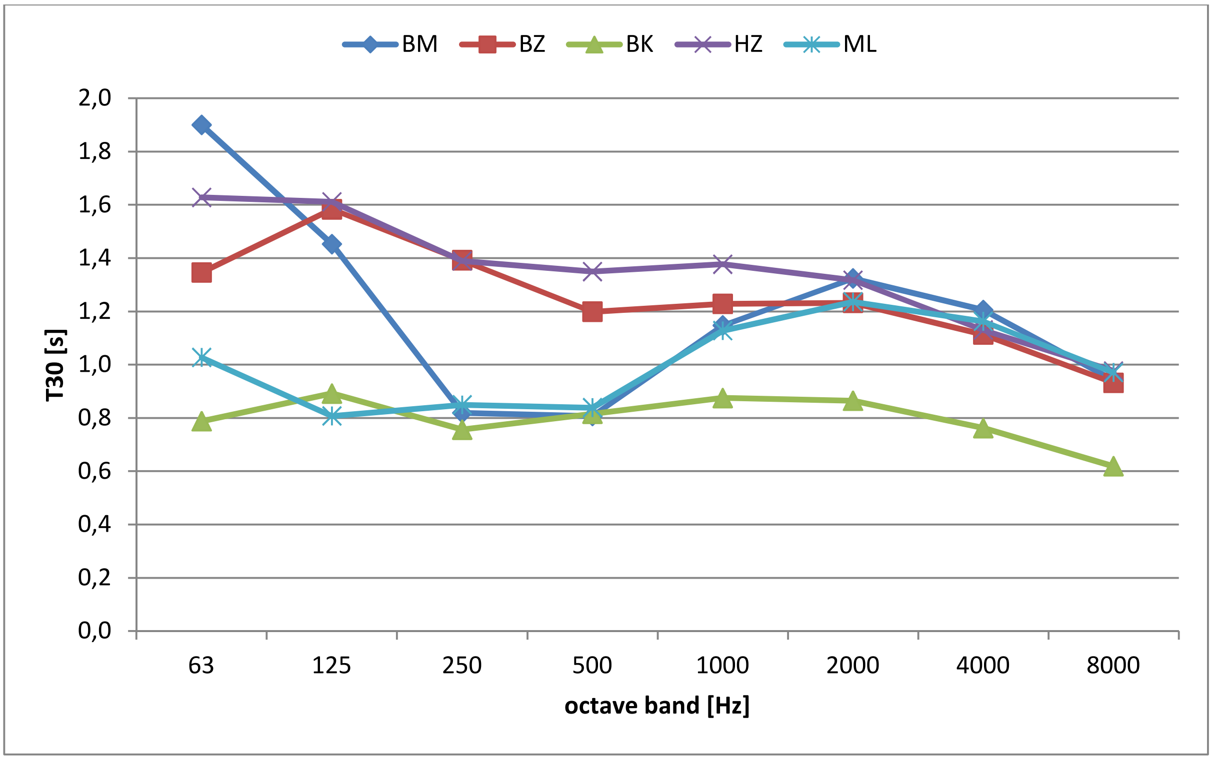

FIGURE 14: REVERBERATION TIME T_{30} PLOTTED AGAINST OCTAVE BANDS FOR THE FIVE ROOMS

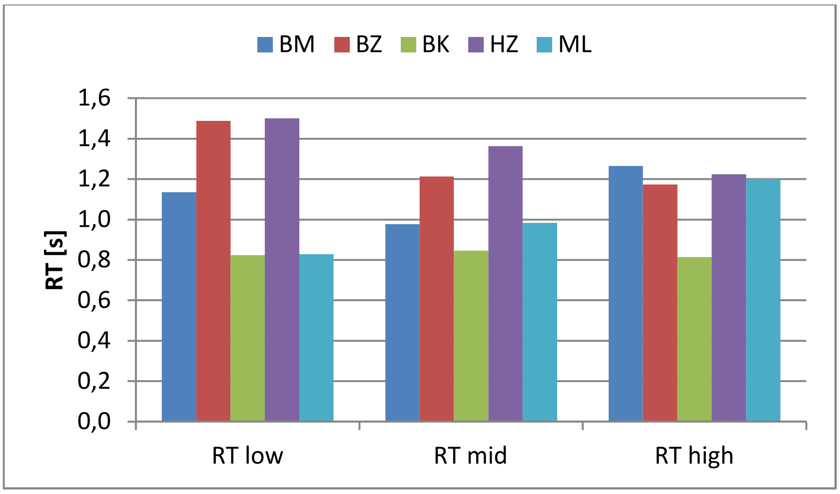

FIGURE 15: REVERBERATION TIMES RT_{LOW}, RT_{MID} AND RT_{HIGH} FOR THE FIVE ROOMS

Next, the reverberation time T_{30} was averaged to three single number ratings: (1) RT_{low}, (2) RT_{mid} and (3) RT_{high}. RT_{low} consists of the average of the 125 and 250 Hz octave band. RT_{mid} consists of the average of the 500 and 1000 Hz octave band. RT_{high} consists of the average of the 2000 and 4000 Hz octave band. These RT values are shown in Figure 15. The values for BK are almost constant (maximum difference of 0.04 seconds). The values for ML increase in steps of about 0.2 seconds, where the values for HZ decrease in steps of about 0.15 seconds. BZ shows a large decrease of about 0.3 seconds from RT_{low} to RT_{mid}, but is almost constant from RT_{mid} to RT_{high}. However, also in this graph BM shows the most alternating values, with a decrease of about 0.2 seconds from RT_{low} to RT_{mid} and then a increase of about 0.3 seconds from RT_{mid} to RT_{high}.

The smallest room (BK) has the shortest T_{30}, but also the least varying values over all octave bands. As a result of the shape of this room, the distance from the edge of the measurement grid to the walls is about the same at all four sides. The walls are also the most sound absorbing surfaces in this room.

The two largest rooms (BZ and HZ) have (on average) the longest T_{30}, which was to be expected from the auditory impression of the rooms. Both these rooms have an increase in T_{30} for the lower octave bands, an almost constant T_{30} for the middle octave bands and a decrease in T_{30} for the higher octave bands. This trend is common for music rooms like theaters and concert halls. For HZ these values were to be expected, since it is a multifunctional hall with a theater like stage. For BZ, however, these values are somewhat higher than expected, since it is a hall designed for lectures, presentations and ceremonies.

ML has values that were to be expected, in terms of requirements for a room of this size. However, the increase in T_{30} for the higher octave bands is striking. This could be caused by the finishing materials of the floor and walls, which are apparently especially reflective for the higher frequencies and causing a lack of diffusivity for these higher frequencies.

BM has the most surprising values of all studied rooms. In this room, the measurements were performed on stage. Due to the proscenium arch that separates the stage from the rest of the hall, the stage could be seen as a small 'box' with a large opening on one side. The shape and materials of the ceiling and walls apparently provide relative more sound absorption in the middle frequencies compared to the lower and higher frequencies. The wooden laths against the ceiling and walls have cavities behind them. This composition seems to function like a resonator, with a resonance frequency that lies in the range of the middle frequencies, thus increasing the sound absorption within this range. When using the RT_{mid} as a single value to describe the reverberation time of this room, this tends to underestimated the total reverberation of the room.

4.1.3 BACKGROUND NOISE

The background noise level L_{eq} [dB] in each of the five test rooms was determined from the background noise level measurements at all ten receiver positions. This was done for the octave bands from 63 to 8000 Hz. For each octave band, all values were averaged for each room. These averages are shown in Figure 16. For the higher frequencies (2000 Hz and above), the L_{eq} for all five rooms lie within a range of 10 dB. However, for the middle and lower frequencies, the L_{eq} for the rooms BZ and BK stand out above the other three rooms. These high values for L_{eq} are most likely the result of noisy building services (e.g. HVAC systems). A clear outlier is the L_{eq} at 63 Hz for BK. For all octave bands, ML has the lowest L_{eq}.

ML has the highest L_{eq} at 63 Hz; L_{eq} then decreases gradually towards its lowest value at 500 Hz and then gradually increases again towards 8000 Hz. The values for HZ follow this same trend, with slightly higher values for all octave bands. The values for BM roughly also follow this same trend, with the exception that the value at 2000 Hz equals the lowest value at 500 Hz, thus also being lower than the value at 1000 Hz. The values for BZ en BK show a decrease from 63 to 4000 Hz and a very small increase to 8000 Hz, with BK showing a steeper slope than BZ.

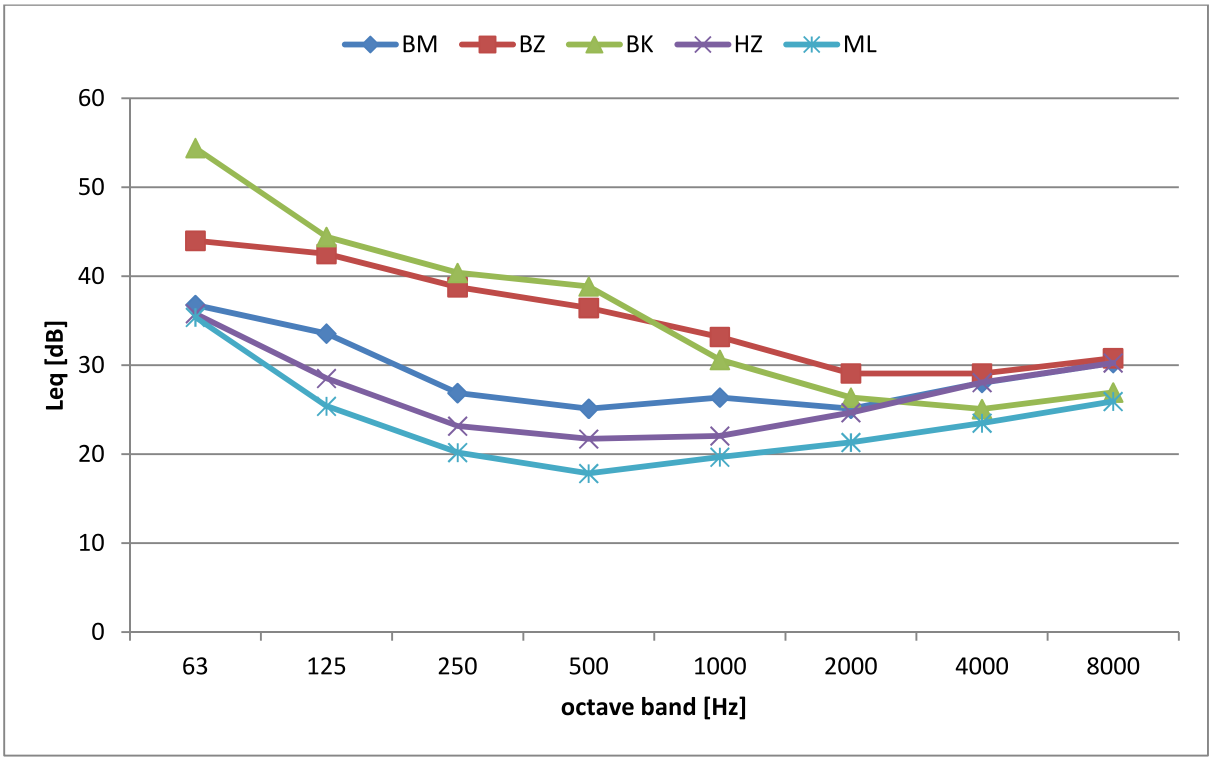

FIGURE 16: BACKGROUND NOISE LEVEL L_{eq} PLOTTED AGAINST OCTAVE BANDS FOR THE FIVE ROOMS

Next, also the A-weighted background noise level L_{Aeq} [dB(A)] and the C-weighted background noise level L_{Ceq} [dB(C)] were determined with the use of Dirac. For each room, the single number rating L_{Aeq} is shown in Figure 17 and the single number rating L_{Ceq} in Figure 18. All rooms have higher values for L_{Ceq} than for L_{Aeq}. For both single number ratings, L_{Aeq} and L_{Ceq}, ML has the lowest value, HZ the second lowest value and BM the third lowest value. For L_{Aeq}, BZ has the highest value and BK the second highest. For L_{Ceq}, these two rooms switch places. The values for L_{Aeq} lie within a range of 11 dB(A), those for L_{Ceq} within a range of 19 dB(C).

The rooms BZ (red) and BK (green) have more low frequency background noise, resulting in clearly higher L_{Ceq} values compared with their L_{Aeq} values. (And low T_{30} values at 63 Hz compared to the values at 125 Hz for BZ and BK, see figure 13.) It is striking that the smallest (BK) and the largest (BZ) room have the highest background noise levels. So, the background noise level seems not dependant on the room volume.

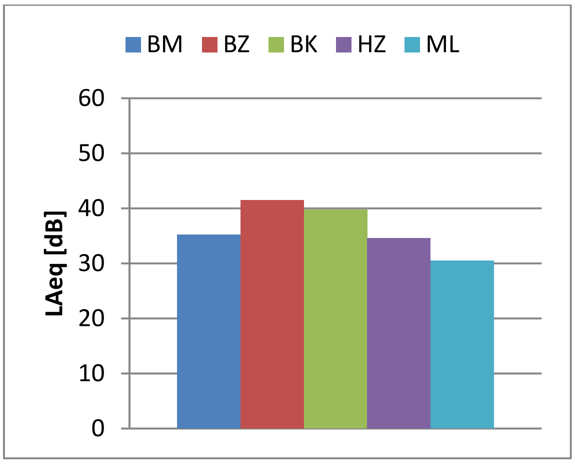

FIGURE 17: A-WEIGHTED EQUIVALENT BACKGROUND NOISE LEVEL FOR THE FIVE ROOMS

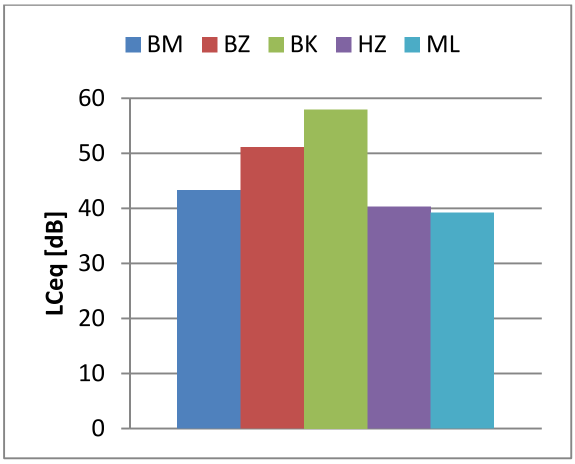

FIGURE 18: C-WEIGHTED EQUIVALENT BACKGROUND NOISE LEVEL FOR THE FIVE ROOMS

4.1.4 Comparison

The most relevant architectural, stage acoustic and room acoustic parameters are given in Table 3. The architectural parameters consist of room dimensions and ratio's. For some of the room dimensions, a range is given. The average value of this range is used to determine the room dimension ratio's. The stage and room acoustic parameters in this table are all single number ratings averages. In this section, interesting trends between these parameters, or the absence of them, are discussed.

TABLE 3: ARCHITECTURAL PARAMETERS (ROOM DIMENSIONS AND RATIO'S); **STAGE ACOUSTIC PARAMETERS** (AVERAGE VALUES FOR EARLY AND LATE SUPPORT OVER ALL MEASURED SOURCE TO RECEIVER DISTANCES); **AND ROOM ACOUSTIC PARAMETERS** (REVERBERATION TIMES AVERAGED OVER TWO OCTAVE BANDS, AVERAGE SOUND ABSORPTION FOR 500 AND 1000 HZ OCTAVE BANDS , AND A- AND C-WEIGHTED EQUIVALENT BACKGROUND NOISE LEVELS).

		BM	BZ	BK	HZ	ML
Width	[m]	12.0	15.0 – 20.5	14.5	11.5 – 16.5	12.5
Depth	[m]	30.0	24.0	11.5	29.0	18.0
Height	[m]	3.0 – 6.7	2.1 – 7.0	3.0 – 4.0	5.5 – 5.9	4.0
Height/Width	[-]	0.40	0.26	0.24	0.41	0.32
Depth/Width	[-]	2.50	1.35	0.79	2.07	1.44
Floor area	[m²]	360	430	165	400	225
Room volume	[m³]	1920	2500	650	2250	900
$\mathbf{ST_{early,d}}$	[dB]	-8.2	-11.2	-6.4	-9.6	-9.3
$\mathbf{ST_{late,d}}$	[dB]	-14.8	-11.9	-11.5	-11.1	-15.1
$\mathbf{RT_{low}}$	[s]	1.14	1.49	0.82	1.50	0.83
$\mathbf{RT_{mid}}$	[s]	0.98	1.21	0.85	1.36	0.98
$\mathbf{RT_{high}}$	[s]	1.26	1.17	0.81	1.22	1.20
$\mathbf{A_{mid}}$	[m²]	316	332	124	266	147
$\mathbf{L_{Aeq}}$	[dB(A)]	35.2	41.4	39.8	34.5	30.5
$\mathbf{L_{Ceq}}$	[dB(C)]	43.3	51.1	58.0	40.3	39.2

There is a linear trend visible between the floor area and room volume: with increasing floor area, the room volume increases too. This often is no surprise, especially for similar type of/equal shaped rooms. However, these five rooms are differently shaped, because there is no linear trend between floor area or room volume and one of the linear measures (width, depth or height). This is confirmed by the absence of a linear trend with the dimension ratio's.

There is a linear trend visible between the floor area and amount of sound absorption for the middle frequencies: with increasing floor area, this sound absorption increases too. Thanks to the relation between floor area and room volume, the same applies for the room volume and amount of sound absorption for the middle frequencies: with increasing room volume, this sound absorption increases too. In both cases, room BM seems to have a rather high amount of sound absorption for the middle frequencies compared to its floor area and room volume. This is emphasized by the values for RT_{mid}, where BM has the same value as ML, while BM has over 1.5 times the floor area and over 2 times the room volume of ML. Despite this outlier for BM, there is also a linear trend visible between the floor area/room volume and reverberation time for the middle frequencies: with increasing floor area/room volume, RT_{mid} increases too. This was to be expected, as sound absorption and reverberation time are related through Sabine's equation: $A = 0.161\ RT/V$.

The only relation between the reverberation time and a linear measure, seems to be between the room depth and RT_{mid}: with increasing room depth, the value for RT_{mid} increases too. Here, also the values for BM do not follow this trend: BM has the longest depth (30.0 m), but a RT_{mid} in the lower region (0.98 s). This could be clarified by the fact that measurements in BM were performed on the fixed stage, which due to the proscenium arch that separates the stage from the rest of the hall, could be seen as a small 'box' with a large opening on one side. Thus, acting like a non-reflective surface on that side and reducing the 'acoustical' room depth.

Surprisingly, there are no clear trends visible between the averaged extended support parameters and the other parameters. Apparently, the room dimensions, reverberation times and sound absorption are all not solitary related to the average early and late support over all measured source tot receiver distances.

There are no trends visible between the A- and C-weighted equivalent background noise levels and one of the room dimensions. This was to be expected, as the background noise level is dependent on external noise (e.g. environmental noise) in relation to the sound insulation properties of the enclosing surfaces and internal noise (e.g. noise from HVAC-systems). However, more reverberation/less sound absorption could result in higher background noise levels. Nevertheless, no trends are visible between the A- and C-weighted equivalent background noise levels and the support, reverberation time and sound absorption parameters. This could be the effect of the use of impulse responses generated by stimuli with high impulse to noise ratio (INR).

4.2 SUBJECTIVE EVALUATION

In this section, the results of the subjective evaluation will be presented and discussed. The recordings of the musical fragment were made to let test persons rank the five test rooms for each condition. These rankings were used to obtain their preferences on the ensemble conditions in the studied rooms.

The rankings showed large fluctuations and dispersions (e.g. standard deviation) between and within the different listening conditions. This has a lowering effect on the significance of the results from this subjective evaluation. An attempt was made to present and discuss these results as clearly and completely as possible. However, sometimes the fluctuation or dispersion is of such magnitude that the significance of the result is unclear. The choice has been made not to omit these results. Instead, the most striking findings have been underlined.

4.2.1 RECORDINGS

In each of the test rooms, except for the first measurements in test room BK, three recordings of the musical fragment were made, for each of the three musical dynamics at each of the five receiver positions (R2,3,4,8 and 10). Each musical dynamic had its own target value $L_{p,eq}$ (as measured by the sound level meter) to maintain the correct musical dynamic. For each dynamic, the target value increased with 15 dB, so there was an even gap between *piano* and *mezzo forte* on the one hand and *mezzo forte* and *fortissimo* on the other hand. This is consistent with the fact that both steps have one other musical dynamic between them (namely *mezzo piano* and *forte*). In Table 4 the average, minimum and maximum value of $L_{p,eq}$ for all the recordings is given, along with the corresponding standard deviation. These values show that the averages reach the target value, when round off to integers. Although there are some outliers, the standard deviation projects a range within +/- 1 dB from the target value (note, the JND for sound level is 1 dB). This shows that the reproducibility of the musical fragment is sufficient.

TABLE 4: STATISTICS TARGET VALUES

Lp,eq [dB]	**p**	**mf**	**ff**
	[target = 75 dB]	[target = 90 dB]	[target = 105 dB]
Average	75.4	90.1	104.7
Min	73.3	88.0	103.1
Max	77.3	92.7	106.0
StDev	0.84	0.85	0.62

From the three recordings per musical dynamic and receiver position, the best recording was selected by extensive listening by the author. This was done using the same playback equipment as for the listening test (see Appendix B).

