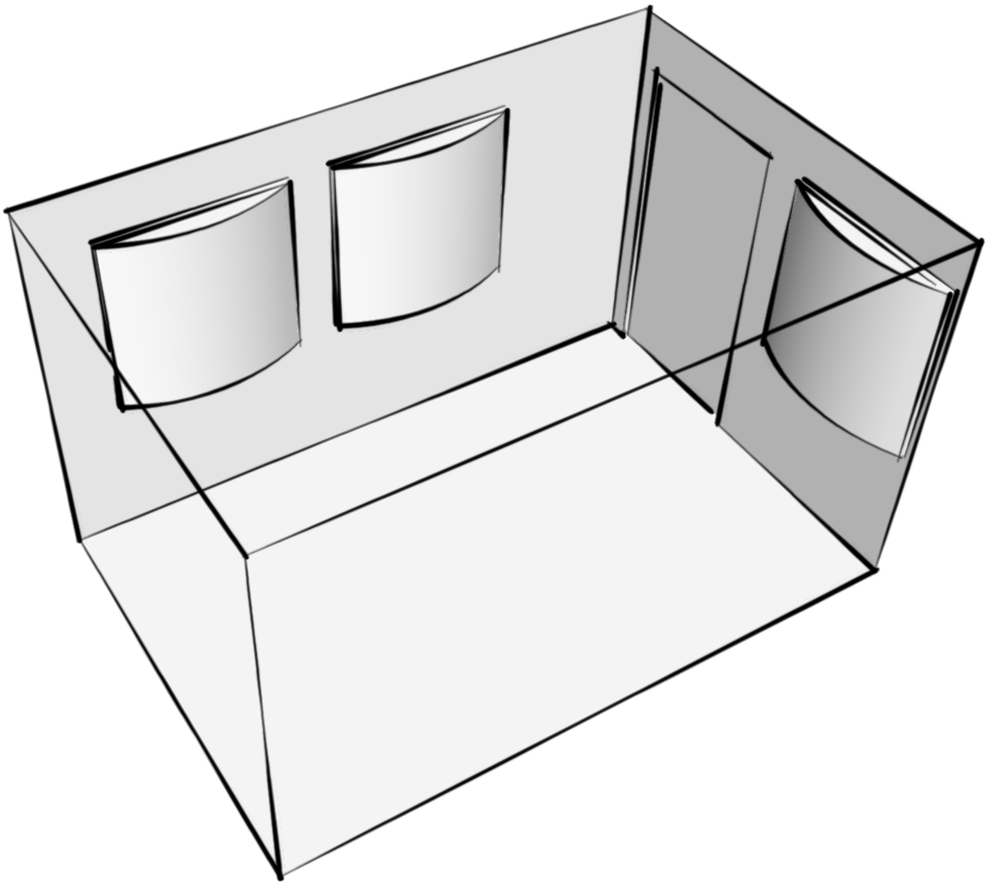

Diffusers in Small Practice Rooms

The effect of adding semi-cylinder diffusers in small practice rooms intended for music rehearsal

Master's thesis in Sound and Vibration

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2023
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Master's thesis 2023

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Cover: Sketchup model of the small practice room used in the investigation.

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Abstract

This master's thesis investigates the acoustical effects on the sound field of a small practice room when adding semi-cylinder diffusers. The study mainly seeks to determine whether general principles and applications for diffusers, proven to be effective in larger spaces, can be applied with satisfactory results to smaller rooms such as small practice rooms.

A combination of subjective and objective investigations was performed to investigate this topic. The subjective investigations involved on-site evaluations by musicians, as well as a blind test where participants listened to binaural recordings of different combinations of diffuser setups. The objective investigations involved measurements of room acoustical parameters, as well as a binaural impulse response measurement to study early reflections.

The findings suggest that semi-cylinder diffusers were not effective in removing coloration due to comb-filtering effects in a small practice room. While strong reflections were attenuated, and the number of reflections increased, the attenuation may not have been enough, and the introduced reflections might have been too strong, as a consequence of the small area of the practice room. This may have caused the frequency response to exhibit an even more distinct comb-filtering pattern, indicating more coloration. However, the increase in coloration may be seen as minor as there were no indications that any coloration was heard by the participants. The findings suggest on the contrary that participants preferred the setups with more diffusers. However, this improvement may have been attributed to a lowering of the reverberation time, where the semi-cylinder diffusers were found to provide membrane absorption in the lower frequency region, and absorption in the higher frequency region from a lowering of the mean-free-path.

Keywords: diffusers, diffusion, small practice rooms, semi-cylinder diffuser, poly diffuser, curve diffusers, acoustics of small practice rooms, coloration, comb-filtering effects, reflections.

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Christopher Herrey, Gothenburg, June 30, 2023

List of Definitions

Below is the list of definitions that frequently have been used throughout this thesis listed in alphabetical order:

ANOVA	Analysis of variance, which is used in order to determine if a set of values can be assumed to have statistical significance.
Artemis sQala	A listening environment software developed by Headacoustics used for listening tests.
Centre-time	Relates the balance between clarity and reverberance. Is defined as: $$Ts = \left(\frac{\int\limits_0^\infty tp^2(t)dt}{\int\limits_0^\infty p^2(t)dt} \right)$$
Chi-Square goodness-of-fit	A statistical measurement similar to ANOVA, but that compares a set of data with only two possible answers.
Clarity	A measure on the early-to-late arriving sound energy ratio. Is calculated for either 50 ms or 80 ms depending on whether the results are intended to relate to conditions for speech or music. In this report C_{50} will be used exclusively due to the small size of the practice room. $$C_{50} = 10log_{10} \left(\frac{\int\limits_0^{50ms} p^2(t)dt}{\int\limits_{50ms}^\infty p^2(t)dt} \right)$$

Coloration	Coloration is defined as when the audible sound is detrimentally altered due to a comb-filtering pattern in the frequency response.
Confidence interval using a student's t-distribution	The estimated interval within which 95% of a population is expected to respond. Student's t-distribution is suited for smaller samples.
Decay Range	The backwards integrated impulse response, which is the signal-to-noise ratio of the impulse response.
Definition	Is similar to C_{50}, but measures the early-to-total energy ratio. $D_{50} = 100 \left(\frac{\int_{0}^{50ms} p^2(t)dt}{\int_{0}^{\infty} p^2(t)dt} \right)$
EDT	Early Decay Time. Is the decay time for early reflections, obtained for the decay curve for the first -10dB of the direct sound.
Haas fusion zone	The time interval where a reflection is indistinguishable from the direct sound. In this report 35 ms is used as the threshold, but it may also vary depending on strength and properties of the reflected wave.
MATLAB	A programming and numeric computing platform.
Mean-free-path	The average length of all reflections in an enclosed space.
Null hypothesis	Is used in statistics to explain correlation. If the null hypothesis is fulfilled, no statistical correlation exist.

Schroeder frequency	The Schroeder frequency is the frequency limit for when a room can be assumed to be diffuse. Modal behavior dominates a room below the Schroeder frequency. The Schroeder frequency is defined as $f_s = 2000\frac{T}{V}$, where T is reverberation time, and V is the volume of the room.
Semi-cylinder diffuser	A type of spatial diffuser which is convex cylinder shaped. It may also be known as poly cylinder diffuser, or curve diffuser.
Spatial dispersion	One way in which a diffuser may disperse sound and essentially breaks up the incoming wave into many different reflected waves which are scattered into many different directions.
Strength	Sound pressure of the impulse response relative to the sound pressure measured in free field 10 m away from the source. Early strength is used throught out this thesis and is defined as: $G_{early} = 10log_{10}\left(\frac{\int\limits_{0}^{80ms} p^2(t)dt}{\int\limits_{0}^{\infty} p_{10}^2(t)dt}\right)$
Temporal dispersion	One way in which a diffuser may disperse sound and essentially breaks up the incoming wave into many different reflected waves separated by a phase shift.
T20	Estimated reverberation time in seconds, for the decay curve from -5 to -25 dB below the sound pressure level of the direct sound and then multiplied by 3.

Contents

List of Figures

List of Tables

1

Introduction

1.1 Background

Small practice rooms are spaces in which musicians individually may practice their instruments. They are prevalent at most music facilities and typically have a floor area ranging from 10 m^2 - 15m^2. Musicians spend a lot of time practicing their instruments in them and it is therefore important that they are designed so that good acoustics is obtained. This include a sound pressure level that is not harmful for the ear, an even frequency response that enables the musician to get accurate feedback from their instruments, and a pleasant timbre and reverberation time.

Perceived sound in a room is a combination of direct sound from the source and indirect sound reflected on surfaces. This combination of direct and indirect sound shapes the acoustics of a space. Reflections affects the time signal and reverberation time of the room, but they may also shape the characteristic of the sound in the frequency domain. When studying the case where an early reflected sound wave from a broad banded noise coincides with its direct sound wave, an interference pattern will be seen in the frequency domain. Depending on the properties of the direct and reflected sound the interference pattern will be more or less prominent.

This interference pattern is referred to as a comb filter and will have distinct peaks and dips evenly distributed for amplitudes of frequencies in the frequency domain. When the sound is detrimentally altered from comb-filter effects it is denoted as coloration of the sound. This coloration is very audible and unfavourable for the acoustics of a space. Coloration is especially prominent when the distance between direct and reflected sound is short. For small practice rooms, coloration may therefore be prevalent at practically every position of the room due to their small size. Measurements have shown that in order to avoid strong coloration the early reflection should have a sound pressure level at least 20 dB lower than the sound pressure level of the direct sound.

One way of reducing the sound pressure level of the reflected sound, and thus reduce effects of coloration, is by means of diffusion. Diffusion disperses the reflected wave into many directions, which reduces the amplitude of the reflected wave without removing sound energy from the room. This has the benefit that the reverberation time of a room can be preserved, one that is already very low in small practice rooms.

Very little study has been made on diffusers in small practice rooms and applications of diffusers in small practice rooms seems be based mostly on precedence and intuition of what works in concert halls, larger ensemble rooms as well as music reproduction rooms. Investigating the effects of diffusers in small practice rooms, both subjectively and objectively, is therefore of interest in order to find out if the general principles and applications of diffusers can be applied into small rooms such as small practice rooms. This master thesis therefore sets out to investigate the effects of diffusers in small practice rooms and their effects on the subjective experience and objective analysis on the sound field and acoustics of small practice rooms.

1.2 Aim

The aim of this master thesis is to investigate diffusers in small music practice rooms. The following questions will be answered throughout the investigation of the master thesis:

- Can the general principles and applications of diffusers be applied to small practice rooms?
- How does the acoustical sound field change objectively and subjectively in a small practice room when increasing the amount of diffusers?
- Does the usage of diffusers yield favourable results compared to other acoustical treatment solutions in a small practice room?