4.2.2 LISTENING TEST

The listening test was presented to 24 test persons, 14 males and 10 females. All test persons had experience with playing in a wind orchestra and played a wood wind, brass or percussion instrument. There also was one test person that plays the cello, but even this is frequently used within contemporary wind orchestras. Despite the fact that it was no requirement, each test person had 'live' experience with at least one of the test rooms. During the whole listening test however, the test rooms were completely anonymous presented to them. The data acquired with the listening test can be found in Appendix E.

There were six sets of recordings, each corresponding with a certain listening condition: a combination of receiver position and musical dynamic. These six listening conditions are given in Table 5. Only the recordings for receiver position 2 and 4 were used in the listening test. The two receiver positions define the proximity of the sound source (playing musician) to the listener (other musician): R2 represents a playing musician nearby to the listener and R4 a playing musician far away from the listener. The musical dynamic defines the focus for the listener: the *piano* fragments focus on the intelligibility of musical details, the *mezzo forte* fragments focus on the overall quality of the ensemble conditions for rehearsal and the *fortissimo* fragments focus on the perception of loudness.

TABLE 5: THE SIX LISTENING CONDITIONS

	R2	R4
p	close & details	far & details
mf	close & overall quality	far & overall quality
ff	close & loudness	far & loudness

The test persons underwent the listening test seriously and attentively. Their answers on the different listening conditions were in general consistent. There were some test persons with a preference for certain 'rehearsal acoustics'. Both preferences for 'dry acoustics' (short reverberation time, much direct sound) and 'concert acoustics' (longer reverberation time, more diffuse sound) were expressed. Most test persons seemed to have no clear preference in advance, but they let their preference depend upon the played back musical fragments.

4.2.2.1 Ranking quantity

The graphs in Figure 19 show the number of times (quantity) each of the five test rooms was ranked at a certain ranking position, with p1 being the most favorable and p5 being the least favorable rehearsal room according to a test person. This ranking quantity is shown in a separate graph for each of the six listening conditions.

The first observation is, there is no room that is clearly ranked best (almost only p1) or worst (almost only p5). However, some trends and outliers can be observed. Most striking are the three outliers for BM. This room is clearly ranked as least favorable for both the close and far loudness listening condition. Apparently, in relation to the other four rooms, the most unpleasant loudness is perceived in BM, especially at close range. However, for the close and details listening condition, the same room is clearly ranked the most favorable. This seems a paradox, but the stage acoustics of this room seem to provide ensemble conditions that facilitate intelligibility of musical details, but at the same time intensify the perception of (too) much loudness.

Room BZ is less favorable for the intelligibility of musical details for both receiver positions and the overall quality of the ensemble conditions at close range. However, this room is much more appreciated for the three other listening conditions. This is almost the reverse situation from room BM, but less distinct.

Room BK seems to be a somewhat moderately favorable room, fluctuating around its own average quantity across all ranking positions. Thus, not showing a consensus among the test persons. Exceptions are, (1) the close and details listening position, where there is an increase in quantity from p1 to p5, and (2) the close and overall quality listening condition, where the quantity of p1, p2 and p3 surpasses the quantity of p4 en p5.

For the far away listening conditions, room HZ is fluctuating around its own average quantity across all ranking positions. Thus, not showing a consensus among the test persons. For the nearby listening conditions, these fluctuations are more extreme, showing a diverse evaluation of this room among the test person. Only for the close and overall quality listening condition, a trend in increase in quantity from p1 to p5 is visible, ranking room HZ as relative less favorable for this condition.

For the close and details listening condition, room ML is fluctuating around its own average quantity across all ranking positions. Thus, not showing a consensus among the test persons. However, for all the other listening conditions, a (strong or gentle) decrease in quantity from p1 to p5 can be observed. Suggesting, the evaluation of room ML by the test persons is mostly favorable.

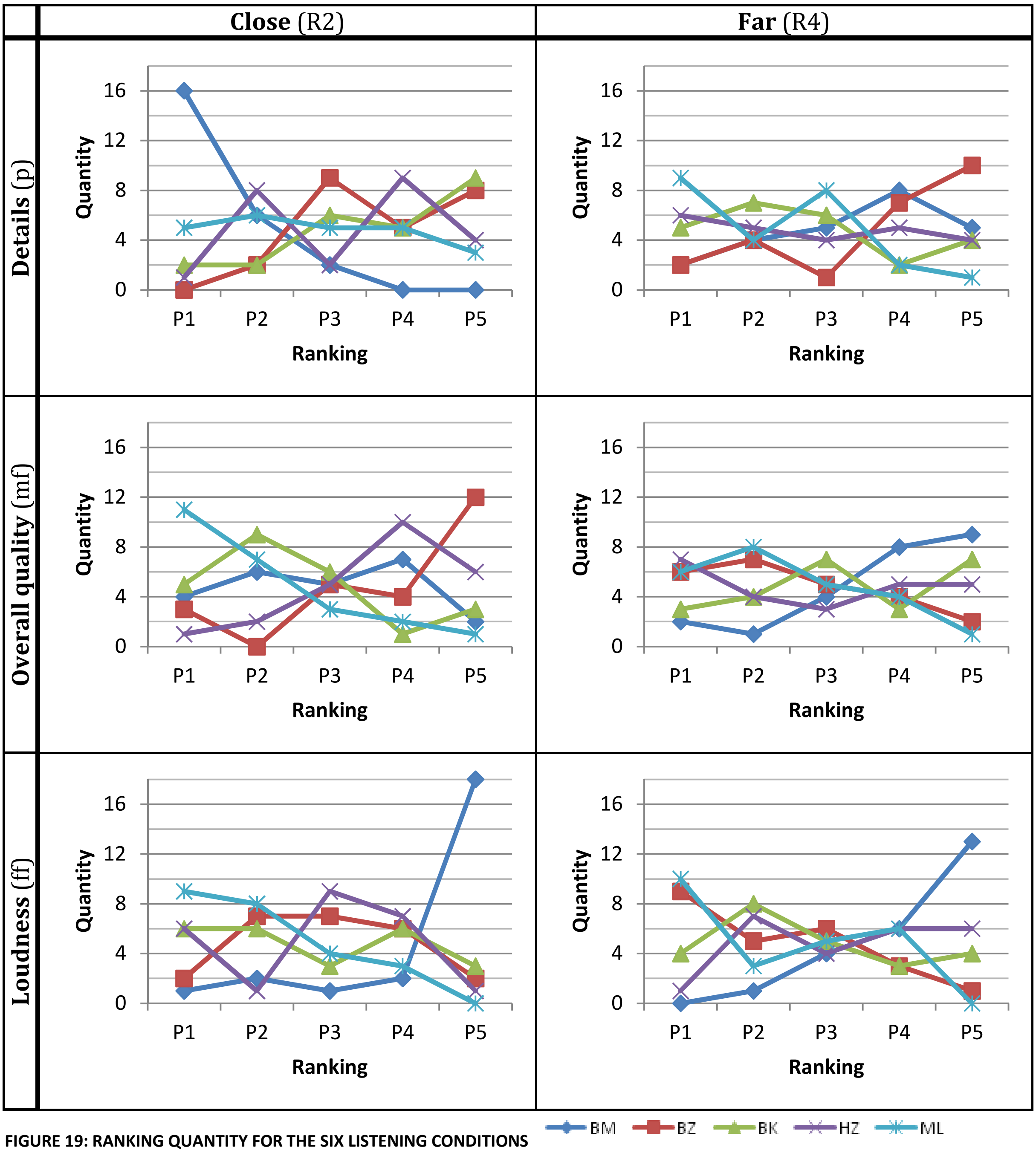

FIGURE 19: RANKING QUANTITY FOR THE SIX LISTENING CONDITIONS

4.2.2.2 Mean ranking

The graphs in Figure 20 show the mean ranking position and its standard deviation for each of the five test rooms. This mean ranking position is shown in a separate graph for each of the six listening conditions.

These graphs also show the paradox for room BM as describe above. It has a very high mean ranking for the close and details listening condition, but at the same time a very low mean ranking for both the close and far loudness listening condition. For the other two far away listening conditions, room BM also has a low mean ranking (>3; <4). However, for the close and overall quality listening condition, it has a moderate mean ranking. The rankings for these last three listening conditions have a large standard deviation, while the rankings for the first three listening conditions have a smaller standard deviation. This suggests there is a better consensus for the three more extreme mean rankings.

Room BZ has a moderate to low mean ranking for four listening conditions, including the three nearby listening conditions. For the overall quality and loudness, both far way, listening condition, room BZ has slightly above moderate mean rankings. For all the listening conditions, the standard deviation is between 1 and 1.5, suggesting little consensus among the test persons.

For five listening conditions, room BK has moderate mean rankings between 2.5 and 3.5. Only for the close and details listening conditions, this room has a slightly lower mean ranking (3.7). However, room BK has even larger standard deviations than room BZ, suggesting little consensus among the test persons.

Room HZ also has moderate mean rankings between 2.5 and 3.5 for given listening conditions. Here, the close and overall quality listening conditions has a slightly lower mean ranking (3.8). The standard deviations lie within the same range as those of room BK, also suggesting little consensus among the test persons.

For all six listening conditions, room ML has moderate to high mean rankings between 2 and 3. This results in the best evaluation overall. However, also room ML has considerable standard deviations, suggesting no clear consensus among the test persons.

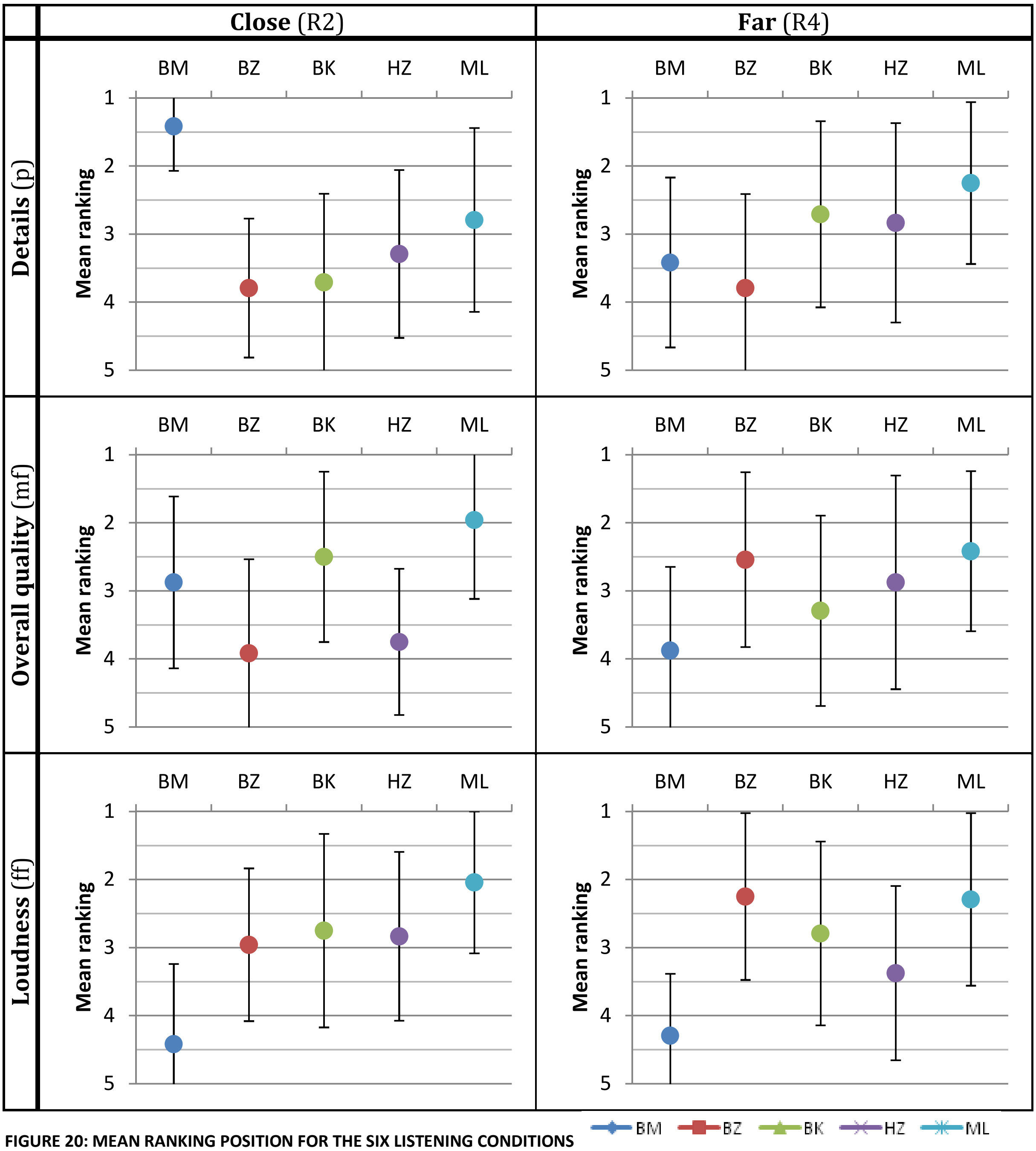

FIGURE 20: MEAN RANKING POSITION FOR THE SIX LISTENING CONDITIONS

4.2.2.3 Total ranking

The graphs in Figure 21 show the total ranking quantity and total mean ranking position for each of the five test rooms. For these total values, the values of all the six listening conditions are cumulated for each test room. The total values seem to support the emerging trends from the discussions above. For the total ranking quantity, room BM shows a steep increase for p4 and p5. Meanwhile, room BZ shows a cautious increase from p1 to p5. The ranking quantities for room BK are fluctuating around its own average quantity across all ranking positions. Besides, those for room HZ seem steady, with a peculiar high outlier for p4. Furthermore, room ML shows a steep decrease from p1 to p5. When looking at the total mean ranking position of the five test rooms, room ML clearly has the highest total mean ranking of 2.3. The other four rooms all have moderate to low total mean ranking between 3.0 and 3.4., with BK being the highest and BM the lowest. However, for all the five rooms, the standard deviation is considerable, providing no clear consensus among the test persons and among the six listening conditions.

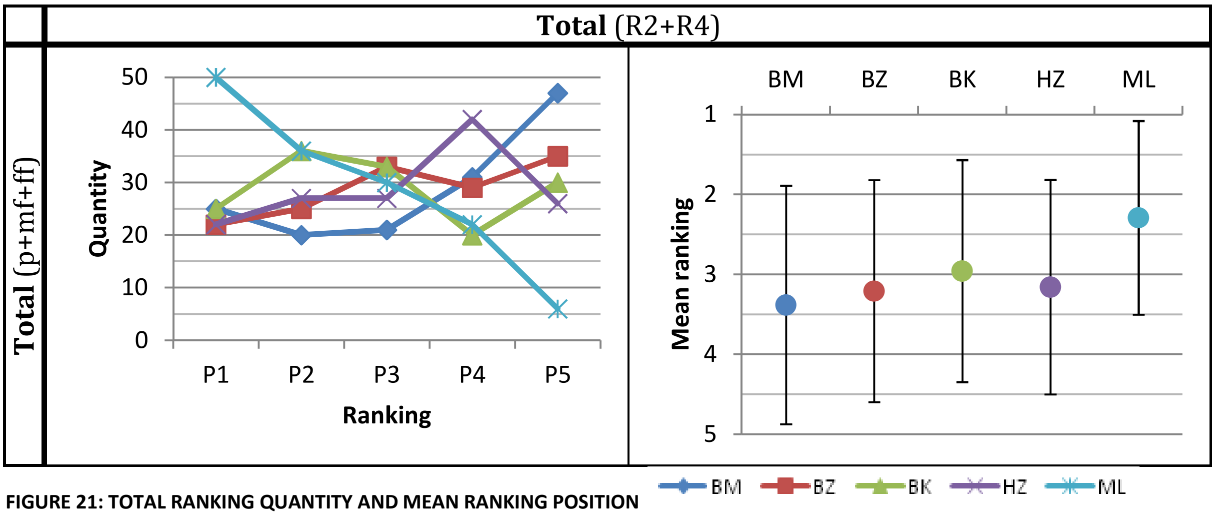

FIGURE 21: TOTAL RANKING QUANTITY AND MEAN RANKING POSITION

Table 6 and Figure 22 show the relation between the total mean ranking of the five test rooms and their mean ranking per listening condition.

TABLE 6: MEAN RANKING POSITION FOR THE SIX LISTENING CONDITIONS AND TOTAL FOR THE FIVE TEST ROOMS

	Total	p R2	p R4	mf R2	mf R4	ff R2	ff R4
BM	3.38	1.42	3.42	2.88	3.88	4.42	4.29
BZ	3.21	3.79	3.79	3.92	2.54	2.96	2.25
BK	2.96	3.71	2.71	2.50	3.29	2.75	2.79
HZ	3.16	3.29	2.83	3.75	2.88	2.83	3.38
ML	2.29	2.79	2.25	1.96	2.42	2.04	2.29

The values in Table 6 are processed in the total mean ranking graph in Figure 21, with the first column being the total mean ranking value of all ranking position data and the other columns being the mean ranking value of the ranking position data per listening condition. In Figure 22 the values from the first column are plotted against the values from the six other columns. The color coding indicates the musical dynamic from soft (*piano* – green) to loud (*fortissimo* – red). The size of the marker indicates the receiver position from nearby (R2 – large boxed) to far away (R4 – small solid). Because there are five rooms with each their own total ranking and six own rankings per listening condition, there are five vertical 'lines' with each six markers visible. Each 'line' represents one test room. When analyzing these 'lines', a striking trend can be observed. The dispersion among the values for the six mean rankings per condition for each room, increases with decreasing total mean ranking. In other words, with a better total mean ranking, the mean rankings per condition are approaching to each other. This trend is illustrated by the two linear dashed lines. The third (curved) dashed line, illustrates the extreme outlier for room BM and the two slightly deviating values for room BZ. Another slightly deviating aspect is the limited dispersion among the values for room HZ.

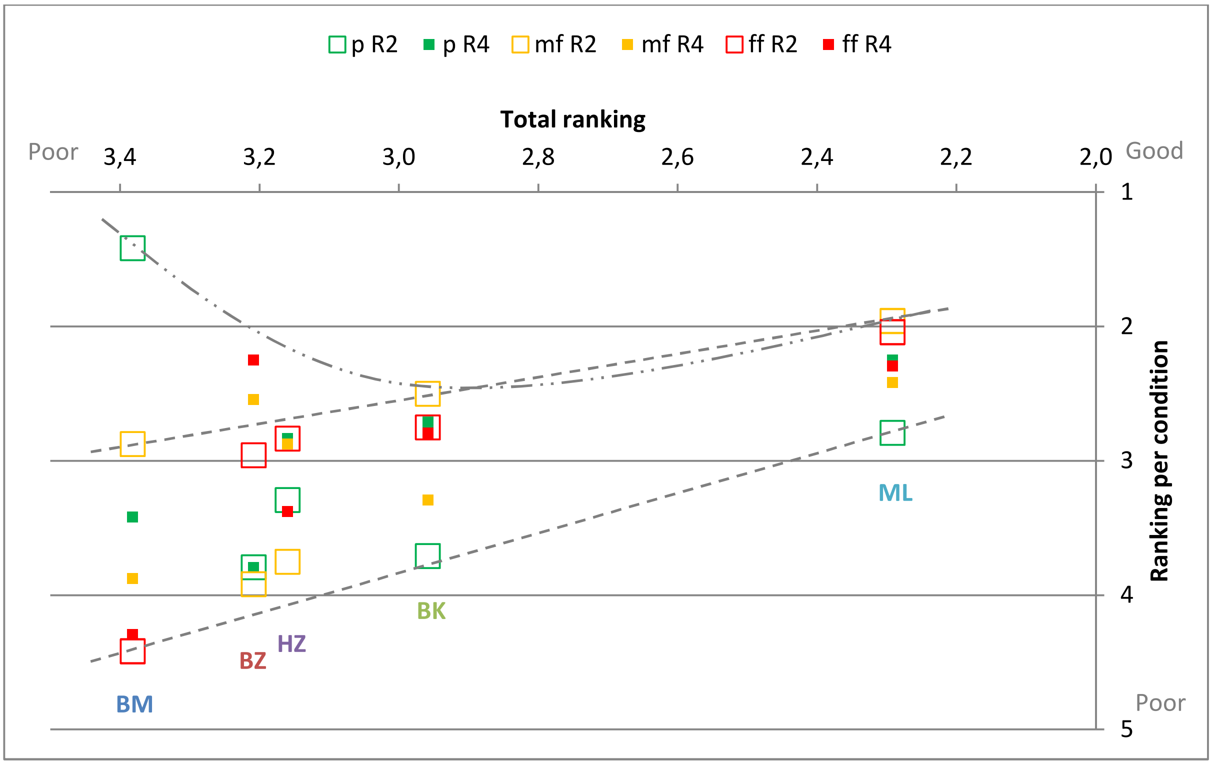

FIGURE 22: RANKING DISPERSION FOR THE SIX LISTENING CONDITIONS FOR THE FIVE TEST ROOMS

4.3 COMPARISON

In this section the relation between the architectural properties and the results of the objective measurements and subjective evaluation is discussed. The architectural properties were analyzed with use of the room dimensions and ratio's. The objective measurements were analyzed with use of the stage acoustics parameters (averaged) early and late support over varying source to receiver distance, and the room acoustic parameters reverberation time for the low, middle and high frequencies (averaged over two octave bands), sound absorption (averaged for the 500 and 1000 Hz octave bands) and A- and C-weighted equivalent background noise level. The subjective evaluation was analyzed with use of the number of times (quantity) each of the five test rooms was ranked at a certain ranking position, leading to a mean ranking value for each test room, for each of the six listening conditions and a total over all six listening conditions.