1.3 Limitations

There exists a large amount of different diffusers, and in order to limit the investigation a decision was made to only study the effects of semi-cylinder diffusers. When doing site visits around music facilities it was found that the semi-cylinder diffusers was a relatively common diffuser to use in small practice rooms in Gothenburg. The investigation is further limited to one small practice room at the temporary facilities of the Gothenburg Academy of Music and Drama. The investigations of the master thesis include both subjective and objective investigations. The main focus was however on the subjective experience of diffusers in small practice rooms, and the objective measurements was therefore made as a means to support the subjective results.

Further limitations include type of instruments used in this investigation. The relevant standard used in the design of small practice rooms, ISO 23591:2021, divides type of instrument into three categories; Quiet, Loud and Amplified, which is then used in the design process. Ideally the investigation would be restricted to one type of instrument class, however, due to a limitation in amount of participants, instruments was used from all categories.

1.4 Previous research

While the research is not in abundance, there are still some investigations which can be found on diffusers in small rooms. The same can be said for relating research which can be studied as to gain an understanding of how the sound field of a room is affected when diffusers are used in small practice rooms. This include both literature from books and papers as well as earlier master theses.

Earlier master theses which have been looked at and which investigates topics closely related to this master thesis are:

- *Rehearsal Rooms for Acoustical Instruments - Comparing Measurements and Subjective Experiences* by Sandaker.
- *Does the type of Diffuser matter?* by Fehlhaber.
- *Perceived Sound Qualities for Trumpet Players in Practice Rooms* by Olsson and Söderström.

Much of the literature from books on the subject is found from the research conducted by Trevor J. Cox and Peter D'Antonio. They condensed a substantial amount of the research done on diffusers by them and others in the book *Acoustic Absorbers and Diffusers*, first released in 2002. The functionality of absorbers and diffusers are discussed in detail by them as well as diffuser application in rooms. Diffuser application is mainly focused on rooms relating to music production and only contains a small portion on music practice rooms.

Further research on coloration and the subjective experience of musicians has been made by Tor Halmrast and additional literature on diffusion in small rooms is made by Mendel Kleiner and Jiri Tichy published in the book *Acoustics of Small Rooms.* In Acoustics of Small Rooms the authors describe sound fields in small rooms, and how the perception of sound in small rooms is influenced by different parameters. Much of the content on diffusers in the book is referring to the research done by Cox and D'Antonio. Acoustics of Small Rooms also contains a small section on diffusers in small practice rooms. Additional literature which provides useful basic acoustical theory that has been studied is *Master Handbook of Acoustics* by Everest and Pohlmann. The content of the previous research will be presented in section 2.2 which presents the literature study.

2

Theory

2.1 Basic acoustic theory in small rooms

As an introduction to the master thesis, basic acoustic theory related to acoustics of small rooms is introduced. This section aims at providing the reader with basic acoustic concepts that are necessary to understand in order to follow the context of the report. Notice that some definitions which are later used in the results are excluded from theory and instead presented in definitions, which can be found in the beginning of the report.

2.1.1 Sound pressure level

Sound pressure is one of the most useful and important quantities in the field of acoustics. Any disturbance in a medium, for instance air, causes energy to be built up which creates pressure fluctuations. These pressure fluctuations travel in a wave-like pattern until the energy eventually has been diminished [1]. Pressure fluctuations are perceived because of the ability of the inner ear to convert pressure acting on the eardrum to signals that the brain can interpret [2]. Due to the high sensitivity of the ear, sound pressure as a measurement is most often represented in a logarithmic scale with the lowest amount of pressure that the ear can perceive as the reference value. Sound pressure represented in this logarithmic scale is known as the sound pressure level.

2.1.2 Frequency components

The fluctuation speed at which the sound pressure fluctuates on the eardrum determines the pitch, or the frequency, of the perceived sound. When the pressure which acts on the eardrum fluctuates in a regular and periodic pattern a pure tone is perceived. If the fluctuations are fast the tone is high pitched and if the fluctuations are slow the pitch is low. Normally the sound pressure which acts on the eardrum has a periodic complex waveform rather than a regular periodic waveform, a consequence of the complexity of the pressure in a medium. The pressure in a medium is complex because the pressure fluctuations come from many different sources and are excited in many different ways. Any complex periodic waveform can however be separated into periodic regular waveforms using the Fourier transform so that individual frequencies with different, amplitudes and phase relationships can be discerned. This makes it possible to analyze sound not only in the time domain but also in the frequency domain [3].

2.1.3 Reflections

When a sound wave encounters a surface, a portion of the energy of the sound wave will be absorbed by that surface, while the rest will be reflected off the surface. In an enclosed space, such as a room, the direct sound will encounter walls, ceiling, and floor and the reflections will continue to be reflected upon surfaces until the energy eventually has been diminished by surface or air absorption [4].

The energy decay of the reflections is what creates the reverberation time of a room [5]. Reverberation time is defined as the time duration for the sound energy of the reflections to decrease with a sound pressure level of 60 dB, which is illustrated in Figure 2.1. For small practice rooms where the distance between surfaces is very small the reverberation time is normally short, meaning that the energy of the reflections is decaying fast. The acoustics for such rooms will typically be referred to as "dry", an indication that the direct sound predominates the auditory environment.

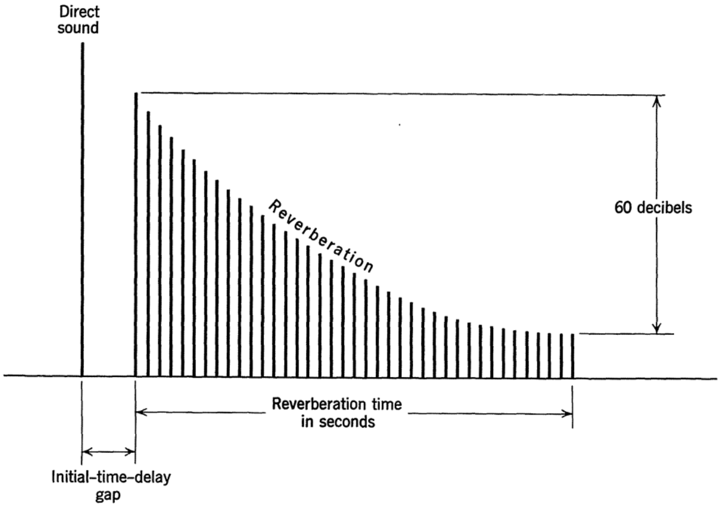

Figure 2.1: Reverberation time (After Beranek, *Concert halls and opera houses*, p.22, 1996)

Figure 2.1 also introduces another acoustical parameters known as the initial-time-delay gap. This parameter represents the time delay between the direct sound and the first reflection often associated with sound qualities such as intimacy or presence. Beranek evaluated acoustical parameters of opera houses and concert halls and found that the best liked halls had an initial time delay gap of 25 ms or less, and poor rated halls had initial time delay gaps which reached 60 ms or greater [5]. Large initial time delay gaps like those of concert halls and opera houses are not achievable for small rooms. In small rooms the distance from any surface of the room would be between 1 m - 2 m and given this distance the initial time delay gap would be between 6 ms - 12 ms.

Geometrical acoustics

Geometrical acoustics is commonly used when estimating reflection paths and impulse responses of rooms, where the reflection paths are predicted using a mirror source and ray tracing method [6]. Using geometrical acoustics, waves can be imagined as rays propagating in space where each reflected sound wave will have a reflection angle the same as the angle of incidence. For a mirror source model a mirrored copy of the room can be visualized and the reflection can be understood as originating from the mirrored room, see Figure 2.2. Geometrical acoustics is limited to mid to higher frequencies. Everest suggests in *Master Handbook of Acoustics* that geometrical acoustics only is applicable four times above the Schroeder frequency [4].

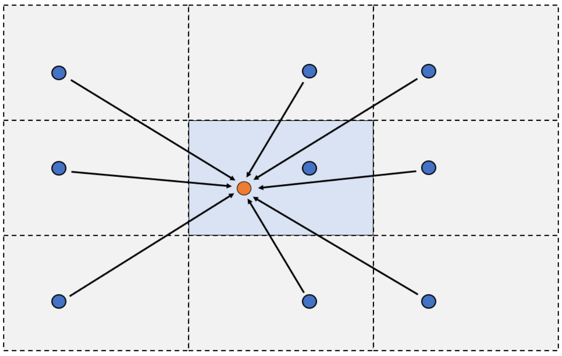

Figure 2.2: Mirror source model for first reflections from mirrored sources (blue) to receiver position (orange) for a square shaped room in 2D.

The Schroeder frequency can be calculated using equation 2.1,

$$f_s = 2000 \cdot \sqrt{\frac{T}{V}} \tag{2.1}$$

where T is the reverberation time, and V is the volume of the room.

Room modes

Frequencies for wavelengths that align with the dimensions of a room will create standing waves due to superposition. The specific frequencies where this phenomenon occurs are called room modes [7]. In small rooms the lower frequency room modes are sparsely distributed and widely separated, resulting in a room response dominated by modal behavior, as seen in Figure 2.3. Within this frequency range the frequency response will be uneven and the pressure distribution for each frequency will vary significantly depending on location within the room.

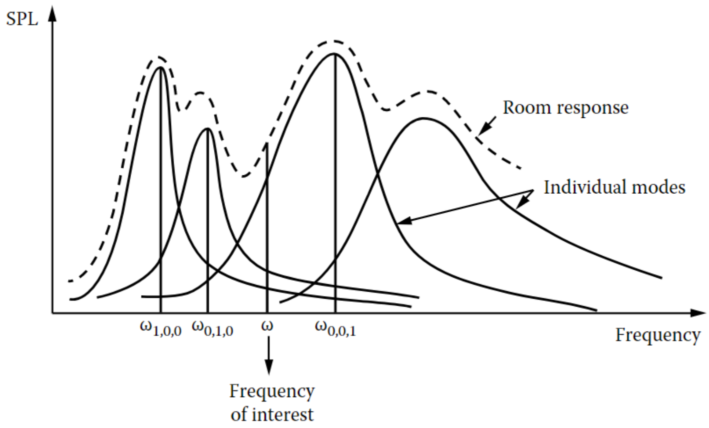

Figure 2.3: The contribution of modes to the room response. (After Kleiner and Tichy, *Acoustics of Small Rooms*, p.55, 2014

Room modes and the pressure at a certain position in a room can be derived using the wave equation shown in equation 2.2.

$$\frac{\delta^2 p}{\delta x^2} + \frac{\delta^2 p}{\delta y^2} + \frac{\delta^2 p}{\delta z^2} + k^2 p = 0 \tag{2.2}$$

The solution to the wave equation leads to equation 2.3 which describes the frequencies for the modes of a room with parallel surfaces and equation 2.4 which describes the pressure within the room boundaries for a certain mode.

$$f_{m,n,l} = \frac{c}{2}\sqrt{\left(\frac{m}{L_x}\right)^2 + \left(\frac{n}{L_y}\right)^2 + \left(\frac{l}{L_z}\right)^2} \tag{2.3}$$

$$p_{m,n,l} = Acos\left(\frac{m\pi}{L_x}x\right) cos\left(\frac{n\pi}{L_y}y\right) cos\left(\frac{l\pi}{L_z}z\right) \tag{2.4}$$

2.1.4 Comb-filtering effects and coloration

When two identical broad banded sound pulses separated by a short time delay interfere, a resulting frequency response exhibiting a comb-like pattern is produced. This is the result of superposition of sound waves and the effect in frequency domain is called comb-filtering. Coloration occur when the sound is severely altered by this comb-filter effect.