In Figure 23, a weak relation can be observed between the floor area and room volume on one hand and the mean ranking for the far and details listening condition (p R4) on the other hand. With increasing floor area/room volume, the mean ranking for this listening condition decreases. This suggests that a small rehearsal room results in better intelligibility of musical details over large distances within a wind orchestra. In contrast, this relation is absent for the close and details listening condition (p R2), suggesting less influence of the room dimensions for smaller distances. For the mean rankings of the other listening conditions, and for the other room dimension parameters, no relations were observed.

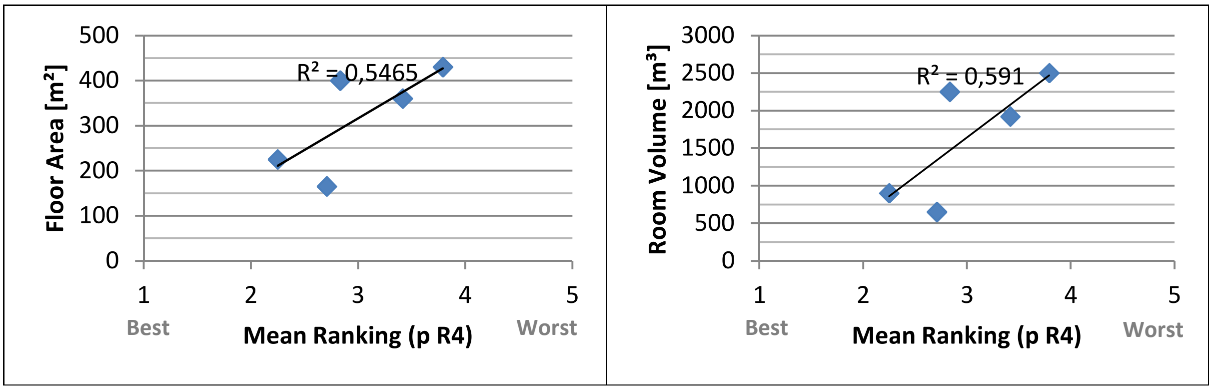

FIGURE 23: MEAN RANKING FOR FAR AND DETAILS LISTENING CONDITION VERSUS FLOOR AREA (LEFT) OR ROOM VOLUME (RIGHT)

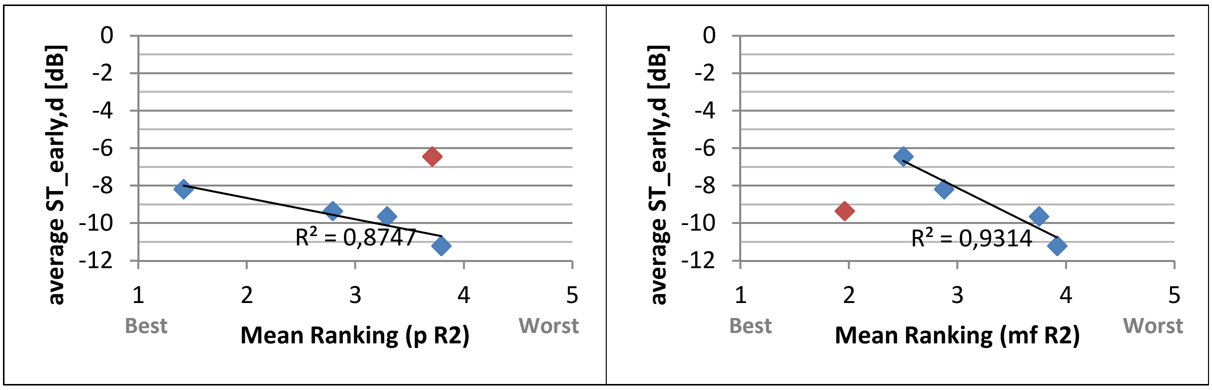

FIGURE 24: AVERAGED EARLY SUPPORT OVER VARYING SOURCE TO RECEIVER DISTANCE VERSUS CLOSE AND DETAILS (LEFT) OR OVERALL QUALITY (RIGHT) LISTENING CONDITION

For the average values of $ST_{early,d}$, partial relations can be observed in Figure 24 between these values and the close and details listening condition (p R2) and the close and overall quality listening condition (mf R2). With decreasing $ST_{early,d}$, the mean ranking for these two listening conditions decreases too. However, for both listening conditions, this is only the case when omitting one of the five rooms (the two red diamonds in Figure 24): for *piano* this is room BK, which has a worse mean ranking than suggested by the trend, and for *mezzo forte* this is room ML, which has a better mean ranking than suggested by the trend. Both relations suggest that, at close distance, relative much early reflected sound is preferred for the intelligibility of musical details and the overall quality of the ensemble conditions for rehearsal. For the other listening conditions, this preference was not supported by the results of the subjective evaluation. So, it might be a matter of wishful thinking. Results for more rehearsal rooms are needed to support or reject these trends. For the average values of $ST_{late,d}$, no relations were found with the results of one of the listening conditions.

In Figure 25, a relation can be observed between the reverberation time for the low frequencies (RT_{low}) and the mean ranking for the close and overall quality listening condition (mf R2). With decreasing reverberation time, the mean ranking increases. Between the reverberation time for the middle frequencies (RT_{mid}) and the same listening condition, a somewhat weaker relation can be observed. For the reverberation time for the high frequencies (RT_{high}), this relation seems absent. However, for these frequencies, the reverberation time for the test rooms (except room BK) lie close to each other. These relations suggest a preference for a (relative) lower reverberation time in rehearsal rooms, especially for the lower frequencies. Besides this trend, no relations were observed between any of the reverberation time (and sound absorption) parameters and any of the other listening conditions.

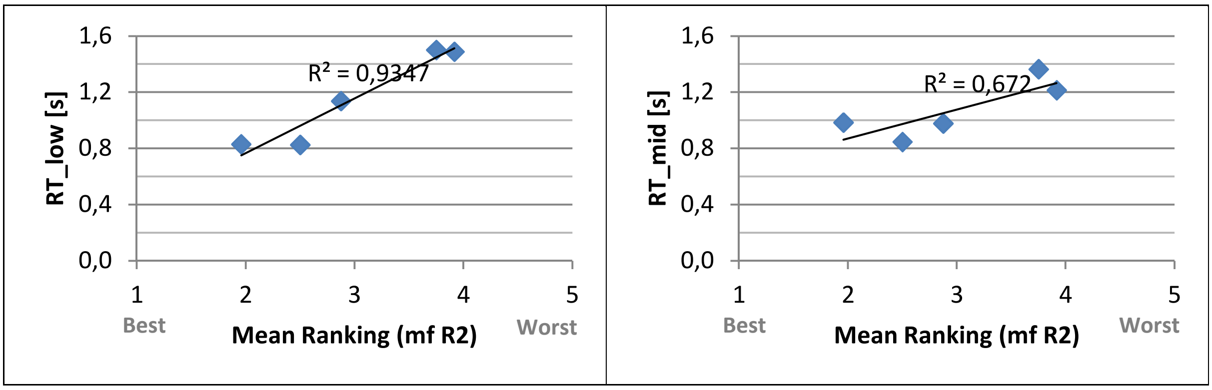

FIGURE 25: MEAN RANKING FOR CLOSE AND OVERALL QUALITY LISTENING CONDITION VERSUS REVERBERATION TIME AVERAGED OVER 125 AND 250 Hz OCTAVE BANDS (LEFT) OR AVERAGED OVER 500 AND 1000 Hz OCTAVE BANDS (RIGHT)

In Figure 26, weak relations can be observed between the A-weighted equivalent background noise level (L_{Aeq}) and the mean ranking of, both the nearby and far away, and details listening condition (p R2 & p R4). With decreasing background noise level, the mean ranking of these two listening conditions increases. This suggests unwanted interference or masking from the background noise with the played musical fragment during *piano* segments. Therefore, emphasizing the need for low background noise levels in music rooms. For the close and details listening condition (p R2), the mean ranking for room BM (red diamond) is higher than would be expected according to the observed trend. In this case, the background noise is probably largely surpassed by the strong early reflections from the (relative) low ceiling at the source and receiver position (S1R2).

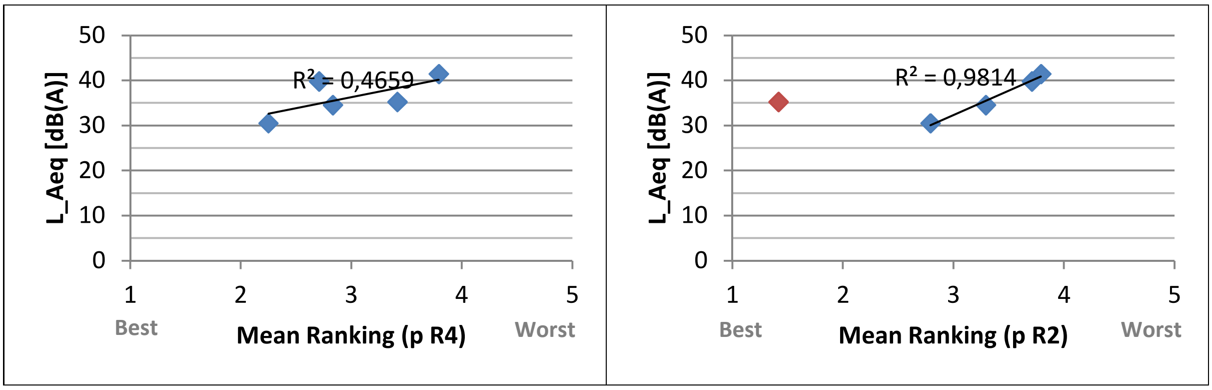

FIGURE 26: A-WEIGHTED EQUIVALENT BACKGROUND NOISE LEVEL VERSUS FAR (LEFT) OR CLOSE (RIGHT) AND DETAILS LISTENING CONDITION

For the other listening conditions (with musical dynamics mf and ff), no relations were found with the A-weighted equivalent background noise level. Apparently, for these conditions, the sound level of the sound source (snare drum) is high enough to eliminate the interference or masking from the background noise. Surprisingly, no relations were observed between the C-weighted equivalent background noise level and the mean ranking of any of the listening conditions. With the C-weighting, the low frequencies are a more important factor compared to the A-weighting. Apparently, these low frequencies provide less unwanted interference or masking from the background noise with the played musical fragment.

The most striking observation from the analyses of the results of the listening test was: the mean rankings per condition show less dispersion, with a better total mean ranking (with the exception of room HZ). No clear relations between this trend and any of the analyzed architectural or stage and room acoustic parameters were found. The only cautious suggestion is an empirical one: the ranking dispersion seems to have a relation with the architectural complexity of the room, especially the complexity of the ceiling.

Room ML, which has the best total mean ranking and least ranking dispersion, is a very straightforward room with a flat ceiling, consisting of a suspended ceiling with a collection of both sound absorptive and reflective ceiling tiles and integrated light boxes and air vents. This room is also ranked in the top 2 for all six listening conditions, scoring good rankings for the complete range of conditions. Apparently, this 'simple' room provides good all-round ensemble conditions, based on only one snare drum, which seem to be largely appreciated by the test persons.

Room BK, which (at a considerable gap from room ML) has the second best total mean ranking and more ranking dispersion, is a slightly more complex room with rough edges and protruding elements from walls and ceiling. From this ceiling, also sound reflector panels, air ducts and light boxes are hung. This room is ranked between p2 and p4 for all six listening conditions, scoring moderate rankings for the complete range of conditions. Apparently, this less 'simple' room provides moderate all-round ensemble conditions, which seem to result in a moderate (not good, not bad) appreciation by the test persons.

Room BM, which has the worst total mean ranking and the most ranking dispersion, seems a relative straightforward room at first sight. However, the room has a small stage at one end of the room where the music ensembles rehearse and the measurements were performed. Due to the proscenium arch that separates the stage from the rest of the hall, the stage could be seen as a small 'box' with a large opening on one side. Also, the room has a curved ceiling which results in a low floor to ceiling height at the back op the stage. At this side of the stage, the sound source (snare drum) was positioned. The shape of the ceiling probably focuses the (early) reflected sound to the receiver positions. This room is ranked between p1 (for close and details listening condition) and p5 (both far away listening conditions). Apparently, this 'complex' room provides extreme ensemble conditions, which seem to result in varying appreciation by the test persons.

Room BZ and HZ have a total mean ranking close to each other, somewhere between room BK and BM. However, room BZ has the second most ranking dispersion, where room HZ has the second least ranking dispersion. Room HZ is a relative straightforward room with non-parallel walls, giving the room a slight funnel shape in the horizontal plane. It has a stage at one end, but measurements were performed in the lower section of the hall. It has a reflective ceiling with integrated air vents and light boxes, but the large middle section of the ceiling is zigzag shaped, alternating in two directions, providing sound diffusion. Room BZ is more complex, having a small stage and an inclined audience area with fixed seats. The ceiling and top part of the walls is even more complex, having protruding square panels making the top of the hall egg-shaped. Room HZ is ranked at p3 and p4 for all six listening conditions, while room BZ is ranked between p1 and p5 over all six listening conditions. Apparently, the more 'complex' room BZ provides more extreme ensemble conditions, which seem to result in a more varying appreciation by the test persons. The much lower total mean ranking (compared to room ML) of the relative 'simple' room HZ, might be the result of the room dimensions. Room HZ has clearly larger dimensions for all architectural parameters than room ML (see Table 3), even when considering the stage as a large sound absorptive surface.

5. Conclusion

The goal of this research project was to investigate the influence of acoustic parameters (e.g. sound absorption or room volume) on the sound transfer in music rooms intended for rehearsal. This influence has been studied both through objective room and stage acoustic measurements and subjective evaluation by non-professional musicians, who are used to playing in music ensembles. A new methodology was composed for the subjective evaluation by test persons (musicians), in an attempt to eliminate prejudices, rising from non-acoustic issues, and let the musicians solely evaluate the acoustics of the room. Recordings were made in selected music rooms and used to compose a listening test for the subjective evaluation. This led to the research question: Can differences in the values of acoustic parameters, in music rooms intended for rehearsal, be investigated by ranking the ensemble conditions of these rooms, based on recordings of rhythmic sounds of indefinite pitch?

The methods used for the objective measurements are imbedded in guidelines or used before by other researchers. So essentially, this has been a feasibility study for this new methodology for subjective evaluation by musicians. All selected test persons fulfilled the listening test and were able to provide output. Based on their reactions to the played back recordings, they were able to evaluate the ensemble conditions of the selected music rooms intended for rehearsal, solely based on these recordings of rhythmic sounds of indefinite pitch, without any prior knowledge about the rooms. Obviously, being musicians, they all had 'live' experience with this type of rooms, but for this evaluation, they could only use their ears. The ranking of the ensemble conditions of the rooms proved to be somewhat difficult for some test persons and some listening positions, but, eventually, they all provided a preferred ranking order. So, it can be concluded, that it is possible to rank music rooms intended for rehearsal, based on played back recordings of rhythmic sounds of indefinite pitch.

The objective measurements showed significant differences in the values of the analyzed acoustic parameters for the selected music rooms. The interesting question is, whether these differences have any relations with the ranking of the rooms provided by the test persons. If so, the preferred ensemble conditions could be expressed in objective parameters.

Some relations were observed between the mean rankings of the test rooms and their architectural and acoustic parameters. For the intelligibility of musical details across an music ensemble, a large room (in terms of floor area and room volume) is disadvantageous. For the intelligibility of musical details at close distance within an music ensemble, much early reflected sound energy is preferred. However, this is disadvantageous for the perception of loudness. The balance of the early reflected sound energy, to satisfy both the intelligibility of musical details and the perception of loudness, seems to be a real challenge. For the intelligibility of musical details, also low background noise levels are required. However, these can be higher when much early reflected sound energy is present. At low frequencies, relative short reverberation times are preferred, especially for the intelligibility of musical details. So, it can be concluded, that differences in the values of acoustic parameters of the selected music rooms can be investigated by ranking the ensemble conditions of these rooms, based on recordings of rhythmic sounds of indefinite pitch. However, this investigation has only led to some minor preferences for the ensemble conditions of music rooms intended for rehearsal. Also, almost all rankings showed considerable standard deviations from their mean value, failing to support the significance of these preferences.

Large fluctuations have been observed in the ranking of the test rooms across the six different listening conditions. A room can, for instance, be ranked as most favorable for the close and details listening condition (p R2), but as least favorable for the close and loudness listening condition (ff R2). Most rankings cannot be predicted by means of the architectural or acoustic parameters. When looking at the average values, by determining a mean ranking (position), some patterns seem to surface. Room ML shows the best total mean ranking, when combining the rankings of all six listening conditions. This room also shows the least dispersion among the mean rankings of the six listening conditions, getting many good evaluations. Apparently, room ML could be considered as a music rooms with good all-round ensemble conditions, based on only one snare drum. The opposite seems to be the case for room BM. This room shows the worst total mean ranking and also the most dispersion among the mean rankings of the listening conditions, getting both many good and poor evaluations. Apparently, room BM could be considered as a music room with varying ensemble conditions.

This cautious trend, between the total mean ranking and dispersion among the mean ranking of the six listening conditions, cannot be predicted by the analyzed architectural and acoustic parameters. However, a new hypothesis has been devised: the architectural complexity of the room, especially the complexity of the ceiling, seems to have an influence on the homogeneity of the sound field over the different listening conditions, where a more homogenous sound field leads to ensemble conditions preferred by musicians for music rooms intended for rehearsal.

Recapitulating, this research showed it is possible to have musicians evaluate music rooms intended for rehearsal, solely based on played back recordings of rhythmic sounds of indefinite pitch. By ranking these music rooms, preferences can be observed and differences in the values of acoustic parameters of these rooms can be investigated. However, apart from some minor trends, no clear relations have yet been found, that could enable a prediction of the preferred sound transfer by determining the objective parameters. Also, as a result of the use of only one snare drum, it has to be seen if these preferences remain valid for a whole (wind) orchestra.

6. RECOMMENDATIONS

In this chapter, some side notes and recommendations for further research will be brought forward, as induced by the discussion of the results, conclusions of this thesis and experiences gathered during the course of the project.

The methodology with the listening test, has allowed the test persons to evaluate solely the acoustics/sound of the selected music rooms. It also has enabled them to do this for rooms in which they have never been (physically) present. However, the main limitation of the used methodology, is the use of only one musical instrument as the sound source. Especially for the representation of realistic sound levels of a whole (wind) orchestra in a music rehearsal room, this methodology falls short. The same can be said for a representative display of the full timbre of an orchestra, and thus a realistic evaluation over all relevant frequency ranges. Another disadvantage for the use of only one musical instrument, at a fixed source position, is the lack of varying sound path orientations. The only sound transfer was from the back of the (imaginary) orchestra to its front. In reality, the sound transfer in an orchestra is very diverse.

Preferably, the use of a full (wind) orchestra would result in realistic sound levels, full timbre and diverse sound transfer. However, this would create a lot of practical difficulties: much longer build up and measurement duration, the need for much more measurement equipment and increased complexity of data collection, to name a few. Also, with the use of at least 50 musicians simultaneously, the effectiveness and repeatability of the whole process would become a real challenge. As a compromise, a gradual increase in the number of musical instruments, used as sound source, could reduce most limitations.

Another comment can be made about the selected test rooms. An attempt was made to get a good representation on the variety of rooms typically used for rehearsal by non-professional music ensembles. However, this variety in rooms introduced a lot of variables in architectural properties, like room dimensions, shape and interior elements. This complicated the comparison between these architectural properties and the objective parameters and subjective evaluation. Probably, it would be better to reduce the number of variables. One way to achieve this, would be the use of only one room with fixed architectural properties, but (room for) variable acoustics. When maintaining the size and shape of the room, but varying the acoustical properties of that room (like the amount and positioning of sound absorption and reflective surfaces), less variables would have to be considered. Thus, this would result in different acoustic environments without altering the architectural properties, making the acoustics of the room a variable to compare, but not the room itself. An interesting issue would be the dose of variation over the different acoustic environments and the selection of the 'base' room. A downside to this method would be the increase in duration, actions and probably expenses. A benefit of this method would be the decrease in the number of test rooms, allowing less transportation and build up of the measurements set-up, provided that this one room would be available for a longer continuous period (e.g. a whole week).

Last, the number of test persons (24) was limited. This is about one third of an averaged sized (wind) orchestra. With the use of more test persons, it would be interesting to study if the fluctuation and dispersion among the rankings would decrease or not. Also, when having much more test persons, they could be divided in sub groups, for instance per instrument or section. This would enable the studying of differences between these sub groups and confirm (or deny) whether all musicians within a (wind) orchestra have the same preferences, regardless of their own musical instrument.

REFERENCES

J.J. Dammerud (2009), "*Stage acoustics for symphony orchestras in concert halls*", PhD thesis, University of Bath

European Union (2003), "*Directive 2003/10/EC of the European Parliament and of the Council of 6 February 2003 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (noise)*", Official Journal of the EU L42, 38-44 (2003), retrieved January 10, 2013, from: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:042:0038:0044:EN:PDF

Federatie van Amateur Symfonie- en Strijkorkesten (2014), "*Over FASO*", general information 01-01-2014, retrieved January 21, 2014, from:
http://faso.eu/content/faso-federatie-van-amateur-symfonie-en-strijkorkesten

A.C. Gade (1989), "*Investigations of musicians' room acoustic conditions in concert halls*", Acustica **69**, 193-203 and 249-261

A.C. Gade (2010), "*Acoustics for symphony orchestras; status after three decades of experimental research*", Proceedings of International Symposium on Room Acoustics, ISRA 2010, Melbourne (AU)

C.C.J.M. Hak, R.H.C. Wenmaekers, L.C.J. van Luxemburg (2012), "*Measuring Room Impulse Responses: Impact of the Decay Range on Derived Room Acoustic Parameters*", Acta Acustica united with Acustica **98**, 907-915

International Organisation for Standardisation (ISO) (2009), "*ISO 3382-1-2009: Acoustics – Measurements of room acoustic parameters – Part 1: Performance spaces*", Geneva (CH)

Koninklijke Nederlandse Muziek Organisatie (2013), "*Nieuwe muziekkoepel voor amateurmuziek beklonken*", news report VNM 08-12-2013, retrieved January 21, 2014, from:
http://www.vnm-nederland.nl/nieuws/0#145

Landelijk Kennisinstituut Cultuureducatie en Amateurkunst (2012), "*Factsheet – Amateurkunst in Nederland 2012*", retrieved January 21, 2014, from: http://www.lkca.nl/downloads/AK_Factsheet_2012_ned.pdf

J.H. Rindel (2014), "*New Norwegian standard on the acoustics of rooms for music rehearsal and performance*", Proceedings of Forum Acusticum, Krakow (PL)

Vereniging van Nederlandse Korenorganisaties (2014), general information homepage, retrieved January 21, 2014, from: http://nederlandsekorenorganisaties.nl/

R.H.C. Wenmaekers, C.C.J.M. Hak, L.C.J. van Luxemburg (2012), "*On Measurements of Stage Acoustics Parameters: Time Interval Limits and various Source-Receiver Distances*", Acta Acustica united with Acustica **98**, 776-789

R.H.C. Wenmaekers & C.C.J.M. Hak (2013), "*Early and Late Support measured over various distances: the covered versus open part of the orchestra pit*", Proceedings of International Symposium on Room Acoustics, Toronto (CA)

R.H.C. Wenmaekers, L.J.W. Schmitz, C.C.J.M. Hak (2014), "*Early and Late Support over various distances: rehearsal rooms for wind orchestras*", Proceedings of Forum Acusticum, Krakow (PL)

APPENDICES

Appendix A: Literature study

Appendix B: Measurement equipment and set-up

Appendix C: Question form listening test

Appendix D: Measurement data extended support parameters

Appendix E: Listening test responses

PROJECT INFORMATION

Music Rehearsal Room Acoustics – A literature study on the acoustical environment of rooms used by (groups of) musicians to rehearse.

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PREFACE

This report gives an overview of a literature study in the field of music rehearsal room acoustics. This literature study has taken place as preparation for my graduation project for the Master track Physics of the Built Environment, part of the Master Architecture, Building and Planning at Eindhoven University of Technology (TU/e).

The choice for this research topic follows from previous research on the "difference in sound level between the two ears of an orchestra musician using in-ear microphones" and own experiences.

Lennart Schmitz
Eindhoven, January 2013

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1. INTRODUCTION

In the field of architectural acoustics, much research is done on the room acoustics of performance spaces such as concert halls, theaters and other auditoria. This research is often done from the listeners' point of view. However, from the musicians' point of view, the specific acoustical conditions on stage are important. The research field of stage acoustics became more interesting with the introduction of the EU directive 2003/10/EC (European Union, 2003). This directive aims to protect workers in the music and entertainment sector from noise exposure, by compelling the EU member states to adopt legislation on this matter. This legislation includes limit and action values for noise exposure. The exposure limit values are $L_{EX,8h}$ = 87 dB(A) and $L_{C,peak}$ = 140 dB(C), the upper exposure action values are $L_{EX,8h}$ = 85 dB(A) and $L_{C,peak}$ = 137 dB(C), and the lower exposure action values are $L_{EX,8h}$ = 80 dB(A) and $L_{C,peak}$ = 135 dB(C) (European Union, 2003). The last decade, a research shift from the general acoustics of music rooms towards the sound exposure of (professional) musicians, both on stage (performance conditions) and in small spaces (most rehearsal conditions), could be observed. To create a pleasant acoustical working environment, (too) high sound levels have to be limited, without hindering conditions needed for playing ensemble and to provide a critical analysis of the music and musicians.

To a very large extend, existing research covers the working environment of professional musicians. However, besides these professional musicians, a lot of people in the Netherlands are playing music for recreation. According to a factsheet from 2012, by the Dutch governmental institute for culture education and recreational art forms (Landelijke Kennisinstituut Cultuureducatie en Amateurkunst, 2012), there were approximately 3.1 million inhabitants, aged 6 or older, in the Netherlands involved in some form of recreational music, both singing and instrumental, and individual and in groups. Many of these non-professional musicians are member of a music ensemble such as a marching or concert band, symphony orchestra, chamber music ensemble or choir. The Dutch national music association for wind and percussion ensembles (Koninklijke Nederlands Muziek Organisatie, 2013) states they represent 2,400 associations with 170,000 members in the Netherlands. The federation of amateur symphony and string orchestras (Federatie van Amateur Symfonie- en Strijorkesten, 2014) states they represent 245 orchestras with 9,000 members in both the Netherlands and Belgium. The national association for choirs (Vereniging van Nederlandse Korenorganisaties, 2014) states they represent thousands of choirs with approximately 180,000 members in the Netherlands.

Most of these music ensembles rehearse on a regular basis (e.g. weekly) to work towards one or more performances per year. In contrast, professional orchestral musicians rehearse almost daily to work towards more performances per week. The rehearsals of professional orchestras take place at the stage of their home concert hall (e.g. *Het Concertgebouw Amsterdam* or *Muziekgebouw Frits Philips Eindhoven*), in large music studios (e.g. *Muziekcentrum van de Omroep* in *Hilversum*) or in dedicated orchestral rehearsal rooms (e.g. the rehearsal room of the *Marinierskapel der Koninklijke Marine* in *Rotterdam*). On the other hand, the rehearsals of non-professional music ensembles often take place in buildings like (cultural) community centers, (music) schools, small theaters or even canteens or sports halls. When lucky, the room used for rehearsal is fitted for this purposes and sometimes even especially designed for it. However, many times costs and floor area are the only factors used to find an available accommodation. Some provisional measures may be taken afterwards to make the room more suitable. Also, with newly built facilities, most rehearsal spaces are limited in their dimensions because of the limited available budget. In both cases, new or re-development, this leads to small rooms in comparison to performances spaces. With the same music ensemble (e.g. an orchestra) size and repertoire, there is a risk of (even) higher sound levels in rehearsal spaces than in performance spaces. Mapping these risks and deriving guidelines to reduce/control these risks is still ongoing research.

First, an elaboration on the used method for the literature search is given. Second, an overview of publications on music rehearsal room acoustics from past to present is given. Third, some findings on this literature study are discussed.

2. LITERATURE SEARCH

Before studying the literature on the topic of music rehearsal room acoustic, relevant literature had to be selected first. This relevant literature was searched with the use of the following keywords:

- rehearsal (room)
- practice (room
- study (room)
- repetitie(ruimte)
- probe(raum)

These last two were added, because also some Dutch and German sources were used for this literature search. No keywords like 'stage acoustics' or 'room acoustics' were used. The first tends to deliver a lot of search results which focus on performance spaces and professional (symphony) orchestras. The second, besides the preceding reason, also tends to deliver a lot of search result on non-music spaces (e.g. lecture halls, offices etc.).

The sources used were common scientific literature sources in the field of (room) acoustics, like conference proceedings (Table 1) and scientific journals (Table 2). Besides these common sources, also the library of the '*Laboratorium voor Akoestiek'* of *Eindhoven University of Technology* and the publication database of the *Fraunhofer Institute* were used. Finally, also websites of acoustical consultants were used as a source to search for relevant literature.

TABLE 1: CONFERENCE PROCEEDINGS

Internoise
International Conference on Sound & Vibration (ICSV)
International Conference on Acoustics (ICA)
Geluid&Trillingen
Forum Acusticum
Euronoise
Euregio
Deutsche Arbeitsgemeinschaft für Akustik (DAGA)
Nederlands Akoestisch Genootschap (NAG)
Active
Audio Engineering Society (AES)

TABLE 2: SCIENTIFIC JOURNALS

Journal of Sound and Vibration
Applied Acoustics
Journal of the Audio Engineering Society
Journal of Building Acoustics
Acta Acustica united with Acustica
Journal of the Acoustical Society of America
Acoustics today
Acoustical Science and Technology
Journal of the Acoustical Society of Japan
Bauphysik

The above mentioned keywords were used to make a first selection, then a rough scan of the abstracts (if available) was used to narrow it down and based on these first impressions, specific literature was studied in full. In the following chapter, an overview of the research history on music rehearsal room acoustics, from past to present, is discussed based on the selected literature.

3. MUSIC REHEARSAL ROOM ACOUSTICS: PAST TO PRESENT

3.1 20TH CENTURY

In 1902, Sabine (1906) carried out an experiment in five small music rooms of the New England Conservatory of Music, used for the purpose of instruction. While listening to piano music, the acoustical quality of the room was judged by a committee of five men, chosen by the Director of the Conservatory. This committee consisted of the Director himself and four staff members of the Faculty. The "absorbing power" of the room was changed, with the use of cushions, until approval on the acoustical quality was reached. The corresponding reverberation times were determined and compared to their mean value of 1.1 seconds. Sabine concluded that "the five determinations, by their mutual agreement, give a numerical measure to the accuracy of musical taste which is of great interest."

However, the previous experiment approached the acoustical conditions for (instrumental) music rehearsal spaces from the listeners' point of view and not the (performing) musicians' point of view. The first scientific articles dealing with the latter were published in the 1950s. Knudsen and Harris (1950) indicated the concepts that are important when playing ensemble. They also gave some recommendations on the room design and reverberation time. Carter (1955) recommended a optimum volume and reverberation time for band and orchestra and also indicated a floor area per musician. Kessler (1955) stated that the use of physical measurements alone to evaluate the acoustical quality of a music room is insufficient and suggested the use of questionnaires. Young and Gales (1956) used questionnaires to define the preferences of music teachers for rehearsal rooms for different types of music ensembles. Blankenship et al. (1955) combined both physical measurements and subjective reactions of musicians. They studied individual practice rooms, teaching studios, ensemble rehearsal rooms and auditoria at one university while asking both musicians and conductors to rate these rooms. One of the difficulties encountered concerned "determining a suitable terminology which would be understood and interpreted similarly by discriminating musicians and also have meaning for the architect and acoustician." Lane and Mikeska (1955) performed a similar study at four different universities but with only the individual practice rooms and teaching studios. They also used the subjective opinions of both students and staff in an attempt to obtain data on the minimum amount of acoustic insulation, optimum reverberation time and minimum acceptable room size. Their conclusions "should be considered as design guides rather than as fixed specifications, and since individual musicians will always have differences of opinion on what constitutes good acoustics, it will always be advisable to provide means for varying the reverberation time."

After these first articles on the acoustical conditions for (instrumental) music rehearsal spaces it became rather quiet for over two decades, except an article by Patrick and Boner (1967). They made a new effort in comparing objective measurements with subjective data. Therefore they studied six rehearsal rooms at music schools that were found acoustically satisfactory by the music teachers that used them. Two interesting observations were found in this article. The first concerns the view point of the music teacher/conductor: many times they found it "difficult to determine whether the lack of achievement is the result of inexperienced performers or a poor acoustical environment." The second concerns the view point of the acousticians: the researchers observed that "although many acousticians have a musical background, they may be unacquainted with the problems of teaching music, which requires a different acoustical situation from that of the auditorium or concert hall.” These observations led to the conclusion that “the acoustical attributes needed in the school teaching situation are decidedly different from those for the performance situation.”

From the late 1970s and early 1980s an increase in scientific publications on music (rehearsal) spaces was recorded. These publications more and more tried to approach the topic from the musicians point of view. For example, Marshall et al. (1978) studied the acoustical conditions preferred for ensemble through experiments in which one of the musicians of a string trio played along with a anechoic recording of the other two parts. Lamberty (1980) tried to provide design guidelines for individual music practice rooms by research work into the likes, dislikes and preferences of a group of full time music students with the use of a large set of questionnaires. Vaughan (1982) made an attempt at describing the physical counterpart of subjective criteria preferred by musicians with an emphasis on how we hear and localize various frequencies. Naylor (1988) discussed the various ways in which groups of musicians synchronize their performance. He defines three meanings of the word ‘ensemble’ being (1) *a group of performers*, (2) *the overall agreement of a group of performers on all aspects of their production: timing, phrasing, articulation, pitch, dynamics, timbre, and possibly other, not identifiable, elements* and (3) *the temporal synchronization of note-onsets amongst the group*.

During the 117th Meeting of the Acoustical Society of America in Syracuse, New York in May 1989 special poster and lecture sessions entitled “Music Education Facilities Since 1975” were organized. The presented posters and lectures were not only from North America (United States and Canada), but also from Australia, France, Japan, Mexico, The Netherlands and South Africa. Afterwards McCue and Talaske (1990) compiled a publication containing essays concerning the acoustical design of music education facilities and reproductions of posters describing the fifty projects presented at those sessions. These essays gave a broad look on many aspects of the design process concerning these facilities, from cost control to stage lighting. One essay was allocated to the acoustical aspects of rehearsal rooms giving a mere enumeration of points of interest. Another essay was allocated to the sound insulation aspects in these facilities. The reproduced posters were mainly a collage of pictures, floor plans and cross-sections with here and there some physical data on dimensions, mid-frequency reverberation time and ambient noise criteria, and some data on the finish materials of the indoor surfaces. This publication mainly emphasized the complexity of the design process of music education facilities and showed some appealing examples of facilities that were the result of a successful process.

The use of music rooms and (small) auditoria for multiple purposes obtained a significant role, especially in smaller towns and at (music) schools. To accommodate this, variable acoustics were increasingly introduced in these type of buildings. A study by Pirn (1992), concerning three acoustically variable halls, showed that these medium sized auditoria could be made more than acceptable for a wide range of musical situations and preferences, with the use of adjustable sound absorption (retractable curtains). But, they still contained limitations for large ensemble. These limitations included, too much reverberation when rehearsing with a large ensemble in an empty hall and too high sound levels with large ensembles and certain music repertoire. This study introduces the limitations with respect to loudness of large music ensembles in relative small rooms.

Völker (1988) stated that “the best rehearsal room is the concert hall itself in which the orchestra works on its quality and develops its reputation”. This ideal situation is hardly ever the case so “the translation from the rehearsal room to the concert hall must follow naturally and is an important consideration in the work of an orchestra”. When rehearsing concerts that will be given in large concert halls, a playing style with high sound levels and high orchestral forces is necessary. This gave rise to the question of the loudness and the potential for hearing damage. Although multiple references of hearing loss studies under musicians are mentioned, the author states that “musicians playing in a symphony orchestra are not faced with an increasing risk of hearing impairment, even though high peak levels exist”. In a later publication Teuber and Völker (1993) described acoustical designs for various individual and orchestral rehearsal rooms. They concluded that “it is not possible to define a standard rehearsal room for orchestras due to differences in size, type of instruments, musical style, etc. The acoustician has to ascertain the wishes and requirements of the orchestra before making his plans and designs”. They also mentioned the possibility of electro-acoustical systems to artificially enhance reflections and reverberation to meet the widely different wishes from recording room to concert hall. Where Teuber and Völker were convinced that the best acoustical conditions for orchestral rehearsal were those as close as possible to performance conditions, Tennhardt and Winkler (1995) perceived a tendency toward acoustical conditions that facilitate “a critical analysis of the musicians”. They stated that the most important task when designing an orchestral rehearsal room is to support the transfer of acoustical/musical details between the musicians mutual and to the conductor. Another important task is the reduction of the sound level without impeding the tone color (timbre), dynamic range and mutual hearing. Further they indicated the lack of a seating area and its accompanying acoustical response as the major difference between a rehearsal room and a concert hall.

3.2 21ST CENTURY

With the introduction of a new noise directive (2003/10/EC), the European Union (2003) required its member states to draw up a code of conduct for the music and entertainment sector, prescribing “minimum requirements for the protection of workers from risks to their health and safety arising or likely to arise from exposure to noise and in particular the risk to hearing”. This led to an increase in research on the topic of hearing loss and protection amongst musicians and, significant for the field of music rehearsal room acoustics, the acoustic conditions for musicians in small spaces.

In this subsection, nine summaries of recent work on music rehearsal room acoustics are presented. These studies are largely, but not solely, inspired by the increased interest in the (acoustical) working environment of professional musicians.

Zha et al. (2002), in advance, already studied the working environment of professional musicians in two German theatres. They proposed measures to improve the acoustical environment within two orchestra pits and one rehearsal room. Their requirements were (1) *sound development control* (reduction of sound intensity levels), (2) *good ensemble playing* and (3) *high sound quality*. In both orchestra pits, “newly developed bass absorbers were only provisionally placed within the pit. After a test period, however, the musicians as well as the conductor would no longer like to work without this innovation.” In the rehearsal room they observed that “from the rear to the front part the clarity is much higher than in the opposite direction. This “one-way” peculiarity impeded the communication and hearing among the musicians.” They proposed changes to the ceiling and the use of reflectors, diffusers and absorbers "in order to (1) reduce the overall sound pressure levels, (2) avoid reflections between hard walls and (3) improve ensemble playing among the musical groups and communication with the conductor." Figure 1 shows a cross section of the studied rehearsal room before and after the acoustical reconstruction as proposed by the authors. Zha et al. concluded from their research and experiences on the acoustic working conditions for musicians in small spaces: "It thus seems no longer questionable that it is the low frequency end of the acoustics, long neglected awfully by acousticians, which is largely responsible for poor communication, difficult ensemble playing and, last but not least, increasing hearing loss in musicians forced into always too small enclosures."

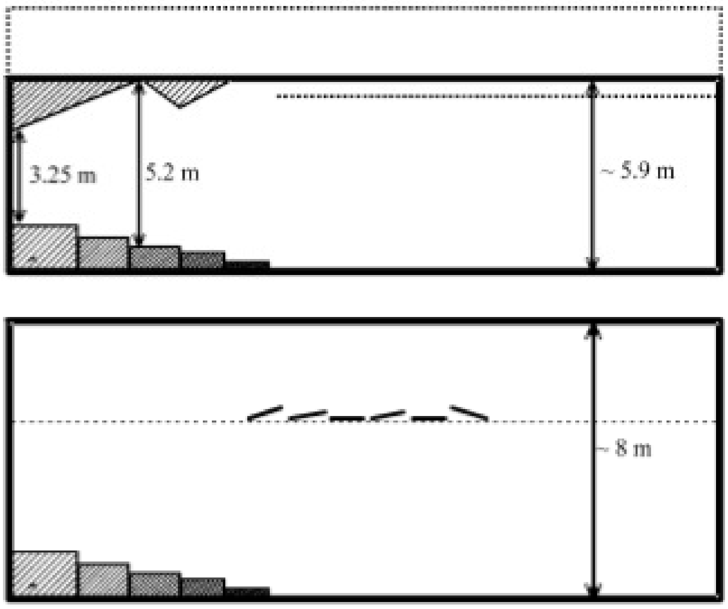


FIGURE 1: CROSS SECTION OF THE REHEARSAL HALL BEFORE (TOP) AND AFTER (BOTTOM) RECONSTRUCTION (ZHA ET AL., 2002).

Valk et al. (2006) tried to optimize the room acoustics for lesson and study rooms of the *Conservatorium van Amsterdam*. They built two test rooms (28 m^3 and 106 m^3) to investigate the desired acoustics of different groups of instruments for these type of music rooms. The acoustical parameters could be changed by varying the amount of absorption panels in the test rooms. These panels were wideband absorption panels, consisting of a combination of low frequency absorption through a resonator and mid and high frequency absorption through porous materials. They combined these objective measurements with subjective tests among the musicians and teachers that used the test rooms. The desired acoustics were expressed in the number of absorption panels, with resulting reverberation time for each of the test rooms, and arranged per instrument group (both classical and jazz music). Besides this experiment, two existing models for the relation between reverberation time and room volume of music halls were discussed. These models were based on halls with a minimum room volume of 1000 and 400 m^3. The authors proposed a new model for music rooms smaller than 400 m^3, based on their experiment. The authors stated that the loudness becomes more critical with a decrease of the room volume. "Apparently it is unpleasant to make music in a room were the sound level is too high. To achieve the desired acoustics, more sound absorption has to be applied at the expense of the amount of reverberance. Due to this, the reverberation time will become relatively lower." They also discussed that "a lot of music schools do not have the luxury to use single-purpose rooms and assign them to only one particular instrument group. At the expense of the desires of the users, teachers and students from different instrument groups, a compromise for the room acoustics has to be chosen. This can best be reached with variable acoustics. However, due to the small room volumes of lesson and study rooms, only variable acoustics through variable sound absorption is eligible. Varying the room volume and the use of electro-acoustical systems are not suitable for such small rooms. When the application of variable acoustics is not achievable, the only option is the chose an average room acoustic, best described by $RT_{musicroom}$ = 0,45 log V – 0,36." Figure 10 shows the relation between reverberation time and room volume of music halls, with the two existing models for large music rooms and the new proposed model for small music rooms.