Superposition of frequencies

Comb-filtering occurs due to the superposition of sound waves. When the reflection of a pure sine wave interferes with the direct sound of the same frequency, the resulting sine wave will preserve its original frequency while being changed in amplitude.

If both sine waves are in phase, the resulting sine wave will have a amplitude change of +6dB, and if they are opposites (phase = 180°) the resulting sine wave will have zero amplitude. For a signal which has a broad banded distribution of energy across the frequency spectrum certain frequencies will be amplified while other frequencies will be attenuated. This is due to the phase differences of different frequencies, and the superposition of these, thus producing a comb-filter across the frequency spectrum [8].

The frequency response of an impulse is evenly distributed across the frequency spectrum. Figure 2.4 illustrates the frequency spectrum of two interfering impulses being delayed with 5 ms and 10 ms. The resulting frequency spectrum on a linear scale reveal a distinct comb filter with dips evenly distributed for both cases, where each peak has +6dB in magnitude. The distance between dips is evenly distributed and is depending on the delay of the reflected impulse according to $\Delta f = \frac{1}{\Delta t}$ [9] [10].

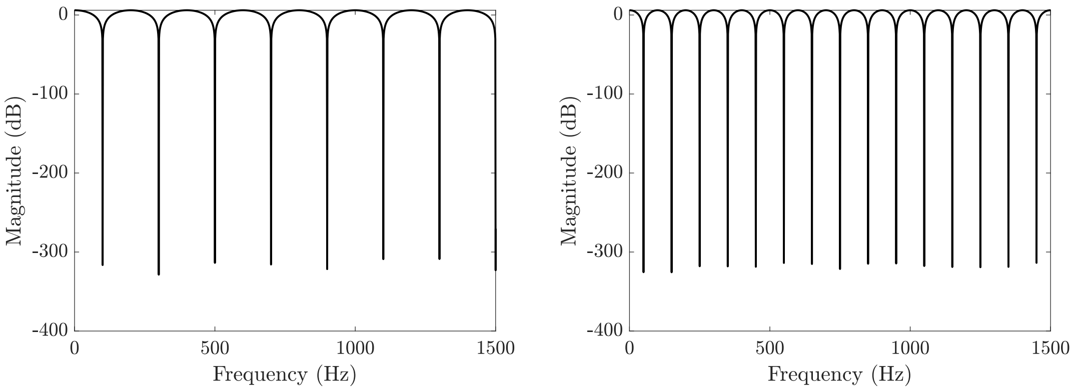

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Figure 2.4: Frequency response of a delayed impulse signal with 5 ms (left) and 10 ms (right).

Audibility of comb-filtering effects

The perceivable impact of comb-filtering is greater when the time delay between the impulses is short. With a shorter time delay, the intervals between the dips in the frequency response become wider, resulting in a more substantial alteration in the frequency domain. Comb-filtering does not occur for individual pure tones, but may severely alter broad banded impulse noises. Olive and Toole investigated the audible effects of reflections ranging from 0 ms to 30 ms for different reflection levels and sounds. They found that the perceptible alterations from comb-filtering were greatest for clicks, followed by speech, music and then pink noise [11].

Coloration

If the audible sound is detrimentally altered due to comb-filtering it is denoted as coloration of the sound [12]. The auditory system perceives reflected sounds arriving within around 35 milliseconds of the direct sound as part of the direct sound, regardless of direction of the reflections. This is called the precedence effect, and the zone in which the precedence effect occurs is called the Haas fusion zone [13]. Generally it can be said that in order to avoid coloration, strong reflections should occur outside of the Haas fusion zone at 35 milliseconds (see Figure 2.5). However, it is also important to consider that this is a generalisation and strong reflections within the Haas fusion zone may not always be harmful as was seen for initial-time-delay gap in larger halls where concert halls with an initial time delay of 25 ms or less was rated higher in acoustical quality.

An investigation was carried out by Michael Barron on the subjective effects of first reflections in concert halls. Barron used two loudspeakers, one radiating from the front and one radiating from the side. When investigating the effects of adding a single reflection at a 90° angle for classical music an apparent source location change was found for delays up to around 18 ms, coloration of the sound between 18 ms and 35 ms, a feeling of spaciousness between 35 ms and 50 ms, and echo for delays larger than 50 ms, see Figure 2.5. Coloration is very much dependent on the strength of the reflected wave. In order to completely avoid the risk of coloration, the reflected wave should have a sound pressure level at least -20 dB of the direct sound, which can also be seen in Figure 2.5.

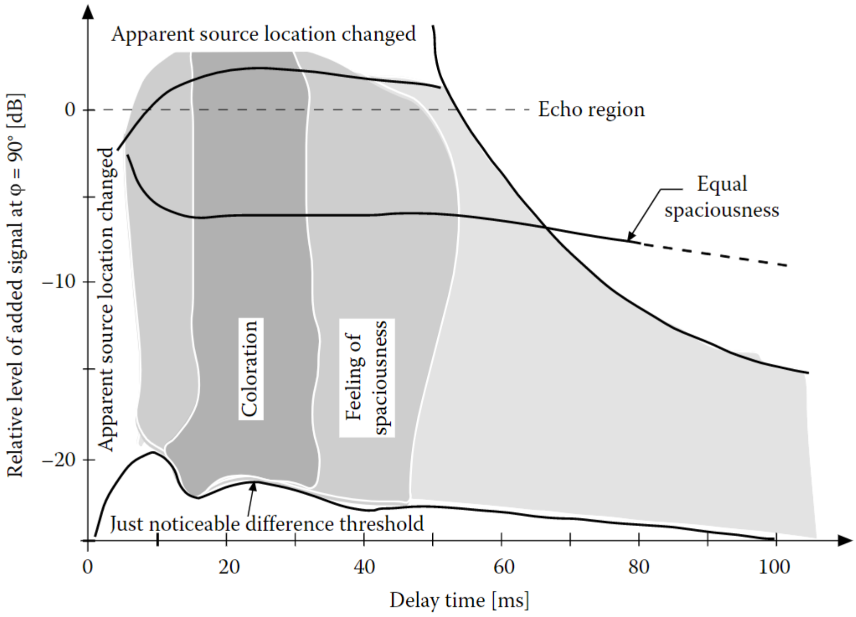


Figure 2.5: Different subjective effects due to an added reflective sound wave relative to direct sound. (After Barron,M.,*J. Sound Vib.*,,15(4),475.1971)

Flutter echo

Reflections which occur between two parallel surfaces may create flutter echo if the time between the reflections are outside the Haas fusion zone [11]. Flutter echo occurs when the reflections are periodic. Flutter echo and coloration due to comb-filtering are closely related in that both are related to reflections. Within the Haas fusion zone flutter echo caused by the periodic reflections will be heard as coloration, while outside of the Haas fusion zone flutter echo may be heard as a rapid succession of echo. For small rooms the distance between surfaces are very small and strong reflections could occur both within and outside of the Haas fusion zone resulting in both coloration and flutter echo.

2.1.5 Treatment of strong reflections

Problems relating to reflections, such as flutter echo or severe comb-filtering causing coloration, is treated using either absorption or diffusion. Measurements have shown that in order to completely avoid such problems, reflections should have a sound pressure level at least 20 dB lower than the sound pressure level of the direct sound [14]. Absorption is obtained through absorbers which removes kinetic energy from the room, thus reducing the overall sound pressure level. Since absorption reduces the sound pressure level the reverberation time is also affected, which may be unwanted if the reverberation time already is too low. In small practice rooms absorption is commonly obtained using curtains, Helmholtz absorbers, porous absorbers, and membrane absorbers.

When using diffusion, sound reduction of the reflected wave is instead obtained by scattering of the reflection. Diffusion is obtained through irregularities of surfaces and objects in a room, but may also be achieved by using modern diffusers. There are two ways in which diffusion may scatter the sound, temporal dispersion as well as spatial dispersion [15]. Temporal dispersion delays certain frequencies of the reflected wave so that the frequency response of the reflected wave is different from the frequency response of the direct sound. Spatial dispersion scatters the sound into many different directions. This reduces the amplitude of the reflected wave but the frequency response remains the same as the direct sound. By diffusing the sound spatially the effect of coloration decreases since the sound is more evenly scattered, decreasing the amplitude of the interference pattern. By diffusing the sound temporally the frequency response is changed and thus the effect of coloration decreases since the direct sound and the reflected sound are not identical. Temporal and spatial dispersion is illustrated in Figure 2.6.

While diffusers primarily scatters the sound wave, some absorption is introduced by most diffusers by their design. Examples of this is for a semi-cylinder diffuser which provides both membrane absorption, as well as diffusion. Diffusers also reduce the mean-free path length, which is the average distance for all reflections between surfaces. When the distance between surfaces is shorter due to a shortening of the mean-free-path, the reverberation time is shortened due to the shorter path to an absorptive surface [16].

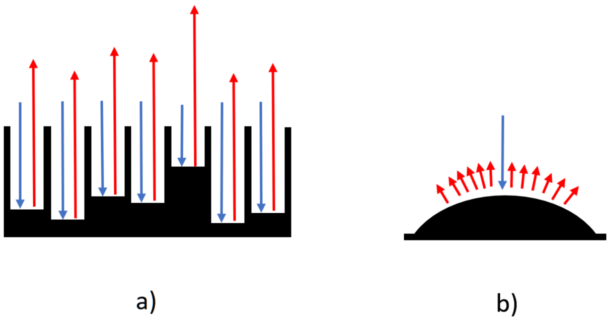


Figure 2.6: Illustration of a) temporal dispersion, and b) spatial dispersion (b), for incoming sound wave (blue) and reflected sound wave (red).

2.2 Literature study

In this section the historical context for diffusers and related previous research will be presented. The literature study aims at highlighting the relevance of diffusers in small practice rooms, while providing a general understanding of the problems which may arise in small rooms in comparison to large rooms.

2.2.1 Historical context

There is much evidence that there existed a general understanding of acoustics based on observation and interpretation stretching far back in history. When studying the outdoor theatres in ancient Greece a systematic placement of steps, corners and pillars can be observed, which obtained dispersion of the sound and a diffuse sound field which may have greatly enhanced the acoustical experience [17]. Principles of acoustical knowledge can also be seen closer in time in some of the great concert halls, one example being the Grosser Musikvereinssaal in Vienna which was built in 1870 and still considered to be one of the best concert halls in the world [18].