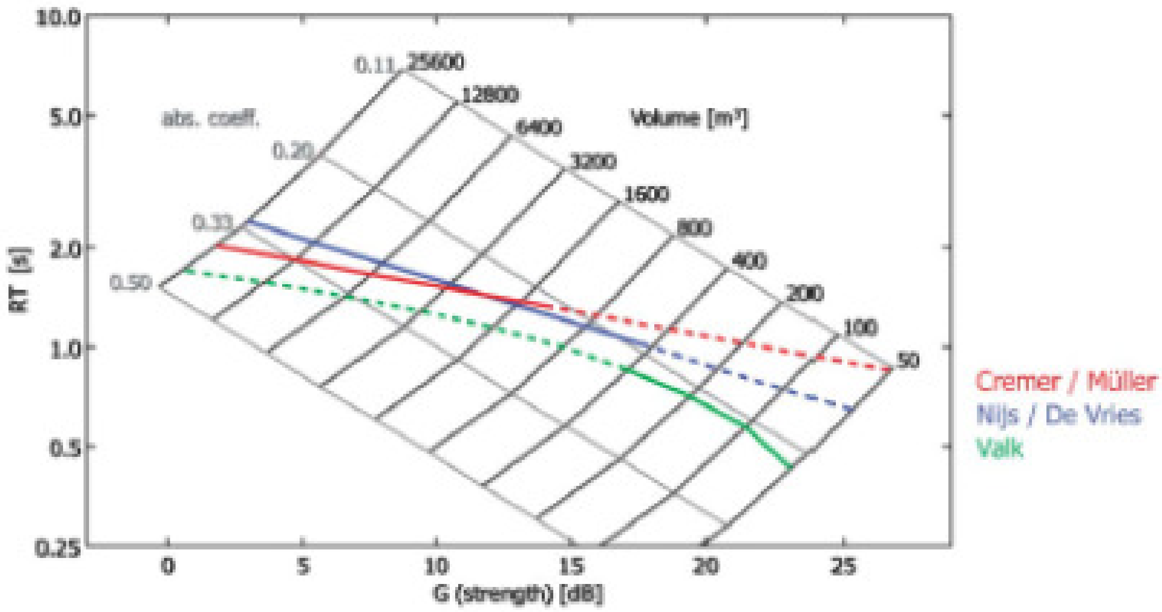


FIGURE 2: THREE DIFFERENT ROOM ACOUSTICAL MODELS IN A G-RT-DIAGRAM (VALK ET AL., 2006).

O'Brien et al. (2008) performed a thorough research on orchestral noise for which they " recorded noise levels within a professional orchestra over three years in order to provide greater insight to orchestral noise environment; to guide future research into orchestral noise management and hearing conservation strategies; and to provide a basis for the future education of musicians and their managers". The recordings were made both during rehearsals and concerts in multiple venues: three concert halls, two orchestra pits and a purpose-built orchestral rehearsal hall. The authors concluded "this study has demonstrated that three key variables – position, venue and repertoire – impact significantly upon the noise exposure of individual musicians." Musicians of brass instruments (especially the principal chairs) "are at greatest risk of exposure to excessive sustained noise levels, and the percussion and timpani (*red. players*) are at greatest risk of excessive peak noise levels. However, the findings also strongly support the notion that the true nature of orchestral noise is a great deal more complex than this." Figure 3 shows contour plots for the average equivalent and peak sound levels, measured in the rehearsal room studied by O'Brien et al. Figure 4 shows a table with the values per measurement position, averages and range, for this rehearsal room.

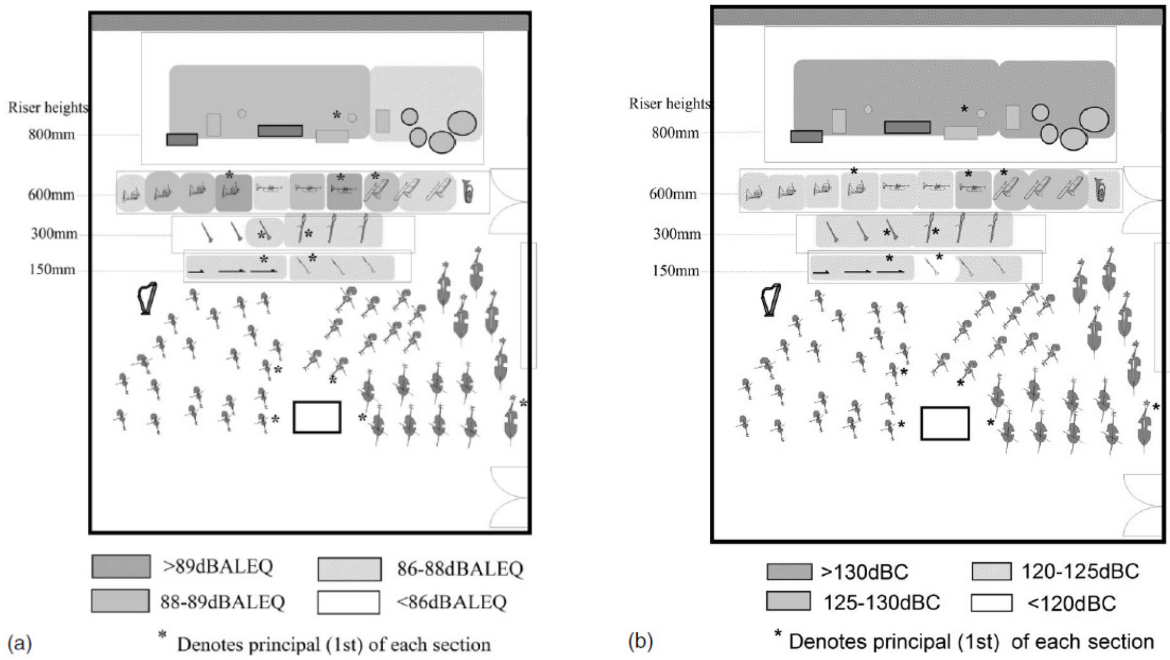


FIGURE 3: AVERAGE MEASUREMENT VALUES FOR THE REHEARSAL ROOM (A) EQUIVALENT SOUND LEVELS AND (B) PEAK SOUND LEVELS (O'BRIEN ET AL., 2008).

TABLE III. Studio 420 summarized data.

Position	dBALEQ average	dBALEQ range	dBC peak median	dBC peak range	Number of samples
Violin 1	81.2	77.4–85.5	115.9	107.1–121.2	4
Violin 2	83.8	78.7–88.3	118.3	111.1–126.6	19
Viola	85	77.6–91.2	119.2	103.7–126.4	27
Cello	84	78.6–87.3	119	113–123.1	15
Bass	83.4	78.4–86.7	119.8	115.1–129.6	21
Harp	84.3	82.5–87.6	117.6	115.7–127	9
Flute 1	87.3	78.1–92.1	120.6	106.5–129.5	47
Flute 2/piccolo	87.1	80.2–92.9	120.4	116.7–127.1	23
Oboe 1	87	80.9–90.7	119.8	112.7–128.6	32
Oboe 2/cor	86.6	81.3–90.9	120.3	112.3–127.6	19
Clarinet 1	87.8	80.4–93.2	122.6	112.1–129.8	60
Clarinet 2/bass Cl	85.7	79.8–89.3	120.4	113.6–129.8	22
Bassoon 1	87.4	80.1–92.8	121.6	112.5–132.3	40
Bassoon 2/contra bassoon	86.9	79.7–94.4	123.5	116.1–129.1	24
Trumpet 1	89.4	83.1–94.9	125.6	119.9–136.6	66
Trumpet 2	88.6	81.1–94.5	124	116.2–138.3	26
Trumpet 3	87.2	79.7–91.6	123.2	118–128	10
Horn 1	89.1	81.4–94.5	122.4	107.3–132.9	67
Horn 2	88.2	81.6–94.1	122.5	116.5–128.9	23
Horn 3	88.9	82.7–95.9	122.7	117.4–133	37
Horn 4	87	84.5–88.9	120.6	118.8–121.2	6
Trombone 1	88.7	82.4–93.6	126.5	117.1–135.3	51
Trombone 2	87.7	78.3–91.7	126.4	118.9–134.2	12
Bass trombone	86.3	80.9–93	126.4	119.4–133.7	15
Tuba	84.6	78.5–90.4	124.9	113.6–128.7	10
Percussion	88	82.3–93.1	135.1	125.5–144.1	31
Timpani	86.2	81.2–91	132.9	123.8–141.3	26
				Total samples:	742

FIGURE 4: TABLE OF MEASUREMENT VALUES FOR THE REHEARSAL ROOM (O'BRIEN ET AL., 2008).

Aretz and Orlowski (2009) carried out sound strength and reverberation time measurements in six small concert halls (50 to 500 seats, room volume 850 to 4100 m³) in Cambridge, UK. The authors stated: “Reverberation times measured with deployed absorbing surfaces appear appropriate for drama theatre or speech. However, it has to be mentioned that excessive loudness may become a critical issue in small recital halls when the acoustic surfaces are not deployed. Considering for example a rehearsal of an orchestra in such a hall, it is not possible to reduce the sound strength in the hall whilst at the same time maintaining high reverberation. Although this problem can obviously be solved with larger volumes, the measures are often considered unpopular due to cost. Therefore the reverberation time in small halls has to be balanced against the total sound level depending on the size and the instrumentation of the orchestra/ensemble. In small halls it might not always be possible to meet Barron’s recommendations for chamber music whilst at the same time avoiding excessive loudness. Consequently sound strength, which is closely related to the subjective sensation of loudness, has to be considered as an important design factor for small concert halls.” Figure 5 shows the average mid-frequency strength as a function of RT/V for five of the measured halls. For four of those five halls, values for different variations in sound absorbing materials (panels or curtains) are given. The measured strength values tend to be lower than both the traditional and revised theory.

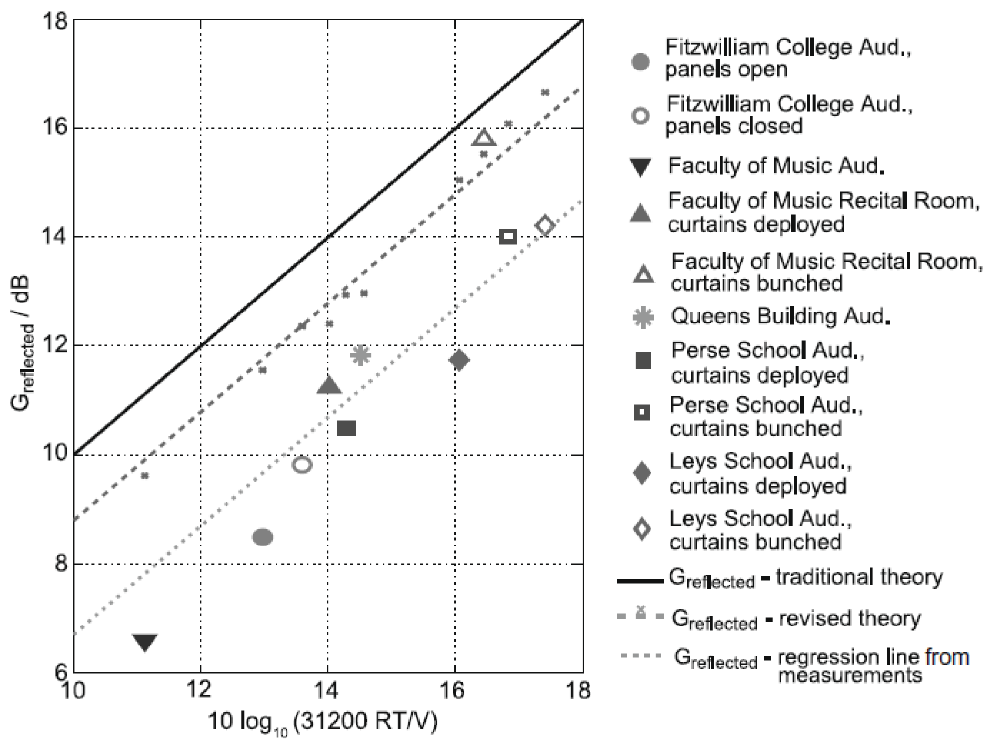


FIGURE 5: AVERAGE MID-FREQUENCY STRENGTH AS A FUNCTION OF RT/V (ARETZ AND ORLOWSKI, 2009).

Ueno et al. (2010) investigated if musicians adjust their performance to suit the acoustics of their playing environment. They developed a schematic model and used it for a performance experiment in which “musicians performed under different acoustic conditions simulated in an anechoic room.” “Explorative interviews with the performing musicians, and an objective evaluation of the recorded music signal through a listening test and an acoustic analysis” were used to “systematically explore the influence of room acoustics on a musician’s performance.” The authors concluded: “Based on the interviews with the musicians, it was inferred that they adjusted their performance to room acoustics, at least subjectively. It was also observed from the listening experiment that there are perceivable differences between the performed music signals depending on the acoustics conditions of the recordings. The attributes that the listeners identified for the variations in the performed music pieces were mostly in accordance with those indentified in the player's subjective report. Acoustic analysis for the musical tempo, the extent of vibrato, and sound level also demonstrated that the difference in music performed under various acoustic conditions were statistically significant."

Koskinen et al. (2010) examined "room acoustics recommendations provided by the Finnish code of conduct", which is based on the noise directive (2003/10/EC) of the European Union (2003). They focused on small practice rooms and the music teachers' perspective. "The Finnish code of conduct provides requirements for the space that is needed for instruments: grand piano and drum set need ≥80 m^3/person, wind instruments ≥20 m^3/person and other instruments ≥10 m^3/person." In addition, the following requirements for good rehearsal facilities were given by the authors: "(1) good sound insulation (should be ensured when built, as it is difficult to improve later without extensive repairs) and proper background noise levels, (2) a sufficient amount of absorption, (3) special requirement for the instruments need to be met (floor, reflecting wall, etc.) and (4) other environmental controls where needed (ventilation, lighting, temperature)." Selected practice rooms at a music institute were renovated by adding more absorption. Questionnaires were spread among the users of the studied practice rooms. The results from these "showed a major improvement in the sound levels of the rooms. However, sound level measurements could not confirm this improvement. One explanation could be that the bass elements decreased low frequency sound, which did not contribute greatly to the A-weighted exposure. Thus, the musicians might have rated their annoyance at the room instead of the sound level."

"The acoustical conditions of rehearsal rooms are of primary importance during the training process of an orchestra" according to Pompoli et al. (2012). "Therefore these spaces should be specifically designed to allow the musicians to clearly hear themselves and each other. At the same time an appropriate sound level should be maintained to avoid extensive exposure to high pressure levels. Despite the peculiar role of these rooms in the musical production, the criteria for their acoustical design are not still sufficiently clarified." The authors investigated the relevance of geometrical and acoustical parameters on the final performance of a rehearsal room and described the influence of the values of the ratio V/N (volume/number of musicians), S/N (floor surface/number of musicians), W/N (sound power/number of musicians) on objective acoustic parameters such as ST_{Early} (Early Support). "Even if optimum values of ST_{Early} for rehearsal rooms do not exist, the values suggested for stage in concert hall have been considered suitable. Moreover, the design procedure estimates the sound level in the room as a function of T_0 and the volume for performer (V^*)." The authors' main conclusion was: "In order to reduce the sound level it seems important to increase as much as possible V^*. Figure 6 gives the scheme Pompoli et al. (2012) used for the disposition of the orchestra in a rehearsal room. Based on a given cell dimension d (= the space from one musician to another) and number of musicians N, the floor per performer S^* could be calculated. When adding the height of the room H, the volume for performer V^* could be calculated. Figure 7 shows the curves of the relation between volume for performer V^* and the number of performers N, for several given cell dimensions d and ceiling height H.

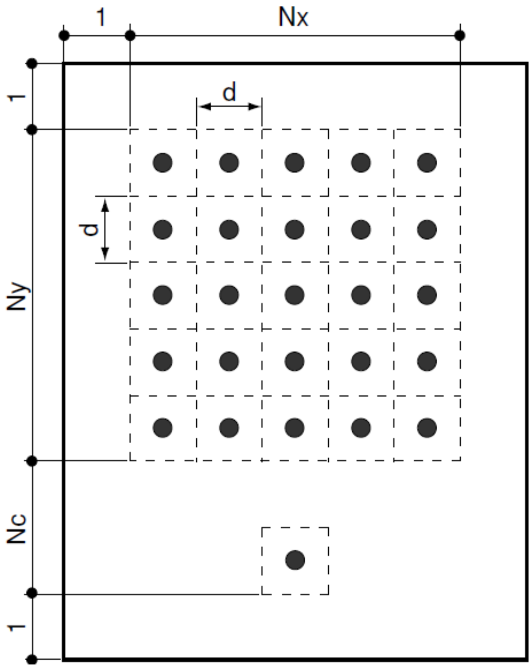


FIGURE 6: ORCHESTRA SHEME (POMPOLI ET AL., 2012).

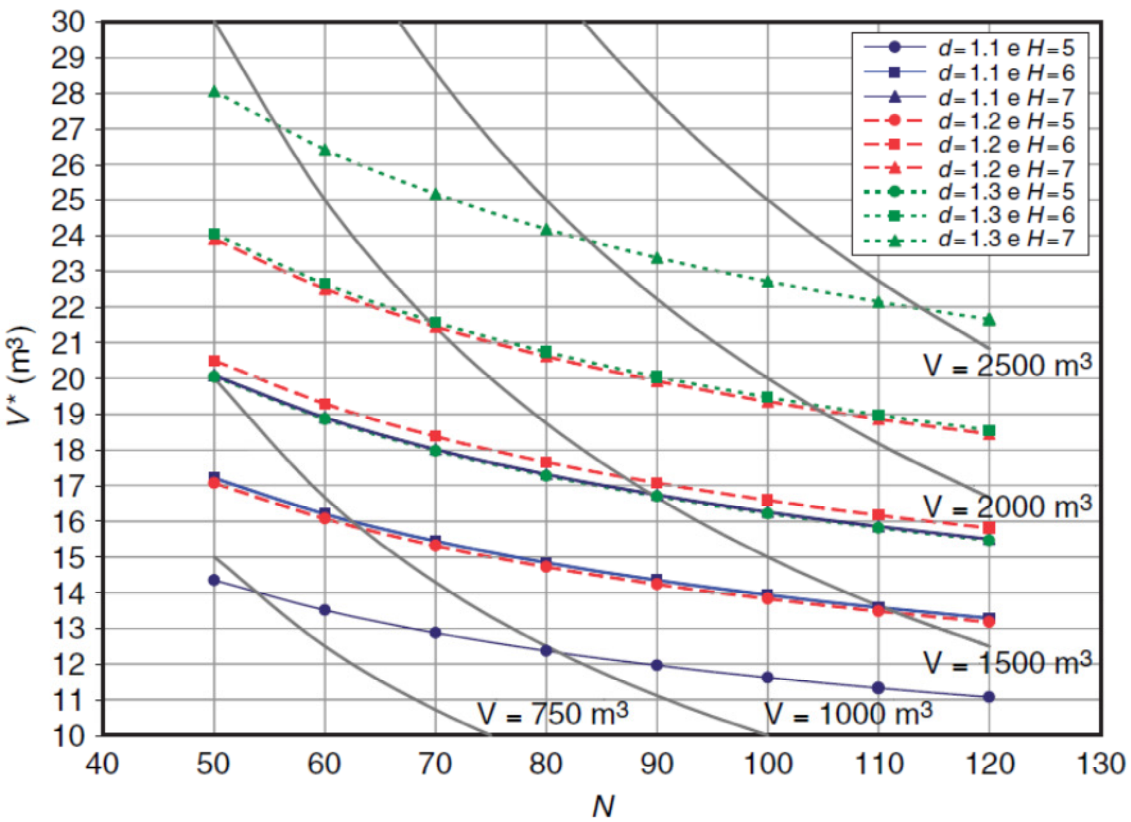


FIGURE 7: V* AS FUNCTION OF N FOR D AND H (BOTH IN [M]) (POMPOLI ET AL., 2012).

”One of the important aspects on the room acoustics in rehearsal rooms/small spaces, as discussed in many (*of the preceding*) studies, is the room volume. The size of the room is often a critical point when it comes to acceptable sound levels when playing music inside these rooms. Unfortunately, orchestras often have to rehearse in rooms with a too small volume for their orchestra size and instrumental forces.” Arau-Puchades (2012a & 2012b) developed a 3D-grid diffuser, “an acoustic labyrinth that increases the effective volume of a spaces without increasing the internal dimensions.” Figure 8 shows photo impressions of this 3D-grid diffuser, as installed in the orchestral rehearsal room at the Liceu Theater in Barcelona and in the Tonhalle St. Gallen.

FIGURE 8: PHOTO IMPRESSIONS OF THE 3D-GRID DIFFUSER IN A REHEARSAL ROOM (LEFT) AND SMALL CONCERT HALL (RIGHT) (ARAU-PUCHADES, 2012A).

“The structure combines the properties of multiple reflections and edge diffraction in such a way as to increase the effective path length of randomly diffused sound. The result is greater clarity and increased reverberance at the same time.” Musicians and audience were enthusiastic about the (acoustical) effects of this new element and measurements confirmed significant improvement in reverberation time (RT), early decay time (EDT) and sound strength (G). The physical phenomena however could not be explained with existing (mathematical) theories, so “further research is needed to determine exactly how these structures work, and how their principles could be incorporated into new forms and designs.” Figure 9 shows tables with measurement values for the reverberation time and sound strength before and after the installation of the 3D-grid diffuser in the Tonhalle St. Gallen. Although the total room volume was not altered, the reverberation time increased and the sound strength decreased.

Table II. Average reverberation time T_{30} before and after the modifications in 2010. The values of EDT are similar to the RT values shown here.

Frequency	125	250	500	1000	2000	4000	RT_{mid}	RT_{low}	RT_{high}
T_{30} (s) 2009	2.47	2.27	1.94	1.90	1.83	1.57	1.92	2.37	1.70
T_{30} (s) 2010	2.42	2.30	2.10	2.06	1.96	1.64	2.08	2.36	1.80
$\Delta T_{30} = T_{30,2010} - T_{30,2009}$	−0.05	0.03	0.16	0.16	0.13	0.07	0.16	−0.01	0.10

Table IV. Average of G values measured on stage as a function of frequency before and after renovation.

Frequency	125	250	500	1000	2000	4000	G_{mid}
Strength G_{2009} (dB)	11.0	8.4	8.0	8.6	9.6	7.6	8.9
Strength G_{2010} (dB)	5.7	7.0	6.0	5.6	6.3	4.6	5.8
$\Delta G = G_{2010} - G_{2009}$ (dB)	−5.3	−1.4	−2.0	−3.6	−3.3	−3.0	−3.1

FIGURE 9: TWO TABLES WITH MEASUREMENT VALUES BEFORE AND AFTER REFURBISHMENT (ARAU-PUCHADES, 2012A).

In his article, Gade (2012) defined a rule of thumb for the amount of sound absorption in a rehearsal room, based on a 90 musicians orchestra playing classical music from the 'standard' symphonic repertoire. This rule of thumb states that the amount of sound absorption in the room needs to be at least 8 m² per musician:

$$A/N = 8m^2,$$

with A as the amount of sound absorption and N as the number of musicians. With a certain room volume, this rule of thumb leads to an accompanying reverberation time. In addition, he stated that when a music ensemble consists of relative more loud instruments (brass and percussion) or amplified instruments, additional (variable) absorption would probably be needed. Also other room requirements, like sufficient stage floor area per musician and a sufficient high ceiling are important in controlling the sound levels. Furthermore, "through the choice of room geometry, rises, reflectors and the distribution of absorption, the balance between early and late arriving sound components can be influenced, which determines both levels, ease of hearing each other and support of the own instrument and the ability to balance with the rest of the orchestra."

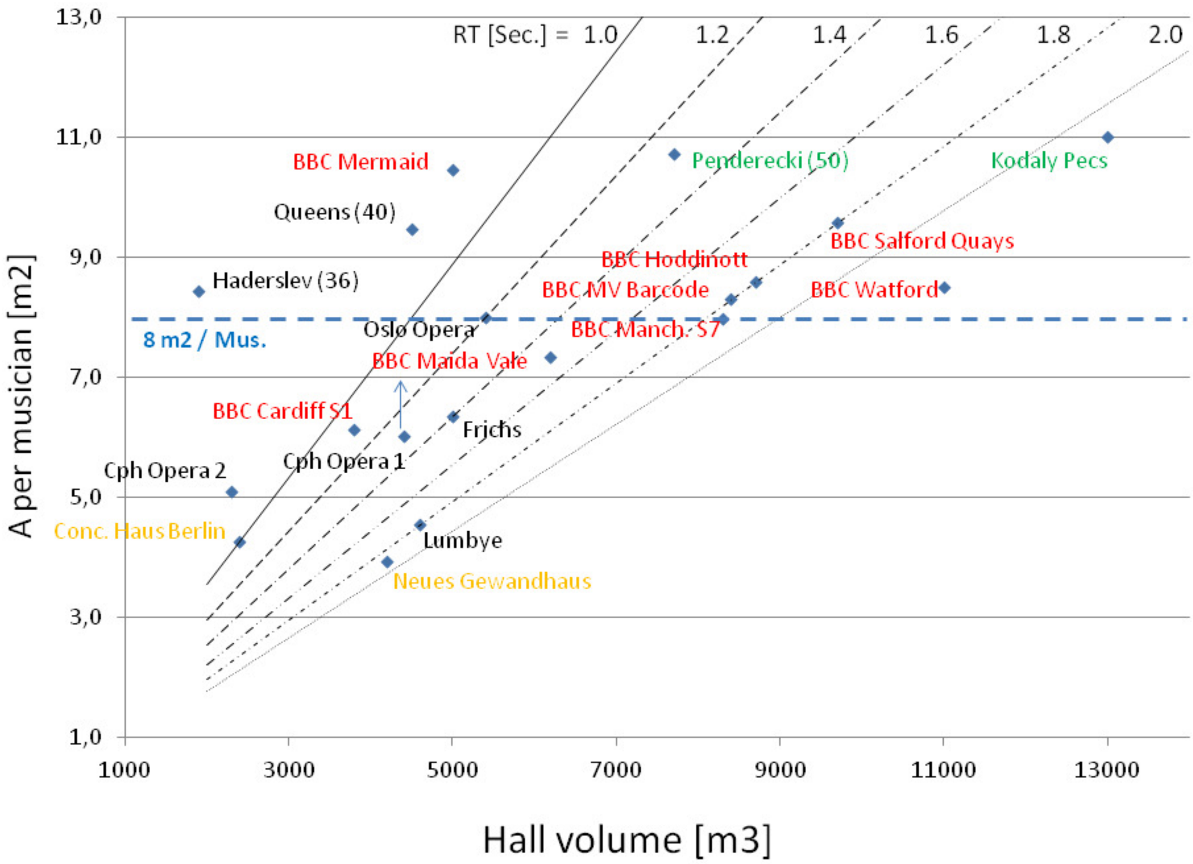


FIGURE 10: ABSORPTION PER MUSICIAN VERSUS VOLUME IN SMALL/MEDIUM HALLS FOR CLASSICAL MUSIC (GADE, 2012)

Figure 10 shows a graph from Gade (2012) and represents the relation absorption per musician versus volume of the studied (dedicated) rehearsal halls and small/medium concert halls. The absorption per musician has been calculated from the measured reverberation time in the hall (without musicians present) and assuming that the hall is to be used for a full symphony orchestra with 90 musicians. The author based his suggestion for a rule of thumb on this graph: "If we draw a horizontal line corresponding with 8m² absorption area per musician in Figure 10, we see that most of the satisfactory halls are above and the ones with level problems fall below this line. In many of the halls shown, RT can be reduced further, which is often used with heavily orchestrated music."

With fixed absorption per musician (A/N), the reverberation time (RT) increases with increasing hall volume (V). However, A/N shows an increase with increasing V and as a result RT increases less than with constant A/N.

4. LITERATURE DISCUSSION

Sabine (1906) already studied the relation between the sound absorption present in a rehearsal room and its room acoustic environment. He made the first scientific attempt to determine desired acoustic parameters in rehearsal rooms. While doing so, he took into account the subjective evaluation of the room acoustics by users of the studied rooms. Kessler (1955) stated that objective measurements only are insufficient to evaluate the acoustical environment of music rehearsal rooms. He proposed the use of questionnaires to obtain subjective data that could be compared with objective measurements and lead to preferences for the desired acoustical environment. The use of questionnaires and interviews, with music teachers, conductors and/or musicians, is a common used method, like in the studies by Blankenship et al. (1955), Lane and Mikeska (1955), Young and Gales (1956), Patrick and Boner (1967), Lamberty (1980), Pirn (1992), Zha et al. (2002), Valk et al. (2006), Ueno et al. (2010), Koskinen et al. (2010), Arau-Puchades (2012a, 2012b) and Gade (2012). Two studies, by Marshall et al. (1978) and Ueno et al. (2010), comprised experiments in a laboratory, where the musicians were asked to play along with recordings under varying acoustical conditions. However, in all these preceding cases the subjective evaluation is performed with respondents that were actual users of the studied rooms. When the respondents are aware of changes made to the studied rooms, it can occur that the subjective evaluation results in improvement or degradation of the perceived acoustical conditions, but at the same time, the objective measurements cannot confirm significant changes to (room) acoustic parameters. With such results, it is difficult to determine whether this is due to a limitation in the measurement methodology, or whether the respondents perceived changes that were not there (Koskinen et al., 2010). To avoid this, it would be better to use a subjective evaluation methodology that 'disconnects' the respondents from the actual room and let them evaluate only the acoustical environment of a room, and not also its appearance or other comforts.

When studying different type of instruments and/or type of ensembles, subjective evaluation can lead to a large variety of preferences (Valk et al., 2006). In this way, the total number of respondents can be reasonable, but the number of respondents per type can be very small. Therefore, it is preferable to focus on one type of instrument or ensemble at a time. However, in reality many rooms, used for music rehearsal, are designed and/or used for multiple purposes. Each purpose can have its own preferences for the acoustical conditions in the room (Lane and Mikeska, 1955; McCue and Talaske, 1990; Pirn, 1992; Aretz and Orlowski, 2009). Drama and speech require a lower reverberation time than music (Aretz and Orlowski, 2009). These variable acoustics can be achieved with the use of variable amounts of sound absorption or variable room volumes. However, the latter, in most cases, is not an option due to the relative high costs (Aretz and Orlowski, 2009), and small rooms ($V > 400$ m^3) have a limited range for variable acoustics (Valk et al., 2006). Also within the domain of orchestral music itself, different orchestra size and repertoire lead to different preferences for acoustics (Pirn, 1992; Teuber and Völker, 1993; Aretz and Orlowski, 2009; Arau-Puchades, 2012a and 2012b; Gade, 2012).

Research by O, Brien et al. (2008) on the orchestral noise environment within a professional symphony orchestra, attributed the greatest risk for excessive sustained noise levels to the brass instrument players and the greatest risk for excessive peak noise levels to the timpani and percussion players. With increasing orchestra size, it often are these sections that increase in number. These are also the sections that vary the most in quantity depending on the repertoire (Gade, 2012). Apart from orchestra size and repertoire, also the venue (e.g. rehearsal room, concert hall, orchestra pit) and position of a musician within the orchestra determine the noise exposure (O, Brien et al., 2008). Prior to the introduction of the new noise directive by the European Union (2003), Pirn (1992), Völker (1988), Tennhardt and Winkler (1995) and Zha et al. (2002) emphasized the challenge of reducing sound levels in music (rehearsal) rooms, without losing preferred acoustical conditions for playing ensemble. After 2003, also Aretz and Orlowski (2009), Koskinen et al. (2010), Pompoli et al. (2012), Arau-Puchades (2012a, 2012b) and Gade (2012) acknowledged this challenge, making the balance between acceptable sound levels and desired ensemble conditions a main preference for a good acoustical environment for music ensembles. The room volume V (Knudsen and Harris, 1950; Lane and Mikeska, 1955; Valk et al., 2006; Aretz and Orlowski, 2009; Pompoli et al., 2012; Arau-Puchades, 2012a and 2012b) and sound absorption A (Sabine, 1906; Pirn, 1992; Zha et al., 2002; Koskinen et al., 2010; Gade, 2012) are important acoustic parameters to achieve this. Together, V and A provide a certain reverberation time RT and sound strength G. Along with the room geometry, risers, reflectors and the distribution of sound absorption this provides a certain balance between early and late arriving sound components, determining the sound levels and ensemble conditions (Gade, 2012).

For performance venues, desired values for RT exist in literature. According to Völker (1988), Teuber and Völker (1993), Aretz and Orlowski (2009), Arau-Puchades (2012a and 2012b) and Gade (2012) the ideal acoustical conditions for rehearsal would be similar to those for performance. However, Aretz and Orlowski (2009) and Gade (2012) stated the reverberation time has to be lowered, by adding sound absorption, when a limited room volume leads to unacceptable sound levels/sound strength. Arau-Puchades (2012a and 2012b) tried to increase the acoustic volume, providing a higher reverberation time and early decay time and a lower sound strength, without altering the internal room dimensions. The first attempts seem promising, but further research and tests are necessary to understand an verify the effects. According to Patrick and Boner (1967), Pirn (1992), Tennhardt and Winkler (1995), and Pompoli et al. (2012), the ideal acoustical conditions for rehearsal would not be similar to those for performance. They stated, rehearsal is a training process where a critical analysis of the music and musicians is more important than the spatial sensation of the total music ensemble.

Finally, there is the difficulty of terminology. Blankenship et al. (1955) already emphasized the variation in used terminology by users (musicians), acousticians and architects to describe (desired) acoustical conditions in music (rehearsal) rooms. Vaughan (1982), McCue and Talaske (1990) and Teuber and Völker (1993) acknowledged the complexity of this communication, along with all the research using respondents for a subjective evaluation. Acousticians want to predict the desired acoustic environment with the use of (room) acoustic parameters, wherefore sometimes new parameters are defined. This desired acoustic environment is based on preferences of users of similar rooms, described in subjective words or phrases. To achieve this desired acoustic environment, the architects want simple design guidelines for dimensions and other architectural features. Even within each group, a large variety of terminology is used, making it difficult to interpret and compare various results.

To conclude, the last decade, the research topic of music rehearsal room acoustics is still present in journals and proceedings. So far, this research has led to some guidelines and rules of thumb from acoustical consultants and manufacturers of music room equipment, for room dimensions and amount of sound absorption, but not to legislation (building codes) on the architectural properties of rehearsal rooms. In contrary, legislation on sound exposure, intended to protect workers from risks "arising from noise owing to its effects on the health and safety of workers, in particular damage to hearing" (EU, 2003), was introduced in the member states of the European Union. This led to a research shift from the general acoustics of music rooms towards the sound exposure of (professional) musicians in small spaces. Most rehearsal spaces are limited in their dimensions because of the limited available budget. This leads to small rooms in comparison to performances spaces. With the same music ensemble (e.g. an orchestra) size and repertoire, there is a high risk of (too) loud sound levels in rehearsal spaces. This risk can be reduced/controlled with the proper use and amount of sound absorption. However, this increase in sound absorption leads to a decrease of the reverberation time for the same room volume.

Another aspect of rehearsal rooms is the large variety of users, not unusual for these rooms. Often, a rehearsal room is shared by different music ensembles, all with their own number of musicians, combination of instruments, musical style and corresponding repertoire. All these different users have their specific desires for the acoustical environment, leading to different acoustical requirements for one room. To some extent, compromises can be reached with the use of variable acoustics, but each room has its physical limitations and each building owner/user his budget limitations. One last challenging aspect is the communication about the desires, requirements, opportunities and limitations between all the stakeholders, because often each group uses their own terminology.

REFERENCES

H Arau-Puchades (2012a), "Increasing the Acoustic Volume of Performance Spaces without Altering the Internal Dimensions", Acta Acustica united with Acustica 98, 309-316

H Arau-Puchades (2012b), "The Refurbishment of the Orchestral Rehearsal Room of the Great Theater of Liceu", Building Acoustics 19(1), 45-56

M Aretz & R Orlowski (2009), "Sound strength and reverberation time in small concert halls", Appl. Acoust. 70, 1099-1110

J Blankenship, R Bernard Fitzgerald & RN Lane (1955), "Comparison of Objective and Subjective Observations on Music Rooms", J. Acoust. Soc. Am. 27(4), 774-780

E Carter (1955), "Music Building, Rooms and Equipment", Music Educators Natl. Conf., Washington D.C.

European Union (2003), "Directive 2003/10/EC of the European Parliament and of the Council of 6 February 2003 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (noise)", Official Journal of the EU L42, 38-44 (2003), retrieved January 10, 2013, from:
http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:042:0038:0044:EN:PDF

Federatie van Amateur Symfonie- en Strijkorkesten (2014), "Over FASO", general information 01-01-2014, retrieved January 21, 2014, from:
http://faso.eu/content/faso-federatie-van-amateur-symfonie-en-strijkorkesten

AC Gade (2012), "Sound levels in rehearsal and medium sized concert halls; are they too loud for the musicians?", Proceedings of ACOUSTICS 2012 HONG KONG

JA Kessler (1955), "On the Evaluation of Concert Halls and Music Rooms", J. Acoust. Soc. Am. 27, 205

VO Knudsen & CM Harris (1950), "Acoustical Design in Architecture", John Wiley & Sons Inc., New York

Koninklijke Nederlandse Muziek Organisatie (2013), "Nieuwe muziekkoepel voor amateurmuziek beklonken", news report VNM 08-12-2013, retrieved January 21, 2014, from:
http://www.vnm-nederland.nl/nieuws/0#145

H Koskinen, E Toppila & P Olkinuora (2010), "Facilities for Music Education and Their Acoustical Design", JOSE 16(1), 93-104

DC Lamberty (1980), "Music practice rooms", J. Sound Vib. 69(1), 149-155

Landelijk Kennisinstituut Cultuureducatie en Amateurkunst (2012), "Factsheet – Amateurkunst in Nederland 2012", retrieved January 21, 2014, from:
http://www.lkca.nl/downloads/AK_Factsheet_2012_ned.pdf

RN Lane & EE Mikeska (1955), "Study of Acoustical Requirements for Teaching Studios and Practice Rooms" J. Acoust. Soc. Am. 27(6), 1087-1091

AH Marshall, D Gottlob & H Alrutz (1978), "Acoustical conditions preferred for ensemble", J. Acoust. Soc. Am. 64(5), 1437-1442

E McCue & RH Talaske (1990), "Acoustical Design of Music Education Facilities", American Institute of Physics, New York

GM Naylor (1988), "The Achievement of Ensemble", Appl. Acoust. 23, 109-120

I O'Brien, W Wilson & A Bradley (2008), "Nature of orchestral noise", J. Acoust. Soc. Am. 124(2), 926-939

NG Patrick & CR Boner (1967), "Acoustics of School-Band Rehearsal Rooms", J. Acoust. Soc. Am. 41(1), 215-219

WC Sabine (1906), "Architectural Acoustics", Proceedings of the American Academy of Arts and Sciences, 42(2), 51-84

R Pirn (1992), "Some Objective and Subjective Aspects of Three Acoustically Variable Halls", Appl. Acoust. 35, 221-231

R Pompoli, N Prodi & A Farnetani (2012), "A Note on the Acoustics of Orchestra Rehearsal Rooms", Building Acoustics 19(1), 1-11

H-P Tennhardt & H Winkler (1995), "Untersuchungen zur raumakustischen Planung von Orchesterproberäumen", Acustica 81, 293-299

W Teuber & E-J Völker (1993), "Acoustical requirements and results for music rehearsal rooms", 94th AES Convention, Berlin, paper number 3549

K Ueno, K Kato & K Kawai (2010), "Effect of Room Acoustics on Musicians' Performance. Part I: Eperimental Investigation with a Conceptual Model", Acta Acustica united with Acustica 96, 505-515

M Valk, L Nijs & P Heringa (2006), "Het optimaliseren van de ruimteakoestiek voor de les- en oefenruimtes van het Conservatorium van Amsterdam", NAG journaal 178, 1-11

D Vaughan (1982), "The perception and appreciation of richness and timbre in rooms for music", Appl. Acoust. 15, 289-306

Vereniging van Nederlandse Korenorganisaties (2014), general information homepage, retrieved January 21, 2014, from: http://nederlandsekorenorganisaties.nl/

E-J Völker (1988), "Symphony orchestra rehearsal rooms – some aspects of acoustics and recording techniques", 84th AES Convention, Paris, paper number 2628

RW Young & RS Gales (1956), "Acoustics of School Music Rehearsal Rooms", J. Acoust. Soc. Am. 28, 791

X Zha, HV Fuchs & H Drotleff (2002), "Improving the acoustic working conditions for musicians in small spaces", Appl. Acoust. 64, 203-221

Appendix B – Measurement equipment and set-up

Ranking the ensemble conditions of music rooms intended for rehearsal using rhythmic sounds of indefinite pitch

In this Appendix, lists with the used measurement equipment and additional information about the measurement set-up are presented. Table 1 presents the measurement equipment used for the stage and room acoustic (impulse response) measurement, Table 2 the measurement equipment used to record the musical fragment and Table 3 the playback equipment used during the listening test. In Table 4, the 50 source-receiver combinations with their corresponding source to receiver distance, delay and limit value are given.