A scientific knowledge of acoustics based on numerical methods was however not obtained until the beginning of the 20th century when a method of calculating reverberation time was invented by Sabine. This was the first time that parameters regarding room acoustics could be determined and used in the design process of acoustical spaces [19]. Before Sabine, the design of concert halls and opera houses were mainly based on precedence that had had satisfactory acoustical results and after Sabine some part of the acoustics could be predicted based on his acoustical model.

During the 20th century the architectural trend changed in concert halls and opera houses from being spaces with ornamentation and relief work to become halls with large flat areas and clean lines. Diffusion which previously had been obtained from ornaments and relief work was eradicated and problems relating to echoes and coloration became prevalent. These problems could be solved by reducing the strength of the reflected wave by adding absorption but was unwanted since it also removes energy from the hall. In concert halls it is desirable that as much energy as possible is kept so that the audience can hear the musicians on the stage [19]. The solution was introduced by the research of Schroeder in the 1970's.

Schroeder researched a certain type of diffusers which today are called Schroeder Diffusers. One very common type of these is the QRD-diffuser which also was the first type of modern diffuser which was installed in a concert hall. These were installed on the rear wall of Carneige hall. The diffusers proved to be effective and the reflection was inaudible after the diffuser installation [18]. In addition to reducing echo, the diffusers also improved the sound by increasing spaciousness and masking echoes from boxes. The Schroeder diffuser dispersed the sound both spatially and temporally. An additional installation of diffuser was made a few years later by Marshall and Hyde in the Michael Fowler centre, New Zealand, in 1978. These type of diffusers dispersed the sound only spatially, but proved to be another successful application of diffusers [20].

Diffusers have since found many other application areas in different types of rooms which may suffer from acoustical problems relating to reflections. Much of the literature on the subject is found in the research conducted by acousticians such as Trevor J. Cox and Peter D'Antonio. They condensed much of the research done on diffusers by them and others in the book *Acoustic Absorbers and Diffusers*, first released in 2002. Their research has contributed to diffusers being introduced in most rooms relating to music production [9]. Today diffusers have also been introduced to small practice rooms, perhaps as a consequence of their widespread use in other music rooms. The research on the topic is however very sparse and more investigations are needed in order to fully motivate their usage in these rooms.

2.2.2 Diffuser application in small practice Rooms

When studying the literature on the subject of diffusers most of the research conducted investigates diffuser application in larger halls as well as music studios and only a few investigations have been made on practice rooms. In a paper written by Cox, he emphasises that there is a need for more studies to investigate how much diffusion is needed and where it should be applied [15].

Principal usage of diffusers

Diffusion as a means to treat audible echoes, such that would arise in a larger hall with flat surfaces, is not particularly relevant in small practice rooms due to their limited size. Jiri and Kleiner discusses in their book *Acoustics of Small Rooms* that the usage for diffusion in small practice rooms is mainly limited to treatment of coloration due to comb-filtering [14]. They also advocate diffusion rather than absorption in treating coloration since absorption would lower the already low reverberation time of small rooms. This is further affirmed by Cox and D'Antonio who asserts that the reducing of comb-filtering is one of the principal reasons for using diffusers [9].

Different diffuser designs

The effectiveness of a diffuser depends on the type of the diffuser, size of the diffuser and material used for the diffuser. Fehlhaber discusses different types of diffuser designs in his master thesis, and if the type of diffuser matter in small rooms. He found that spatial diffusers such as the semi-cylinder diffuser had little effect in treating coloration in small rooms and that it was important that the diffuser primarily dispersed the sound temporally [21]. However, he also found that while there certainly were some measurable differences between spatial and temporal diffusers, these may not necessarily be subjectively audible. Fehlhaber further discusses that the angle of incidence matter greatly and that unless the angle of incidence is close to perpendicular to the diffuser surface, the diffuser may act only as a flat surface.

Cox discusses semi-cylinder diffusers and has the same conclusion as Fehlhaber, claiming that semi-cylinder diffusers which only have spatial dispersion, are not very effective in treating coloration [15]. Cox claims that semi-cylinder diffusers might even increase coloration. He advocates Schroeder diffusers and temporal dispersion so that the reflected sound wave will obtain a different frequency response due to superposition of frequencies, as discussed in section 2.1.5.

Effective and valid frequency range

Regarding effective frequency range the size of the semi-cylinder diffuser matters greatly. Everest and Pohlmann asserts that a semi-cylinder diffuser with a width of just above 1 meters would be an effective diffuser only at around 1000 Hz [22]. Diffusion at these high frequencies may not be relevant for the fundamental tones of most music instruments, and might only affect the overtones of these.

Cox explains that diffusion works best if the listener is three wavelengths away from the diffuser [15]. Therefore, a consideration must be made between effective frequency range and size of the room. If Cox's statement holds true, that diffusers work best at a distance of three wavelengths from the diffuser, then the lower limit of the effective frequency range in a small room may not extend much lower than around 1000 Hz, as this corresponds to a distance of approximately 1 meter. If the desire is to achieve a lower effective frequency range, such as in the range of 300 Hz - 400 Hz, the distance from the diffuser would need to be increased to approximately 3 meters. However, this might not be possible in a small practice room due to their limited sizes.

Diffusers further assumes a specular model, and may not behave predictably unless they are used in rooms and for frequencies where geometrical acoustics can be applied. Everest and Pohlmann claims that geometrical acoustics is only applicable at four times the Schroeder frequency [4]. The behavior of diffusers in small practice rooms would be uncertain with an effective frequency range of 300-400 Hz given that 4 times the Schroeder frequency would be well above that frequency range.

Sound pressure levels and reverberation time

The sheer size of the diffuser makes the distance certain sound waves has to travel shorter since they bulge outwards. This might pose problems in small rooms where the distance to the diffuser is very small. The consequence could be that the sound pressure level would increase at higher frequencies, which may result in larger peaks in the transfer function. Furthermore if two semi-cylinder diffusers are next to each other, additional focusing may occur in between which further might increase and worsen coloration [22].

In the book *Acoustics of Small Rooms* Kleiner and Tichy discusses the influence of diffusers on the reverberation time in small rooms. They adhere that spatial diffusion will shorten the mean-free-path that sound waves have to travel before encountering an absorptive surface, thus reducing the reverberation time [16]. Semi-cylinder diffuser further acts as a membrane absorber for lower frequencies. These type of diffusers would therefore shorten the reverberation time at lower frequencies through membrane absorption, and at higher frequencies through shortening of the mean-free-path.

Coloration in small practice rooms

Cox and D'Antionio asserts that the reducing of comb-filtering is one of the principal reasons for using diffusers [9]. In a paper by Halmrast he investigates coloration due to reflections on a concert platform, and discusses audible coloration and how this may be measured [10]. He says that in order to find coloration one needs to look at the frequency response of early reflections by using a short time window rather than the whole signal, which he says agrees with the psycho-acoustic studies that timbre is determined from the early reflections. Further comments from Kleiner and Tichy include studying the frequency spectrum in sixth-octaves, since this more accurately correspond to human perception of sound [6].

However, for instruments which plays one note at a time, which is likely in a small rehearsal room for individual practice, coloration and comb-filtering might not be audible. Everest and Pohlmann claims that coloration due to comb-filtering is a steady state phenomenon, and that it has very limited application to transient phenomenon such as music [8]. The audibility of comb-filtering is further more prominent for broad banded noise, where even dips across the frequency spectrum alters the audible sound.

Related research

On the subject of diffusers in small practice rooms the research is as previously mentioned very limited. Earlier master theses which has looked at practice rooms in general are by Sandaker, and Olsson and Söderström. Sandaker studied measurement parameters and tried to find a correlation between these and the subjective experiences of musicians in small practice rooms. While Sandaker does not directly discuss diffusion, there are some key points discovered which is useful in the investigation of amount of diffusers in small rooms. She found that musicians tend to favour rooms with lower reverberation time, high clarity and an evenness in amplitude both over frequency and time for the first 15 ms of the impulse response [23]. Olsson and Söderström investigated perceived sound qualities in small practice rooms and discovered that trumpet players tended to favour rooms which were less diffuse [24]. They found a strong negative correlation between (1-IACC) values, which measures a rooms diffusivity, averaged over the 500 Hz - 2000 Hz octave bands.

Primary research of master thesis

The literature seem to be in an disagreement regarding diffusers in small practice rooms. While certain literature advocate diffusion in order to remove coloration due to comb filtering in small practice rooms, some literature claims that coloration and comb-filtering are steady-state phenomenon and not applicable to transient phenomenon as music. The usage of temporal diffusers is also encouraged instead of spatial diffusers, but the audible differences between spatial and temporal diffusers in small rooms are simultaneously questioned. A need for more studies to investigate how much diffusion is needed and where it should be applied is however emphasized. This master thesis will use the information provided in the literature study and undergo a subjective and objective analysis with its aim to answer the question on how diffusers affect the sound field of a small practice room. The study will limits its investigation to semi-cylinders, which diffuse the sound spatially, and additional study on temporal diffusers will be left for future studies.

2.2.3 Current standards and the design of small practice rooms

Practice rooms which are built are often designed so that multiple different instruments can be utilized in them. This may be a demanding task since the characteristics of each instruments is different and is affected by the room in a variety of ways. The relevant standards issuing the design of practice rooms is the international standard ISO 23591:2021 [25] and the Norwegian standard NS 8178:2014 [26] which ISO 23591:2021 is based on. These standards groups the instruments in three different subcategories which are quiet, loud and amplified, and have different recommendations for the room based on what instrument category will be used in the room. If a room is built following the recommendations of the certain category then all instruments within this category should be able to utilize the room with a satisfactory acoustical response.

At the time when the Norwegian standard was first issued in 2014 rehearsal rooms often failed to meet expectations. According to the Norwegian standardization group which produced the standard, 85% of rehearsal rooms in Norway were not suited for the type of music in which they were played at the time [26]. When the Norwegian standardization group put together the standard they also found that that 76% of the rooms were too small, with a majority being less than half the size of what they should have been. They also found that the room geometry ratio was off in most cases and that the reverberation time was often too short for quiet music and too long for loud music.

Having a longer reverberation time has a consequence of less sound being absorbed by the surfaces of the room, and the strength of the room therefore inherently increases making the music more loud. If the music is too loud the musician is exposed to a higher risk of hearing damages. In order to compensate for the louder volume the musician may also be restricted, playing softer and more quiet. If the strength and reverberation time is too low however, the musician may on the contrary play forcefully trying to compensate for the lack of the room response [25]. The way the musician compensates may occur on a subconscious level. When the acoustics of the practice room is good however, the musician will no longer compensate for bad acoustics and may thereby be less restricted when practicing [16].

Guidelines for small practice rooms

The current guidelines which can be found in both ISO 23591:2021 and NS 8178:2014, recommends that individual practice rooms regardless of use should have; a net volume $\geq$35 m^3, a net area $\geq$13-15 m^2 and an average room height $\geq$2.7 m. In addition to having a sufficient enough volume, the width, length and height should have a specific ratio to avoid modes in the lower frequencies to be unevenly distributed. This ratio is described in equation 2.5.

$$\frac{l}{h} = 2.36 \cdot \frac{w}{h} - 1.38 \tag{2.5}$$

Plotting $\frac{l}{h}$ as a function of $\frac{w}{h}$ Figure 2.7 is obtained. As can be seen in the figure, examples of ratios that will produce a satisfactory modal distribution are 1:1.2:1.44, 1:1.4:1.89 and 1:1.48:2.12. The standard also suggests that the walls should be slightly off-parallel so that flutter-echo may be avoided. For a small practice room it is also recommended to use; wall absorbers, ceiling absorbers, bass absorbers and diffusors. The standard discusses reverberation time and room ratio, but criteria regarding diffusivity of a room is excluded.

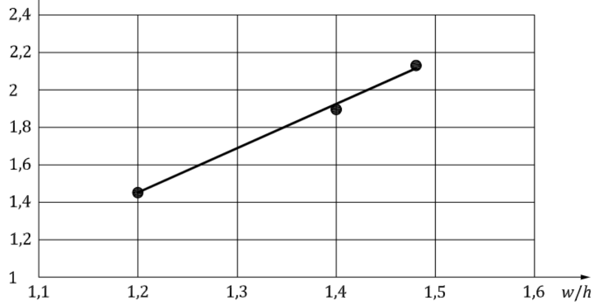


Figure 2.7: Ratio of length/height and width/height for optimal acoustics in a small practice room (After ISO23591:2021).

2.2.4 Examples of existing practice rooms

As part of the research, site-investigations have been carried out to the Gothenburg Concert Hall, the Gothenburg Academy of Music, the Gothenburg Opera House and the Kungsbacka Music and Arts School. The purpose of these visits was to study examples of how individual practice rooms are built in different music facilities and investigate the overall acoustics of these. The acoustics were investigated by playing the violin.

Gothenburg Concert hall

The Gothenburg Concert Hall is home to the Gothenburg Symphony Orchestra and is equipped with multiple rehearsal rooms for individual practice, including choral soloist practice rooms, general practice rooms, and violin practice rooms. The rooms vary in size, with the choral soloist practice rooms having a floor area ranging from 11 m^2 - 15 m^2, the general practice rooms ranging from 9 m^2 - 16 m^2, and the violin practice rooms ranging from 5 m^2 - 7 m^2. Figure 2.8 shows examples of such practice rooms.

Figure 2.8: Examples of practice rooms at the Gothenburg Concert Hall. Choral soloist practice room (left), general practice room (middle), violin practice room (right).

All practice rooms in the Gothenburg Concert Hall were shoebox shaped with slightly slanted side walls, making these off-parallel. All of the practice rooms had acoustic ceiling tiles, which covered the entire ceiling area. Each room had a ceiling height close to 3 meters, and curtains were installed in all of them to allow for adjustable absorption. There were some differences between each type of practice room. The choral soloist practice rooms were furnished with parquet floors and included amenities such as a piano, armchair or sofa and in some cases a dressing table with mirrors, with windows facing greenery. On the other hand, the general practice rooms were windowless and sparsely furnished, with a linoleum mat covering the floor. The violin practice rooms resembled those of the general practice rooms but were half the size. However, unlike the general practice rooms, the violin practice rooms all had windows facing greenery, which added a pleasant feeling.

The acoustics of each room was dry with a short liveness as would be expected due to their small size. The perceived loudness of each room varied when playing the violin, where it was perceived as highest in the violin practice rooms and lowest for the choral soloist practice rooms. This is expected since the choral soloist practice rooms were both larger and had more furniture which would absorb sound.

Gothenburg Opera house

The Gothenburg Opera House accommodates the Gothenburg Opera Orchestra, which consists of 86 musicians. The orchestra members play various instruments, and the opera house provides several practice rooms for them to practice in. These rooms varied in size and were distributed amongst the different departments. The floor area of a typical practice room was 8 m^2. All of the practice rooms in the Gothenburg Opera House were equipped with diffusers and curtains covering the walls. As can be seen in Figure 2.9 the diffusers were either semi-cylinder diffusers as can be seen in the left and middle image, or slanted as can be seen in the right image. The semi-cylinder diffusers were used in small to mid sized rooms, and the slanted diffusers were used in larger rooms.

Figure 2.9: Examples of practice rooms at the Gothenburg Opera House.

The majority of the rooms had windows and were well-insulated, with acoustic ceiling tiles covering the entire ceiling. In talks with some of the musicians at the facility many preferred to practice in larger rooms due to high noise levels, low reverberation time, and low bass control in the smaller sized rooms. One member of the orchestra who played the trumpet said that when he played in the small practice rooms he preferred to play with extended curtains so that the room was made completely dry. He said that the sound otherwise was too shimmery, harsh, and jangled.

Gothenburg Academy of Music and Drama

The Gothenburg Academy of Music and Drama is a part of University of Gothenburg. A visit was made to two practice rooms in their old facilities. The practice rooms can be seen in Figure 2.10. The rooms varied in size where the left room had a floor area of 10 m^2 and the right room had a floor area of 17 m^2. Both practice rooms had slanted wall type of diffusers, but in contrast to the Gothenburg Opera

House, these tilted upwards instead of downwards. Both rooms were equipped with heavy curtains and had acoustic ceiling tiles covering roughly 70% of the ceiling area. The right room had two semi-cylinder shaped diffusers moving across the ceiling as well as Helmholtz absorbers covering one side wall.

Figure 2.10: Examples of practice rooms and diffusor at the Gothenburg Academy of Music and Drama.

Kungsbacka Music and Arts School

The Kungsbacka Music and Arts School is attached to the Kungsbacka library and holds teaching rooms intended for one student and one teacher. As such these rooms were slightly larger than those solely intended for one musician with a floor area ranging from 16 m^2 to 20 m^2. Even though these rooms were larger in size than most other practice rooms at the other institutions, these rooms had very low reverberation time due to added absorption on the walls and the ceiling. The ceiling was covered with acoustic ceiling tiles and the walls had porous absorbers which can be seen in Figure 2.11.

Figure 2.11: Two examples of practice rooms at the Kungsbacka Music and Arts School, and the ceiling in these.

3

Methods

3.1 The Investigations

In order to study the behaviour of diffusers in small practice rooms it was determined that a limitation would be made to utilize only spatial diffusers. The type of spatial diffuser decided on was the semi-cylinder diffuser, and for the studies three identical semi-cylinder diffusers were used, seen in Figure 3.1. The investigations were made using a small practice room at the temporary facilities of the Gothenburg Academy of Music and Drama.

Figure 3.1: The small practice room, binaural recording head Artemis HMS V, and the semi-cylinder diffusers used in the investigation.

It was determined that the investigations would involve two subjective investigations and two complementary objective measurements, where each investigation would add to the study of the behaviour of spatial diffusers in the small practice room. The first subjective investigation was an assessment on-site where musicians played their instruments in the practice room for three different diffuser setups. Each participant was asked to answer a survey on how the acoustics of the room changed with different amounts of diffusers.

For the second subjective investigation, participants performed a listening comparison test in the sound listening environment Artemis sQala, listening to binaural recordings of a violinist made in the small practice room. The first investigation sought to answer if participants perceived any improvement in the practice room using diffusers, and the second subjective investigation sought to answer if these differences were audible when removing the visual stimuli of the diffusers and the practice room.

In addition to the subjective investigations, two objective measurements were made to complement each subjective investigation. The first objective measurement was a room response measurement done according to ISO 3382-2:2008 for different room parameters which were obtained and compared with the results of the surveys [27]. The second objective measurement utilized the binaural head which was also used for the second subjective measurement. The impulse response of the room was obtained for both ears of the binaural head using white noise and an omnidirectional speaker. The source and receiver positions were the same as for the second subjective investigation.

3.2 Room parameters

The small practice room had a floor area of 10.8 m^2 and a height of 2.5 m. The interior wall surfaces were made of gypsum, and the floor was covered with a linoleum mat. The ceiling was a suspended ceiling with gypsum tiles, where 60% of the ceiling tiles was perforated gypsum. Two heavy curtains were hanging on the walls, (5.3x2.5)m^2 and (2.5x2.5)m^2, both contracted during measurements to a length of 0.65 m and 0.35 m. The diffusers had a width of 1.15 meters, a height of 1.15 meters, and a depth of (0.15 + 0.04) meters. The material of the diffusers was plywood, and the front of the diffuser consisted of a 2-3 mm thick plywood board. The interior of each diffuser was filled with mineral wool.

The room modes for the small practice room was calculated and is shown in Figure 3.2. The first 10 modes can be seen for 42 Hz, 63 Hz, 69 Hz, 76 Hz, 81 Hz, 84 Hz, 94 Hz, 103 Hz and 106 Hz. The room can be assumed diffuse somewhere above 200 Hz as it is where the mode density seems to be dense enough. Calculating the Schroeder frequency for the room, estimating a reverberation time between 0.3 s - 0.5 s, the answer is given between 213 - 275 Hz.

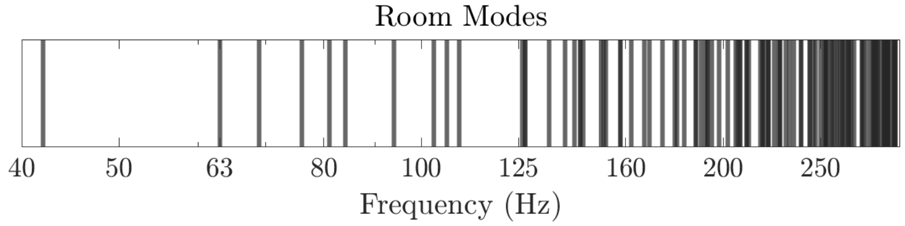


Figure 3.2: The first room modes of the small practice room illustrated as lines on a logarithmic frequency axis.

Finally, the room dimensions were used in relation to the optimal room dimensions for practice rooms given in ISO 23591:2021 [25]. This demonstrates that the room dimensions are not optimal for rehearsal, as shown in Figure 3.3. This was expected however, since this room was part of the temporary facilities of the Gothenburg Academy of Music and Drama, and its original use was not intended for music practice. However, it was chosen due to the close availability to Chalmers and to the students of the Gothenburg Academy of Music and Drama.