TABLE 1: MEASUREMENT EQUIPMENT STAGE AND ROOM ACOUSTIC MEASUREMENTS

Equipment	Manufacturer	Type / Model	ID / Serial number
Calibrator	Brüel & Kjær	4230	ID.1060
USB Audio Interface	Acoustics Engineering	Triton	Pro 001
Netbook	Dell	Latitude 2110	2PPD9M1
Acoustics measurement software	Acoustics Engineering	Dirac 5.5 (7841)	
Thermo/RH-meter	Lambrecht	Hydrolog-D	19813 008
Microphone power supply	Acoustics Engineering	DeltaTron	1 (custom made)
Measurement amplifier	Acoustics Engineering	Amphion	0101
Prepolarized free field microphone ½"	Brüel & Kjær	4189	2703329 (Ch.1)
Prepolarized free field microphone ½"	Brüel & Kjær	4189	2471031 (Ch.2)
Dodecahedron sound source	Acoustics Engineering	Pyrite	ID.1145

TABLE 2: MEASUREMENT EQUIPMENT RECORDINGS MUSICAL FRAGMENT

Equipment	Manufacturer	Type / Model	ID / Serial number
Microphone (IEC 60804:2000 Type 2)	RION	NL-21	ID. 0996
Calibrator	Brüel & Kjær	4230	ID.1060
USB Audio Interface	Acoustics Engineering	Triton	Pro 001
Netbook	Dell	Latitude 2110	2PPD9M1
Acoustics measurement software	Acoustics Engineering	Dirac 5.5 (7841)	
Thermo/RH-meter	Lambrecht	Hydrolog-D	19813 008
Head and Torso Simulator	Brüel & Kjær	4100	ID.1110
Metronome (& Tuner)	Clifton	WMT-555C	-
Microphone power supply	Acoustics Engineering	DeltaTron	1 (custom made)
Measurement amplifier	Acoustics Engineering	Amphion	0101
Headphones	Sennheiser	HD280 professional	3457261128
Snare drum	Adams	13" x 3.5" red copper shell	1335RK
Snare drum stand	-	-	-
Drum sticks	Pro-mark	Millennium II American Hickory 7A	TX7AW

TABLE 3: PLAYBACK EQUIPMENT LISTENING TEST

Equipment	Manufacturer	Type / Model	ID / Serial number
Headphones	Sennheiser	HD280 professional	3457261128
Notebook	Hewlett-Packard	EliteBook 8540w	CND0251NG8
Audio playback software	foobar2000	foobar2000 v1.1	-

TABLE 4: SOURCE-RECEIVER COMBINATIONS

Source	Receiver	S-R distance	Delay	Limit value
		[m]	[ms]	[ms]
1	1m	1.00	3	100
	2	1.84	5	98
	3	4.84	14	89
	4	6.62	19	84
	5	1.84	5	98
	6	4.84	14	89
	7	6.62	19	84
	8	3.86	11	92
	9	3.86	11	92
	10	6.80	20	83
2	1m	1.00	3	100
	1	1.84	5	98
	3	3.05	9	94
	4	5.00	15	88
	5	2.80	8	95
	6	5.73	17	86
	7	6.38	19	84
	8	2.40	7	96
	9	3.69	11	92
	10	5.77	17	86
3	1m	1.00	3	100
	1	4.84	14	89
	2	3.05	9	94
	4	3.86	11	92
	5	5.73	17	86
	6	8.40	25	78
	7	7.87	23	80
	8	3.05	9	94
	9	5.73	17	86
	10	6.08	18	85
4	1m	1.00	3	100
	1	6.62	19	84
	2	5.00	15	88
	3	3.86	11	92
	5	6.38	19	84
	6	7.87	23	80
	7	5.60	16	87
	8	2.78	8	95
	9	4.84	14	89
	10	2.91	9	94
8	1m	1.00	3	100
	1	3.86	11	92
	2	2.40	7	96
	3	3.05	9	94
	4	2.78	8	95
	5	3.69	11	92
	6	5.73	17	86
	7	4.84	14	89
	9	2.80	8	95
	10	3.49	10	93

LUISTERTEST 'MUSIC REHEARSAL ROOM ACOUSTICS'

Ranking the ensemble conditions of music rooms intended for rehearsal using rhythmic sounds of indefinite pitch.

VRAGENFORMULIER

Wat is uw leeftijd en geslacht?

[1] U hoort nu vijf *mezzo forte* fragmenten, opgenomen in vijf verschillende oefenruimtes op steeds dezelfde positie. In welke van deze ruimtes zou u het liefst repeteren met een muziekensemble? Zet de vijf fragmenten in volgorde van uw voorkeur, beginnend met de meest gewaardeerde.

Welk(e) muziekinstrument of –instrumenten bespeelt u?

[2] U hoort nu weer vijf *mezzo forte* fragmenten, opgenomen in vijf verschillende oefenruimtes op steeds dezelfde positie. In welke van deze ruimtes zou u het liefst repeteren met een muziekensemble? Zet de vijf fragmenten in volgorde van uw voorkeur, beginnend met de meest gewaardeerde.

Hoeveel jaren muzikale speelervaring heeft u en hoeveel jaren daarvan heeft u in groepsverband muziek beoefend?

[3] U hoort nu vijf *piano* fragmenten, opgenomen in vijf verschillende oefenruimtes op steeds dezelfde positie. In welke van deze ruimtes kunt u de muzikale details het beste onderscheiden? Zet de vijf fragmenten in volgorde van uw voorkeur, beginnend met de meest gewaardeerde.

In hoeveel verschillende muziekensembles bent u momenteel actief?
(*Inclusief projectmatige muziekensembles.*)

[4] U hoort nu weer vijf *piano* fragmenten, opgenomen in vijf verschillende oefenruimtes op steeds dezelfde positie. In welke van deze ruimtes kunt u de muzikale details het beste onderscheiden? Zet de vijf fragmenten in volgorde van uw voorkeur, beginnend met de meest gewaardeerde.

Wat is de samenstelling van de muziekensembles waarin u met regelmaat muziek beoefend? (*Meerdere opties mogelijk.*)

- □ Harmonieorkest
- □ Fanfareorkest
- □ Brassband
- □ Blaaskapel (dweilorkest)
- □ Slagwerkensemble
- □ Bigband
- □ Symfonieorkest
- □ Kamermuziekensemble (één instrumentsoort)
- □ Kamermuziekensemble (gemengde ensembles)
- □ Anders, namelijk…

[5] U hoort nu vijf *fortissimo* fragmenten, opgenomen in vijf verschillende oefenruimtes op steeds dezelfde positie. In welke van deze ruimtes is voor u de luidheid van dit *fortissimo* het beste te verdragen? Zet de vijf fragmenten in volgorde van uw voorkeur, beginnend met de meest gewaardeerde.

In hoeveel verschillende oefenruimtes repeteert u structureel (meer dan een enkele keer per jaar) in groepsverband?

- □ 1
- □ 2
- □ 3-5
- □ 6-10
- □ 11 of meer

[6] U hoort nu weer vijf *fortissimo* fragmenten opgenomen, in vijf verschillende oefenruimtes op steeds dezelfde positie. In welke van deze ruimtes is voor u de luidheid van dit *fortissimo* het beste te verdragen? Zet de vijf fragmenten in volgorde van uw voorkeur, beginnend met de meest gewaardeerde.

Appendix D – Measurement data extended support parameters

Ranking the ensemble conditions of music rooms intended for rehearsal using rhythmic sounds of indefinite pitch

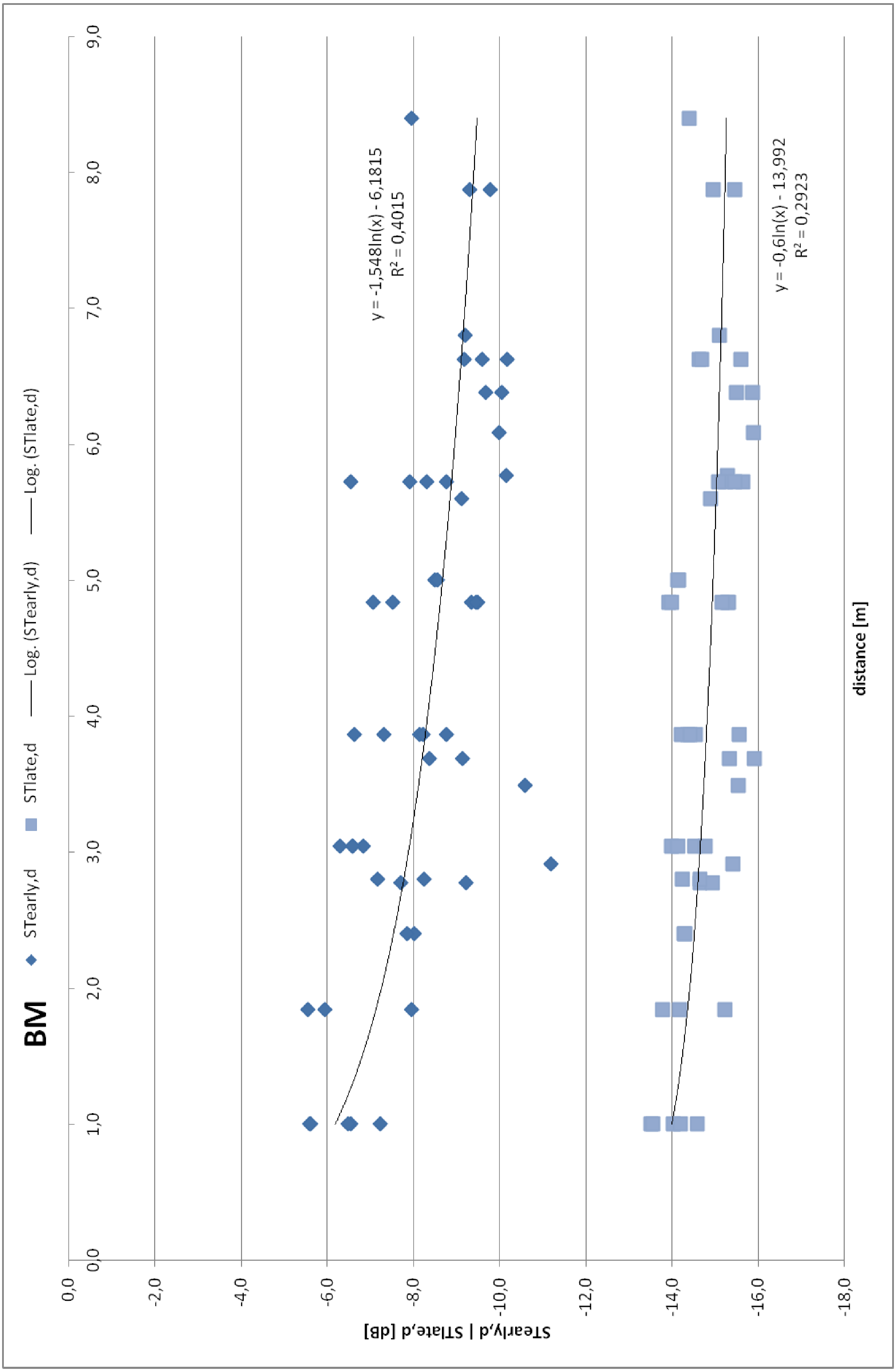
In this Appendix, the measurement data for the extended support parameters $ST_{early,d}$ and $ST_{late,d}$ is presented. On the first two pages, the calculated values for the extended support parameters are given for each measured source-receiver combination. On the subsequent pages, detailed graphs of these parameters are given for each room.

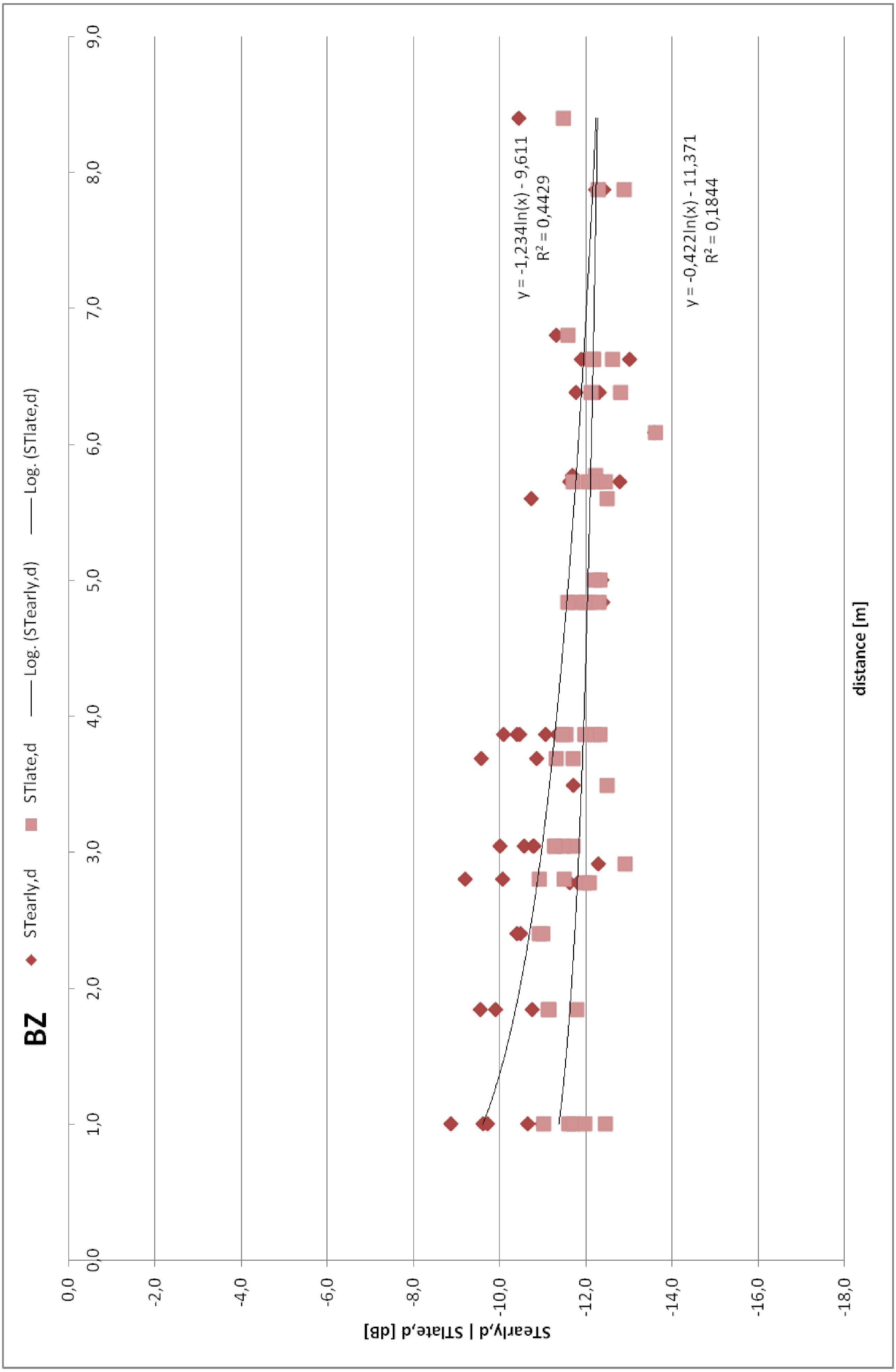
			BM		BZ		BK		HZ		ML	
S-R	**delay**	**distance**	**$ST_{early,d}$**	**$ST_{late,d}$**	**$ST_{early,d}$**	**$ST_{late,d}$**	**$ST_{early,d}$**	**$ST_{late,d}$**	**$ST_{early,d}$**	**$ST_{late,d}$**	**$ST_{early,d}$**	**$ST_{late,d}$**
	[ms]	**[m]**	**[dB]**	**[dB]**	**[dB]**	**[dB]**	**[dB]**	**[dB]**	**[dB]**	**[dB]**	**[dB]**	**[dB]**
S1R1m	3	1,0	-5,6	-13,5	-9,6	-11,0	-4,2	-10,6	-8,2	-10,2	-7,2	-14,3
S1R2	5	1,8	-6,0	-14,2	-9,6	-11,1	-5,0	-10,8	-9,4	-10,6	-7,5	-14,6
S1R5	5	1,8	-8,0	-15,2	-10,8	-11,8	-7,0	-12,3	-9,6	-11,8	-8,2	-15,2
S1R8	11	3,9	-7,3	-14,4	-10,4	-11,5	-6,1	-10,9	-9,4	-10,7	-8,1	-15,3
S1R9	11	3,9	-8,8	-15,6	-10,5	-12,0	-7,9	-12,0	-10,3	-11,5	-8,9	-15,4
S1R3	14	4,8	-7,1	-13,9	-11,9	-11,8	-5,9	-10,8	-9,2	-10,5	-7,6	-14,5
S1R6	14	4,8	-9,3	-15,3	-11,7	-12,0	-7,3	-12,3	-10,2	-11,7	-8,0	-15,3
S1R4	19	6,6	-9,6	-14,6	-12,0	-12,2	-6,7	-11,1	-9,7	-11,2	-9,3	-15,4
S1R7	19	6,6	-10,2	-15,6	-13,0	-12,6	-8,6	-12,5	-11,2	-11,9	-10,0	-15,7
S1R10	20	6,8	-9,2	-15,1	-11,3	-11,6	-8,2	-11,8	-10,8	-11,8	-11,1	-15,3
S2R1m	3	1,0	-5,6	-14,0	-8,9	-11,6	-4,2	-10,5	-8,2	-10,5	-7,3	-14,6
S2R1	5	1,8	-5,5	-13,8	-9,9	-11,1	-4,8	-11,1	-9,1	-10,7	-7,1	-14,3
S2R8	7	2,4	-8,0	-14,3	-10,5	-10,9	-4,8	-10,8	-9,2	-10,5	-8,4	-15,0
S2R5	8	2,8	-7,2	-14,2	-9,2	-10,9	-6,5	-12,1	-9,7	-11,4	-8,0	-14,6
S2R3	9	3,0	-6,8	-14,0	-10,0	-11,7	-5,2	-10,9	-8,9	-10,6	-8,0	-14,7
S2R9	11	3,7	-8,4	-15,3	-10,8	-11,7	-7,6	-12,0	-10,1	-11,1	-8,5	-15,4
S2R4	15	5,0	-8,5	-14,1	-12,4	-12,3	-5,9	-10,8	-9,1	-10,2	-10,2	-15,0
S2R10	17	5,8	-10,2	-15,3	-11,7	-12,2	-7,3	-11,5	-10,7	-12,3	-10,8	-15,3
S2R6	17	5,7	-8,3	-15,2	-12,2	-11,7	-8,0	-12,0	-9,7	-11,9	-8,7	-14,5
S2R7	19	6,4	-10,0	-15,9	-12,3	-12,1	-8,6	-12,4	-10,7	-11,6	-10,4	-15,8
S3R1m	3	1,0	-6,5	-14,2	-11,0	-11,7	-4,2	-11,0	-7,5	-11,0	-7,9	-15,0
S3R2	9	3,0	-6,6	-14,1	-10,8	-11,5	-4,9	-10,7	-8,6	-11,0	-8,0	-15,0
S3R8	9	3,0	-6,3	-14,5	-10,6	-11,3	-5,4	-10,7	-8,9	-10,3	-9,3	-15,1
S3R4	11	3,9	-8,1	-14,2	-11,3	-12,2	-5,6	-11,4	-9,4	-10,7	-9,3	-15,9
S3R1	14	4,8	-7,5	-14,0	-12,1	-11,6	-6,2	-10,9	-9,5	-10,7	-7,7	-13,9
S3R5	17	5,7	-8,8	-15,1	-12,4	-12,2	-6,7	-12,4	-9,6	-12,1	-9,0	-14,6
S3R9	17	5,7	-6,5	-15,6	-12,8	-12,1	-7,3	-11,9	-10,0	-11,5	-9,8	-15,5
S3R10	18	6,1	-10,0	-15,9	-13,6	-13,6	-8,7	-12,6	-11,2	-11,7	-12,3	-15,8
S3R7	23	7,9	-9,8	-15,4	-12,4	-12,3	-7,7	-12,6	-11,0	-11,7	-11,7	-14,8
S3R6	25	8,4	-7,9	-14,4	-10,4	-11,5	-8,0	-12,3	-9,6	-11,0	-7,3	-14,3

Appendix D – Measurement data extended support parameters

Ranking the ensemble conditions of music rooms intended for rehearsal using rhythmic sounds of indefinite pitch