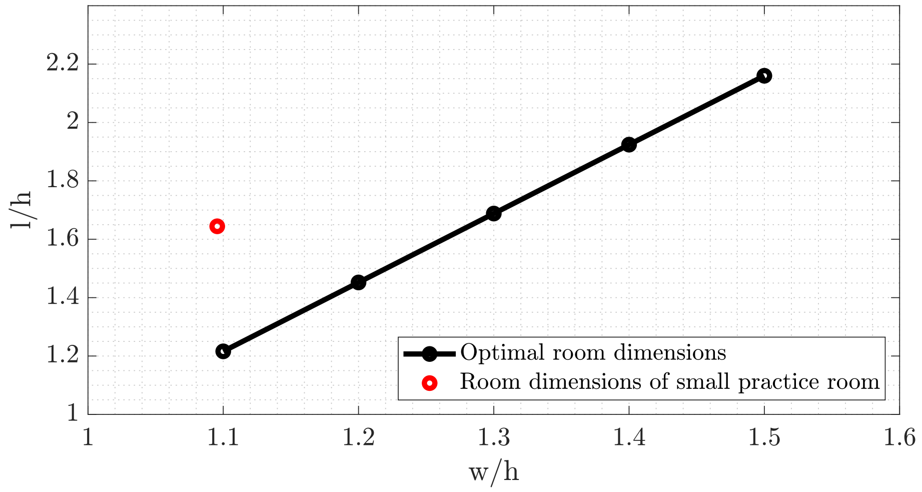


Figure 3.3: Optimal room dimensions according to ISO 23591:2021 and dimensions of small practice room used in the investigation.

3.3 Procedure of the Investigations

The overall investigation consisted of two subjective investigations and two objective investigations made during the spring of 2023 at the temporary facilities of the Gothenburg Academy of Music and Drama. The investigations were all made in the small practice room which can be seen in Figure 3.1, and later analyzed or further studied at Chalmers University of Technology. The temperature in the practice room ranged from 20° - 21° degree Celsius during the investigations.

3.3.1 Subjective assessment on-site

The subjective assessment on-site was done with eight musicians who had varying degrees of music experience. Among the participants, there were three music students from the Gothenburg Academy of Music and Drama, one professional musician, one member of the Gothenburg Academy Symphony Orchestra, and three participants with music experience exclusively from music schools. In terms of their main instruments, three participants used song as their main instrument, two participants used song and guitar, two participants used only the guitar, and one participant played the flute. The median age was 27 years old for the participants and the average amount of weekly practice was 7.5 hours.

The participants were asked to play their instruments and fill out a survey on how they experienced the acoustics of the small practice room while comparing with different amount of diffusers. In addition to the participants filling out the survey, an interview was also conducted to complement the survey with qualitative answers. In order to remove the possibility that the order of performing the investigation would affect the result, the participants performed the investigations in two different orders. Five participants performed the study starting with no diffusers, then one diffuser was added and lastly two more diffusers were added for a total of three diffusers. Three participants performed the study in the other direction starting with three diffusers, then one diffuser, and lastly with all of the diffusers removed. In Figure 3.6 a sketch-up model of the practice room has been made. The diffuser position marked with "1" is the diffuser position used for the setup with one diffuser.

Questions of the survey

The survey aimed at enabling the musicians to describe their acoustic experience while also generating measurable results. For each setup the participants were asked to answer questions on acoustical parameters, evenness of sound, and quality of rehearsal. The following questions were asked for all setups:

- How do you perceive the loudness of the room?
- How do you perceive the liveness of the room?
- How do you perceive the balance of the room?
- Do you perceive the sound as even over all tones? If no, for what frequencies is the sound uneven?
- What is your overall impression of the room with this setup?

For the two last setups, one diffuser and then no diffusers or three diffusers, depending on what setup each participant started with, the following questions were added which gave further insight into the rated quality of rehearsal:

- Do you perceive a difference compared to the previous setup?
- How do you perceive the acoustics in comparison to the previous setup?

At the end of the survey, each participants was asked to summarize their experience and to also answer the last question of rated quality of rehearsal:

- What setup did you prefer the most?

The survey is included in Appendix A.1.

Obtaining the results

The results of the survey was obtained for most answers on a scale of -4 to 4, where 0 was seen as "neutral". The exception to this was the question on evenness as well as the question on what setup the participants preferred the most. The mean values of the answers as well as the confidence intervals according to a students t-distribution was calculated along with an ANOVA-test. The amount of participants were few but an ANOVA-test with a p-value < 0.05 would suggest that the participants were in an agreement, and that the results were not merely by chance.

3.3.2 Room acoustic parameters

In order to complement the subjective assessment on-site, objective measurements were made following the standard ISO 3382-2:2009 [27], using a Core Sound TetraMic Microphone and a dodecahedron omnidirectional speaker. Both microphone and loudspeaker were valid for a frequency range of 125 Hz - 8 kHz. For each setup of diffusers, 6 microphone positions and 2 source positions were used, resulting in a total of 12 recordings for every setup. The measurements were recorded using the computer software IRIS and the parameters were obtained using a sine sweep.

Figure 3.4: Equipment used for measuring room acoustic parameters, Core Sound TetraMic (left) and Dodecahedron omnidirectional speaker (right).

Parameters for Decay Range, EDT, T_{20}, C_{50}, D_{50}, T_s, and G_{early} were obtained in the IRIS software for octave bands. The data from these were imported into MATLAB and averaged over positions. Plots for each parameter is presented in Results, see section 4.3. The measurements required the person performing the measurements to be situated in the room.

3.3.3 Subjective listening test

The subjective listening test was done as a comparison test in the listening environment Artemis sQala, and was done in order to fully exclude the visual impression of the diffusers. The test used binaural recordings that each participant listened to using headphones in a controlled listening environment. The recordings had been made using a violinist and a binaural head placed in front of the violinist in the small practice room. There were 21 participants in total and their median age was 26. 81% of the participants answered that they had a background in acoustics and/or music.

The recordings

For the subjective listening test recordings for the different setups were made in the small practice room with the help of a violin student at the Gothenburg Academy of Music and Drama. The student played four bars from *Bach: Sonata for Violin Solo No. 3 in C Major, BMW 1005 - III. Largo*, which can be found in Figure 3.5. Each recording was around 30 seconds long and two recordings were made for each diffuser setup. The violinist were asked to play as equal as possible, and not deviate between the recordings.

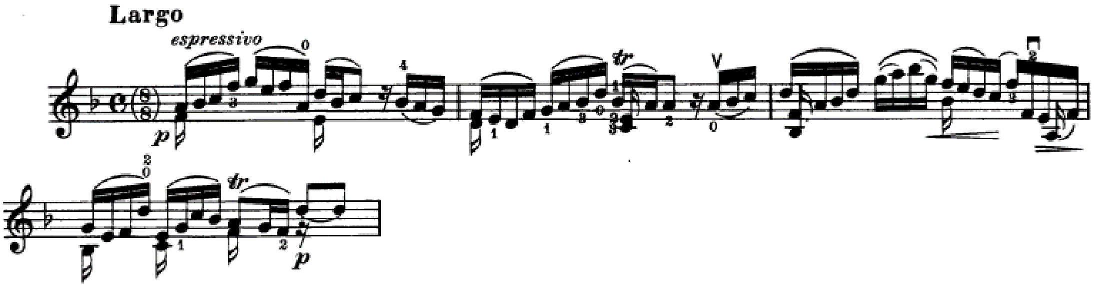



Figure 3.5: Violin piece used in the listening experiment. Beginning of J.S. Bach: Sonata for Violin Solo No. 3 in C Major, BWV 1005 - III. Largo

Figure 3.6 shows the practice room and position of source (S) and receiver (R) for the binaural recordings. At the recording position was the Head acoustics HMS V, facing the direction of the arrow, while the violinist was standing on the source position facing the binaural head. It was determined to use an artificial head in front of the violinist, instead of binaural recordings placed on the head of the violinist himself, since the binaural recordings from the binaural head provided a superior sound quality. In Figure 3.6 the diffusers are labeled 1, 2 and 3. The three different setups recorded were:

1. No diffusers installed
2. With diffuser "1" installed
3. All three diffusers installed.

Listening test in Artemis sQala

When constructing the listening test in Artemis sQala only the last bar shown in Figure 3.5 was used in order to make the comparison test more concise. The last bar was chosen as it also contained a lot of variety. During the recordings there were some leakage from adjacent rooms which could be heard at the tail of the recordings. It was decided that the tail of the recordings would be cut short in order to remove any indication of leakage. This also removed any indication of reverberation however.

The participants performed the listening test in a controlled listening environment using the listening environment software Artemis sQala and Sennheiser HD 650 headphones. The headphones were connected to a computer via Head Acoustics BPU, a USB adapter which enables aurally accurate playback. The listening test was performed individually by each participants.

The listening test consisted of two parts. The first part was a comparison test, following an ABX model. An ABX model asks: "which of A or B is X?" and is used to determine if there are any audible differences between A and B. If there are no differences the answers would be close to 50%. Two different recordings had been made for each setup of zero, one and three diffusers giving a total of 48 possible combinations. In order to reduce the length of the comparison test the combinations were reduced to 12, where the comparisons deemed as most crucial were kept. The comparisons were randomized and appeared in no particular order. For each comparison the participants listened to a reference recording with zero, one or three diffusers, and was asked to choose which of A or B they thought contained equal amount of diffusers. The participants were not disclosed what diffuser setup they were listening to.

The second part asked each participant to rate all recordings for preference on a scale 1-5, where 1 was "prefer the least", 3 was "neutral, and 5 was "prefer the most". The participants were asked to pick one recording which they preferred the least, and one which they preferred the most, and then rate the remaining in between.

Obtaining the results

The results of the listening test was imported into MATLAB. For the comparison test, the percentage values of each correct answer was calculated for each comparison. In order to verify that the results of the comparison test were statistically significant a chi-square goodness-of-fit test was made with the prerequisite that the results would be 50% if there were no audible differences between the comparisons. For the preference test the mean value as well as confidence intervals according to a students t-distribution was calculated. An ANOVA test was performed to ensure that the results were statistically significant.

3.3.4 Binaural measurements

In order to further study the effects of the diffusers, specifically looking for indications of comb-filter effects, an impulse response was measured using the binaural head for the same position as for the recordings of the subjective listening test. An omnidirectional speaker was used at the location of the violinist, see Figure 3.6 for source and receiver position. The impulse response measurement was made using white noise for 30 seconds at a sample rate of 51200 Hz and a block size of 51200 samples. The list of equipment for the omnidirectional impulse response measurement were as follows:

- Bruel and Kjaer omnidirectional speaker model 4295, (frequency range 50 - 6300 Hz).
- Head acoustics Squadriga III.

- Bruel and Kjaer Amplifier Type 2735.
- Head acoustics HMS V (code 1502), artificial head.

The sQadriga III, which is a mobile sound and vibration measurement device, generated white noise and was connected to the Bruel and Kjaer amplifier, which in turn was connected to the omnidirectional speaker. The head acoustics HMS V was also connected to the sQadriga and the device recorded both the input signal and the signal from the left and the right ear of the HMS V.

The data was then imported into MATLAB, where measurement parameters such as the coherence, impulse response and transfer function was obtained for both left and right ear. The impulse response for the first 35 ms was studied for strong reflections, and the FFT of the same impulse response was studied for differences in comb-filter effects. A transfer function of the whole signal was also obtained in sixth octave bands to get a good overview of the frequency response of the room at the position of the binaural head.

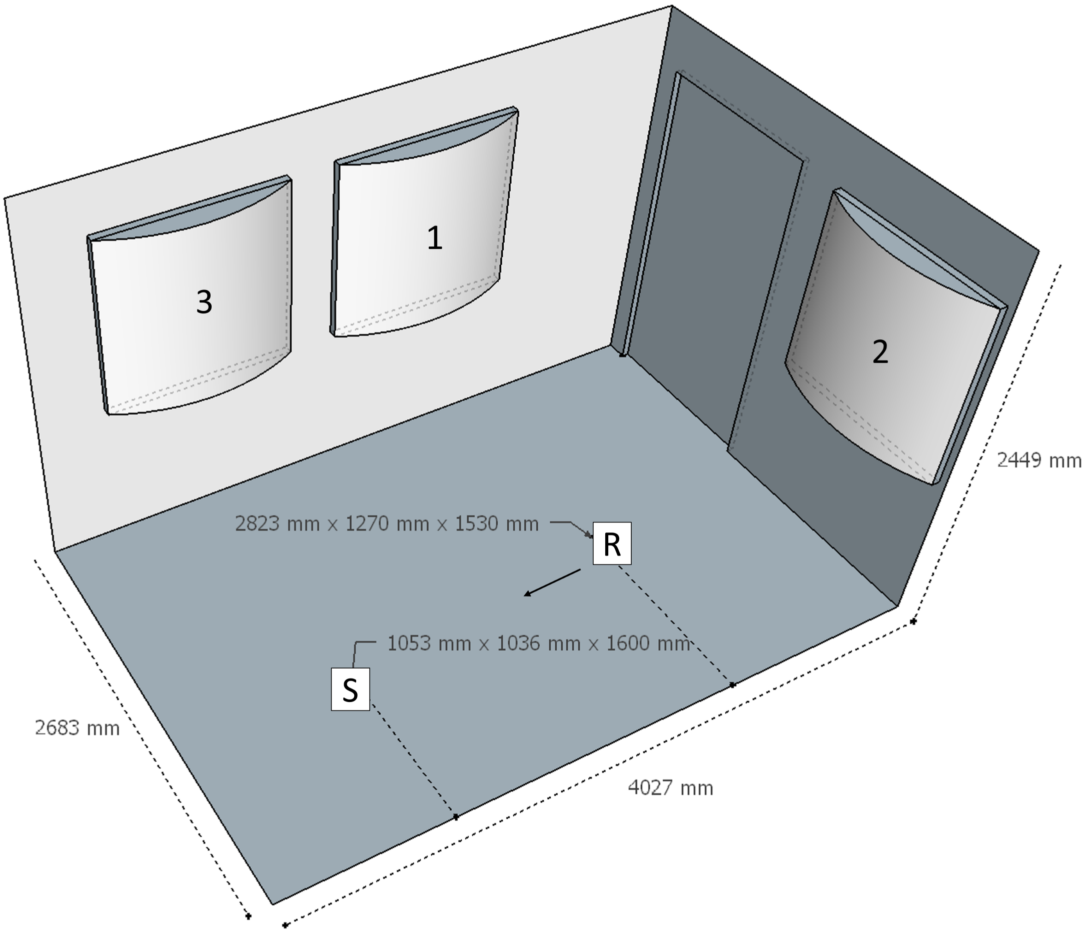


Figure 3.6: Overview of the small practice room made in Sketchup. Room dimensions are (4027 x 2683 x 2449) mm^3. Recording position marked with R and source position marked with S.

4

Results

4.1 Subjective Assessment On-site

In the following section the results from the subjective assessments on-site will be presented. The subjective assessments took place in the small practice room and was performed with eight musicians with various degrees of music experience. The survey which the results are based upon can be found in Appendix A.1.

4.1.1 Rated acoustical parameters

The first evaluating questions on the survey treated acoustic parameters such as perceived loudness, perceived liveness and perceived balance. In Figure 4.1 the results of the participants perceived strength of the room is shown. The figure illustrates the arithmetic mean and confidence intervals using a student's t-distribution for all participants for the different setups. In addition, an ANOVA test has been performed to test the null-hypothesis where a p-value < 0.05 may be seen as statistical significant. The result shows that the participants perceived three diffusers as being the most neutral. The result also shows that the room is perceived as more neutral with added diffusers, but the arithmetic mean shows that the participants still felt that the room was slightly too loud even with three diffusers installed. The p-value is higher than 0.05, which suggests that the result may not be statistically significant.

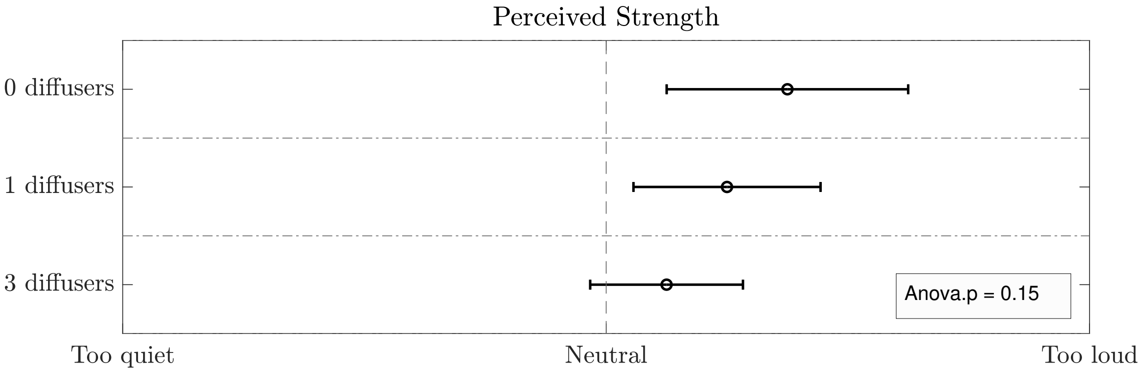


Figure 4.1: Results from the question in the survey: "How do you perceive the strength?".

Figure 4.2 shows the arithmetic means and confidence intervals of perceived liveness for the different diffuser setups. The participants perceived no diffusers as being live, while three diffusers were perceived as dry. The ANOVA p-value suggests that the participants were in a consensus and that the result may be seen as statistically significant.

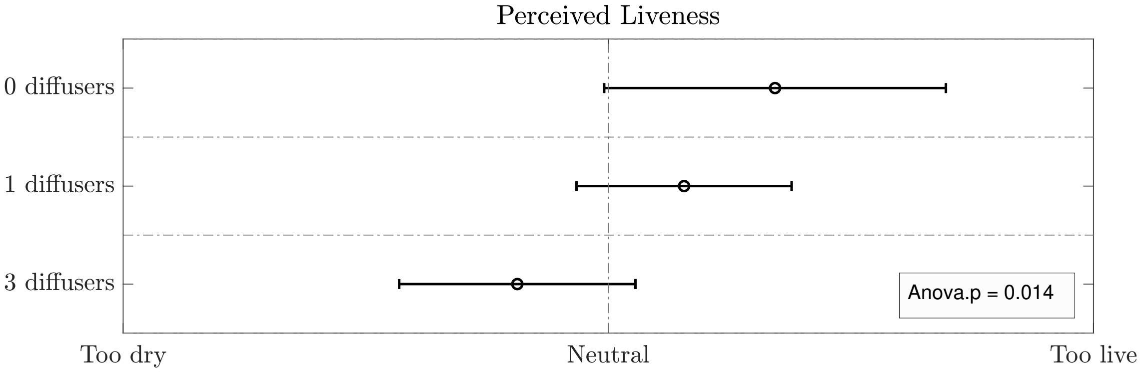


Figure 4.2: Results from the question in the survey: "How do you perceive the liveness?".

Figure 4.3 shows the arithmetic means and confidence intervals as well as p-value from ANOVA test for perceived balance. The results varied greatly for no diffusers where some participants rated the room as being too warm, while others as being too brilliant. For three diffusers the balance was rated as more neutral and had a narrow confidence interval. The result suggests that participants rated the balance as being close to neutral or slightly too brilliant for three diffusers. However, the p-value suggests that the answers varied too much for any trend to be seen as statistically significant.

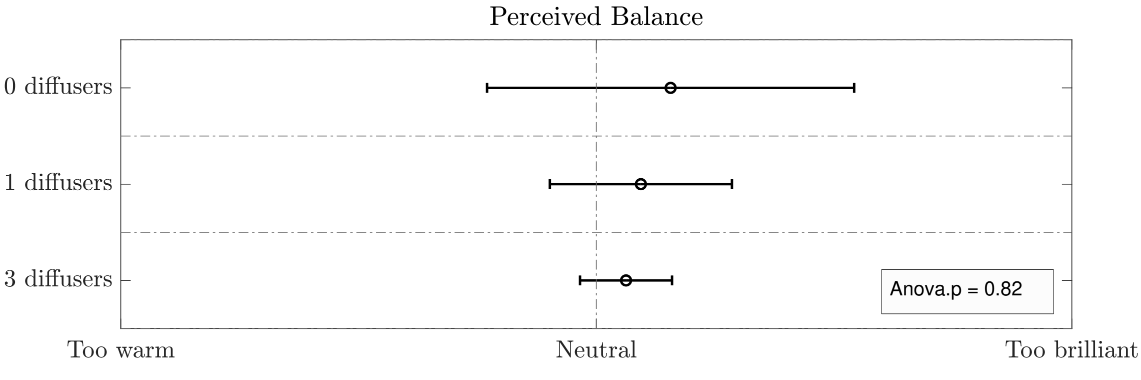


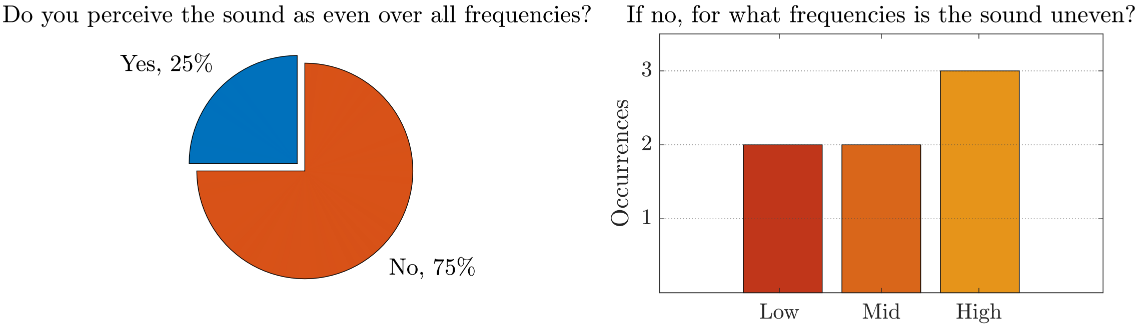
Figure 4.3: Results from the question in the survey: "How do you perceive the balance?".