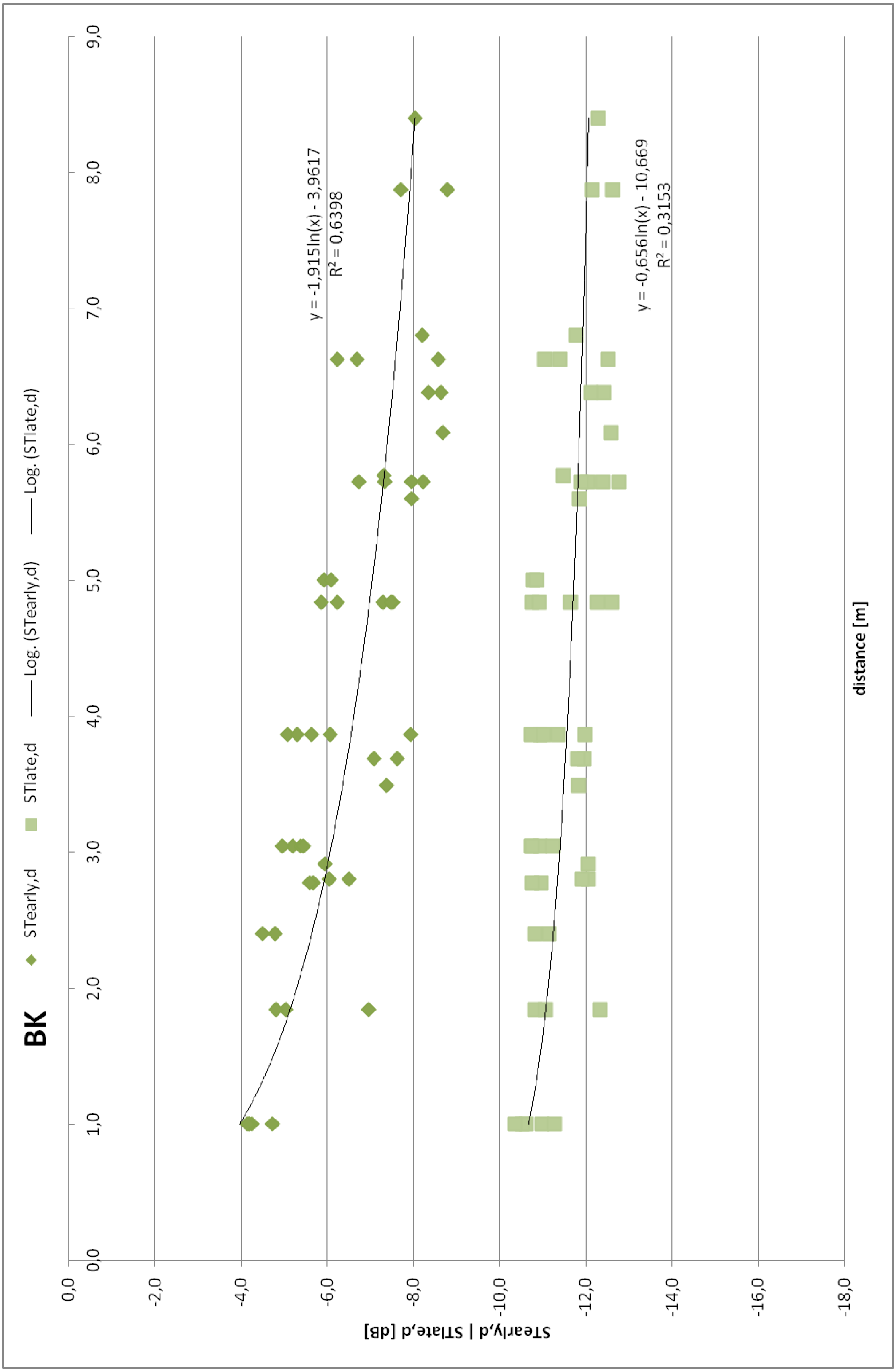
			BM		BZ		BK		HZ		ML	
S-R	**delay**	**distance**	$ST_{early,d}$	$ST_{late,d}$	$ST_{early,d}$	$ST_{late,d}$	$ST_{early,d}$	$ST_{late,d}$	$ST_{early,d}$	$ST_{late,d}$	$ST_{early,d}$	$ST_{late,d}$
	[ms]	**[m]**	**[dB]**	**[dB]**	**[dB]**	**[dB]**	**[dB]**	**[dB]**	**[dB]**	**[dB]**	**[dB]**	**[dB]**
S4R1m	3	1,0	-7,2	-13,6	-9,7	-12,5	-4,7	-11,3	-8,4	-10,1	-9,0	-15,7
S4R8	8	2,8	-7,7	-14,7	-11,6	-12,0	-5,7	-11,0	-9,8	-10,7	-9,9	-15,0
S4R10	9	2,9	-11,2	-15,4	-12,3	-12,9	-5,9	-12,0	-10,4	-11,6	-12,8	-15,9
S4R3	11	3,9	-8,2	-14,5	-11,1	-12,3	-5,1	-10,7	-9,7	-10,8	-9,4	-15,9
S4R9	14	4,8	-9,5	-15,3	-11,9	-12,1	-7,5	-11,6	-10,8	-11,8	-10,7	-16,2
S4R2	15	5,0	-8,5	-14,2	-12,3	-12,2	-6,1	-10,9	-8,9	-10,3	-9,8	-15,2
S4R7	16	5,6	-9,1	-14,9	-10,7	-12,5	-8,0	-11,8	-10,6	-11,5	-12,3	-15,3
S4R1	19	6,6	-9,2	-14,7	-11,9	-12,2	-6,2	-11,4	-9,3	-10,9	-9,4	-15,0
S4R5	19	6,4	-9,7	-15,5	-11,8	-12,8	-8,4	-12,1	-10,4	-12,0	-10,5	-15,7
S4R6	23	7,9	-9,3	-15,0	-12,2	-12,9	-8,8	-12,1	-9,8	-11,4	-11,6	-15,4
S8R1m	3	1,0	-6,5	-14,6	-10,6	-12,0	-4,1	-10,4	-7,7	-10,5	-9,0	-14,7
S8R2	7	2,4	-7,9	-14,3	-10,4	-11,0	-4,5	-11,2	-9,0	-10,7	-8,3	-14,7
S8R4	8	2,8	-9,2	-14,9	-11,8	-12,1	-5,6	-10,8	-9,0	-10,4	-9,9	-15,3
S8R9	8	2,8	-8,2	-14,7	-10,1	-11,5	-6,0	-11,9	-9,5	-11,6	-10,4	-15,2
S8R3	9	3,0	-6,6	-14,8	-10,8	-11,3	-5,4	-11,2	-9,2	-10,6	-9,6	-15,1
S8R10	10	3,5	-10,6	-15,5	-11,7	-12,5	-7,4	-11,8	-10,7	-12,4	-11,9	-15,2
S8R1	11	3,9	-6,6	-14,4	-10,1	-11,5	-5,3	-11,0	-9,2	-10,7	-8,1	-15,0
S8R5	11	3,7	-9,1	-15,9	-9,6	-11,3	-7,1	-11,8	-9,6	-11,4	-9,1	-15,5
S8R7	14	4,8	-9,5	-15,2	-12,4	-12,3	-7,5	-12,6	-10,7	-11,8	-10,9	-15,4
S8R6	17	5,7	-7,9	-15,5	-11,6	-12,4	-8,2	-12,8	-10,8	-11,4	-9,2	-15,6
MEAN	12,3	4,2	-8,2	-14,8	-11,2	-11,9	-6,4	-11,5	-9,6	-11,1	-9,3	-15,1


BM
STearly,d
STlate,d
Log. (STearly,d)
Log. (STlate,d)
y = -1,548ln(x) - 6,1815
R² = 0,4015
y = -0,6ln(x) - 13,992
R² = 0,2923
STearly,d | STlate,d [dB]
distance [m]
0,0
-2,0
-4,0
-6,0
-8,0
-10,0
-12,0
-14,0
-16,0
-18,0
0,0
1,0
2,0
3,0
4,0
5,0
6,0
7,0
8,0
9,0


BZ
STearly,d
STlate,d
Log. (STearly,d)
Log. (STlate,d)
y = -1,234ln(x) - 9,611
R² = 0,4429
y = -0,422ln(x) - 11,371
R² = 0,1844
distance [m]
STearly,d | STlate,d [dB]
0,0
1,0
2,0
3,0
4,0
5,0
6,0
7,0
8,0
9,0
0,0
-2,0
-4,0
-6,0
-8,0
-10,0
-12,0
-14,0
-16,0
-18,0

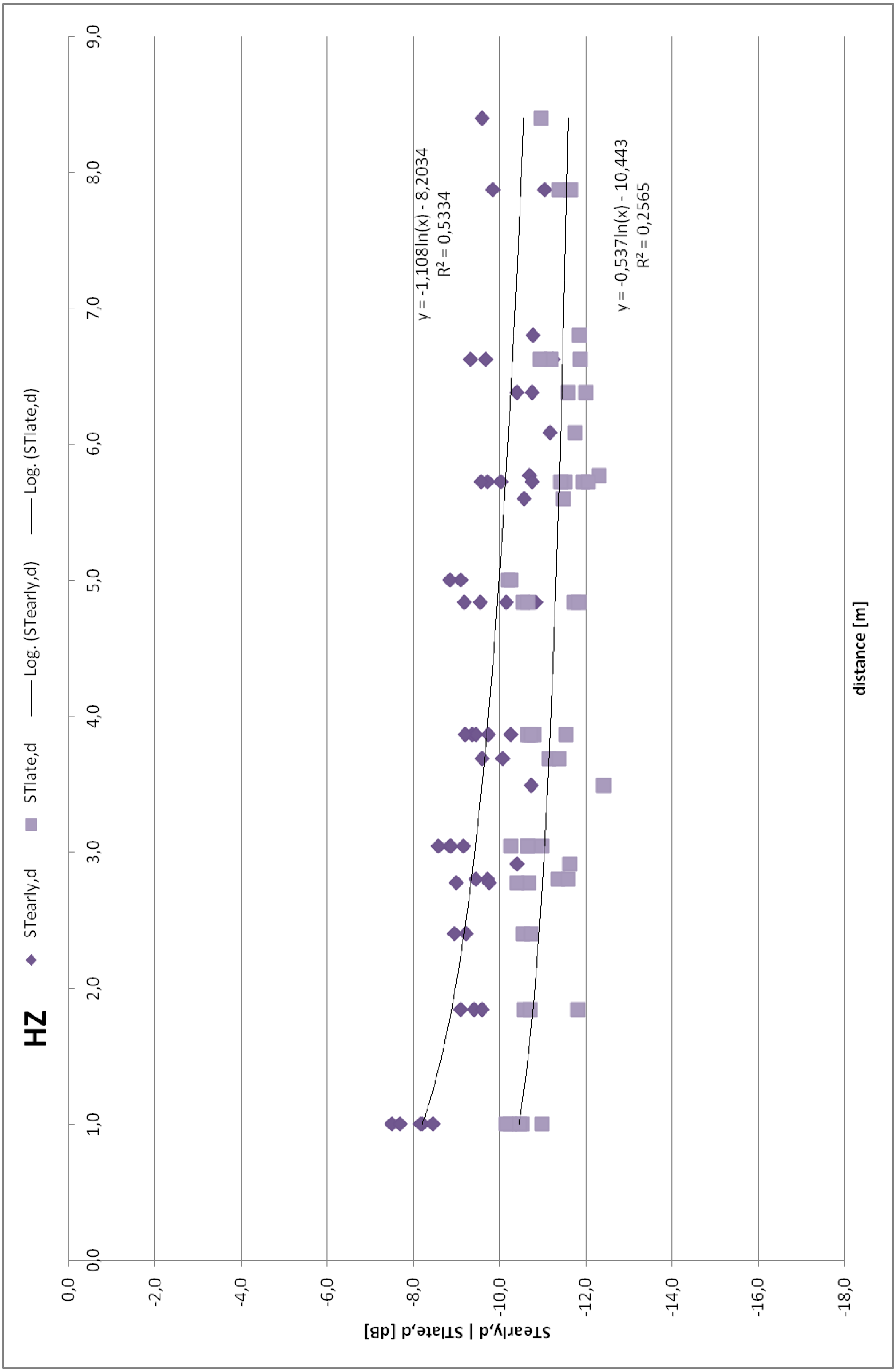
Appendix D – Measurement data extended support parameters

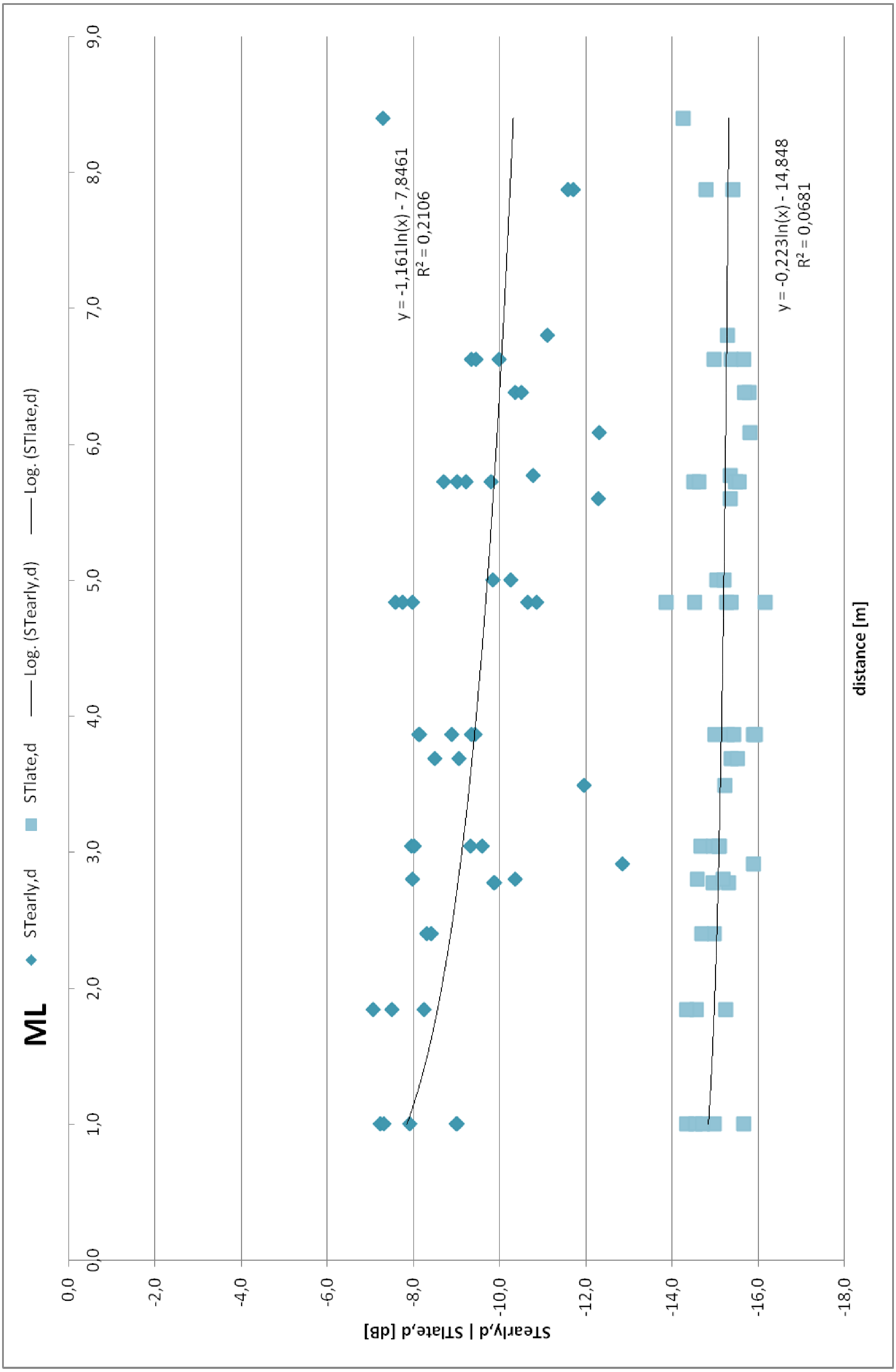
Ranking the ensemble conditions of music rooms intended for rehearsal using rhythmic sounds of indefinite pitch



Appendix D – Measurement data extended support parameters

Ranking the ensemble conditions of music rooms intended for rehearsal using rhythmic sounds of indefinite pitch




ML
STearly,d
STlate,d
Log. (STearly,d)
Log. (STlate,d)
y = -1,161ln(x) - 7,8461
R² = 0,2106
y = -0,223ln(x) - 14,848
R² = 0,0681
distance [m]
STearly,d | STlate,d [dB]
0,0
1,0
2,0
3,0
4,0
5,0
6,0
7,0
8,0
9,0
-2,0
-4,0
-6,0
-8,0
-10,0
-12,0
-14,0
-16,0
-18,0

Appendix E – Listening test responses

Ranking the ensemble conditions of music rooms intended for rehearsal using rhythmic sounds of indefinite pitch

In this Appendix, the responses from the 24 test persons to the listening test are presented. On the first page, the rankings for each of the six listening conditions are given. In the second row from the top are the ranking positions 1 to 5, with 1 being the most favorable and 5 being the least favorable. Each ranking position column has 24 entries. The entry value (1 to 5) corresponds with the order in which the recordings were played back to the test persons. For each listening condition, this order was different. Thus, the five test rooms are represented by a varying entry value for each listening condition.

	1) mf R4					2) mf R2					3) p R4					4) p R2					5) ff R4					6) ff R2				
#	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
1	5	4	2	3	1	3	1	5	4	2	2	1	5	3	4	4	1	5	3	2	4	1	3	2	5	5	4	1	2	3
2	4	2	3	1	5	3	2	1	5	4	2	1	3	5	4	4	1	2	5	3	4	2	5	1	3	2	5	4	1	3
3	2	4	5	3	1	5	2	1	3	4	1	4	2	3	5	1	3	5	4	2	1	3	2	4	5	1	5	2	4	3
4	2	5	3	1	4	3	2	1	5	4	5	4	2	3	1	1	2	5	3	4	1	4	2	5	3	1	2	4	5	3
5	4	1	5	2	3	3	1	4	2	5	5	1	4	2	3	4	1	3	5	2	1	4	5	3	2	5	4	2	1	3
6	4	5	2	3	1	1	2	4	5	3	2	1	3	4	5	2	4	1	3	5	2	1	4	5	3	1	4	2	5	3
7	3	5	1	2	4	3	1	4	2	5	1	5	2	3	4	1	2	4	3	5	2	4	1	3	5	4	5	1	2	3
8	4	5	2	1	3	3	5	2	4	1	4	5	2	1	3	1	3	2	4	5	2	1	4	3	5	5	4	2	1	3
9	2	4	1	5	3	4	3	5	2	1	5	4	2	3	1	1	5	3	4	2	1	3	5	4	2	1	5	2	3	4
10	4	2	1	5	3	4	5	3	2	1	4	3	2	5	1	1	4	5	3	2	4	3	2	1	5	5	2	1	4	3
11	4	2	5	1	3	2	1	3	5	4	2	5	1	4	3	1	3	2	4	5	1	2	4	3	5	4	5	2	1	3
12	2	5	3	1	4	1	3	5	2	4	5	4	1	2	3	1	4	2	3	5	1	2	3	4	5	5	4	1	2	3
13	5	3	4	1	2	3	1	2	5	4	3	5	1	4	2	4	5	1	3	2	4	2	1	3	5	3	2	5	4	1
14	2	3	4	5	1	4	3	1	5	2	5	2	1	3	4	3	1	4	5	2	4	5	1	3	2	5	4	1	2	3
15	5	2	3	4	1	3	2	1	5	4	2	1	5	3	4	1	4	2	5	3	4	2	1	5	3	4	3	5	1	2
16	5	3	4	2	1	3	1	2	5	4	2	1	3	5	4	1	4	5	2	3	4	3	1	2	5	5	1	2	4	3
17	1	2	5	4	3	2	3	1	5	4	3	2	1	5	4	1	3	5	2	4	2	1	3	4	5	4	5	1	2	3
18	5	4	3	2	1	1	3	4	2	5	1	2	3	4	5	1	3	2	4	5	1	2	4	5	3	5	2	4	1	3
19	1	5	2	4	3	2	1	4	3	5	2	5	3	4	1	1	3	5	2	4	3	1	4	5	2	2	5	1	3	4
20	5	2	3	4	1	1	3	2	5	4	1	2	5	3	4	4	1	5	3	2	1	3	2	4	5	1	2	5	4	3
21	3	5	2	1	4	2	1	3	4	5	1	3	2	5	4	2	1	4	3	5	4	2	3	1	5	4	5	1	2	3
22	3	2	5	4	1	1	3	2	4	5	2	3	1	4	5	1	4	5	2	3	1	3	2	4	5	1	2	3	5	4
23	4	5	3	1	2	3	2	5	1	4	5	1	2	4	3	1	3	4	2	5	4	2	1	5	3	5	2	1	4	3
24	2	3	1	5	4	3	1	5	2	4	2	3	5	1	4	1	3	4	5	2	4	3	5	2	1	4	3	5	1	2

Appendix E – Listening test responses

Ranking the ensemble conditions of music rooms intended for rehearsal using rhythmic sounds of indefinite pitch

On this page, the responses to the general questions, as part of the question form for the listening test, are given. The question form was in Dutch, so are these responses.

# Respondent	**Leeftijd**	**Geslacht**	**Muziekinstrument**	**Jaren speelervaring**	waarvan in groepsverband	**Muziekensembles momenteel actief**	**Soort muziekensemble**	Harmonieorkest	Fanfareorkest	Brassband	Blaaskapel (dweilorkest)	Slagwerkensemble	Bigband	Symfonieorkest	Kamermuziekensemble (één instrumentsoort)	Kamermuziekensemble (gemengd ensemble)	**Verschillende oefenruimtes per jaar**	1	2	3 - 5	6 - 10	11 of meer
1	26	m	slagwerk	19	17	6		x			x	x		x						x		
2	26	m	trompet	19	18	4		x			x		x							x		
3	28	m	trombone	21	18	5		x			x										x	
4	26	v	euphonium	20	17	4		x	x		x					x				x		
5	29	v	blokfluit	21	18	3									x					x		
6	26	m	euphonium	18	15	4		x			x									x		
7	34	m	(bas)klarinet	23	16	2		x												x		
8	26	m	altsaxofoon	18	16	6		x	x							x					x	
9	24	v	klarinet	15	13	1		x			x								x			
10	21	m	trompet	13	10	2		x			x			x	x					x		
11	21	v	(contra)fagot	14	11	2		x						x					x			
12	25	v	klarinet	17	14	2		x												x		
13	28	m	slagwerk	20	19	5		x			x			x							x	
14	27	v	altsaxofoon	20	19	1		x										x				
15	20	m	trompet	12	11	2		x						x					x			
16	24	m	hoorn	14	12	2		x	x											x		
17	26	m	cello	19	8	1								x		x			x			
18	24	v	dwarsfluit	14	12	2		x												x		
19	36	m	trombone	20	18	1								x				x				
20	20	v	altsaxofoon	13	11	1		x											x			
21	20	v	altsaxofoon	12	8	2		x			x									x		
22	26	m	klarinet	15	7	1		x											x			
23	30	v	klarinet	21	17	1		x											x			
24	30	m	klarinet	21	18	2		x												x		