4.1.2 Rated evenness of sound

In addition to rating acoustical parameters such as perceived loudness, liveness, and balance, the participants were also asked to rate how even they perceived the sound to be. This question was given in two steps where the first question asked: Do you perceive the sound as even over all frequencies? The participants were given an option of "yes" or "no". An uneven sound was described to the participants as containing certain tones that were more noticeable or more prominent than others. If the participants marked "no" as an answer they were asked to answer in what frequency region they perceived the sound to be uneven.

Zero Diffusers

Figure 4.4 shows the result of the rated evenness of sound for the setup with zero diffusers. The ratio of participants who perceived the sound as even were 25%. Of the remaining 75%, three answers indicated a greater unevenness for high frequencies, two answers indicated mid frequencies, and two answers indicated low frequencies. It is worth noting that some participants marked more than one frequency area.

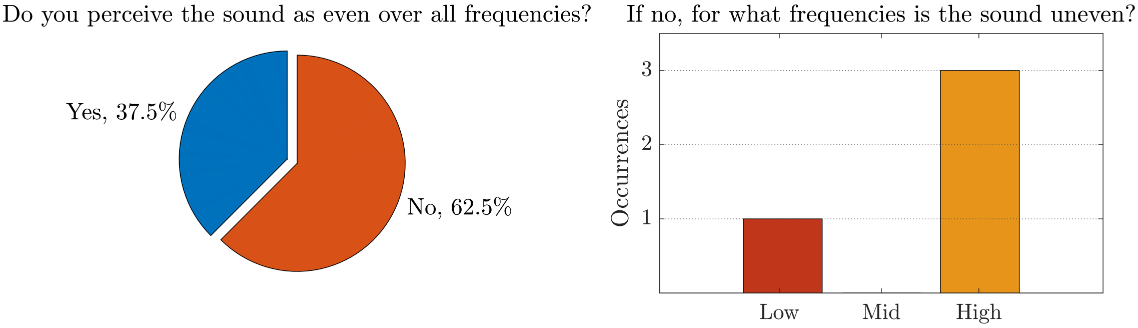

Do you perceive the sound as even over all frequencies?

If no, for what frequencies is the sound uneven?

Figure 4.4: Rated evenness for setup with zero diffusers.

One Diffuser

Figure 4.5 shows the result of the rated evenness for the setup with one diffuser. The ratio of participants who perceived the sound as even were 37.5%. Of the remaining 62.5%, one participant answered that the frequencies were more uneven in the lower frequency region and three participants answered that the sound was more uneven in the higher frequency region.


Do you perceive the sound as even over all frequencies?

If no, for what frequencies is the sound uneven?

Figure 4.5: Rated evenness for setup with one diffusers.

Three Diffusers

Figure 4.6 shows the result of the rated evenness for the setup with three diffusers. Most participants, 87.5%, perceived the sound as even over all frequencies. Only one participant perceived the sound to be uneven over the frequencies range for high frequencies.

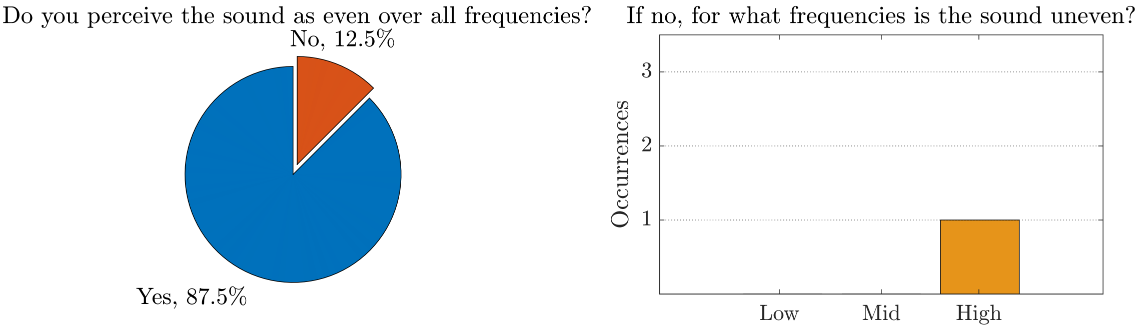


Figure 4.6: Rated evenness for setup with three diffusers.

4.1.3 Rated quality of rehearsal

On the measure of rated quality of rehearsal the participants were asked three questions. These questions were in order: 1. What is your overall impression of the room with this setup? 2. How do you perceive the sound in comparison to the previous setup? 3. What setup did you prefer the most? Five participants did the subjective assessment on-site starting with no diffusers, and then adding one diffuser, and lastly three diffusers. Three participants performed the test in the opposite direction so that the possibility that order of assessment would influence the result would be removed. For the answers relating to the participants which did the assessment backwards, the question which relates to figure 4.8 was inverted.

On the question of the overall impression of the practice room the participants seemed to agree that three diffusers was the best for rehearsal, as can be seen in Figure 4.7. The result also displays a very low p-value indicating that the trend is statistically significant. However, on the last question of the survey which asked what setup the participant preferred the most, half of the participants answered the setup with one diffuser, and the other half answered the setup with three diffusers.

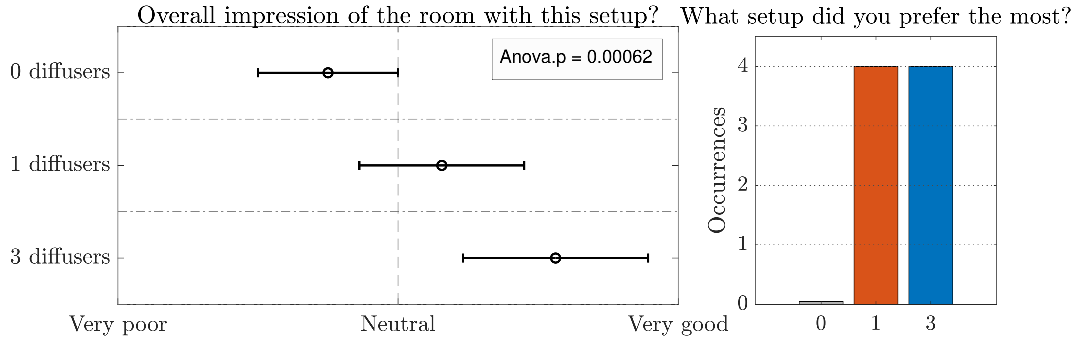


Figure 4.7: Answers relating to questions on which setup the participants thought provided the best rehearsal environment.

Figure 4.8 shows the arithmetic means and confidence intervals according to a student's t-distribution comparing how the acoustics change with increasing diffusers. The result shows that the increase in acoustical quality was slightly higher when changing from zero to one diffusers, in comparison to changing from one to three diffusers. However, both changes are rated fairly equal with the exception of zero to one having a better confidence interval. The p-value is not low enough to indicate any statistical significance however.

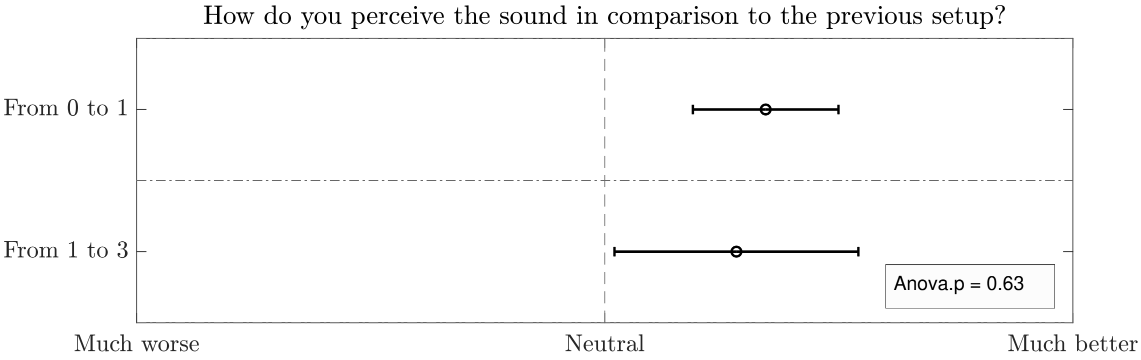


Figure 4.8: Answers relating to the question on how the participants perceived the current setup in regards to the previous. For participants performing the assessment backwards their answers have been inverted.

4.1.4 Qualitative interviews with the participants

In addition to each participant playing their instrument and answering the survey questions, a qualitative interview was conducted with each participant. This was done to complement the quantitative answers of the survey. In this section a summary of each participants answers is presented. Participant 1-5 performed the assessment starting with no diffusers, then adding one diffuser, and lastly for three diffusers. Participants 6-8 performed the assessment in the other direction starting with three diffusers.

Participant 1 - Song and Guitar

Participant 1 said that that with no diffusers the room was too live and too loud and the balance was a bit too brilliant. With one diffuser, the acoustics became less live, however participant 1 conveyed that it was difficult too assess if this was an audible difference or if it was because participant 1 expected there to be a difference. Finally having a setup of tree diffusers, participant 1 perceived the room as even more dry, but at the same time the sound was also less brilliant and more pleasant. Overall participant 1 preferred tree diffusers and thought that this setup provided the best acoustics.

Participant 2 - Song

Participant 2 perceived the setup with no diffusers as live, saying that there was a lot of response from the room, but at the same time the liveness was very short and "sudden". Participant 2 perceived the mid frequencies as being very amplified and the overtones and higher frequencies sounding rather distorted. Participant 2 perceived that when adding more diffusers the lower frequencies was given a richer tone while the mid and higher frequencies was attenuated making the sound overall more even. Participant 2 preferred the setup with tree diffusers.

Participant 3 - Amplified Guitar

Participant 3 perceived the setup with no diffusers as very bass heavy, and felt that the room did not help with the acoustics at all. Participant 3 described the liveness as very unpleasant and annoying. When adding more diffusers participant 3 described that the higher frequencies got more defined and the room became more balanced. Participant 3 perceived the difference between one and 3 diffusers as very minor, but added that the difference may be that the strength along with the bass was reduced a bit. Participant 3 preferred the setup with one diffuser stating that this provided the best acoustics, while also maintaining some of the liveness of the room.

Participant 4 - Acoustic Guitar

When asked about the setup with no diffusers participant 4 was neutral to the acoustics and perceived the room as neither good or bad. However, changing the setup to one diffuser made a huge difference according to participant 4. Participant 4 perceived the room with one diffuser as more live, warm and rich than for no diffusers. The strength of the room was also more pleasant for one diffuser making practicing less strenuous. Changing the setup to three diffusers made no major difference according to participant 4, and reasoned that most difference was between zero and one diffusers. Participant 4 preferred the setup with one diffuser with the motivation that there was no audible difference between one and three diffusers.

Participant 5 - Song

Participant 5 perceived the room as having a "distorted liveness" with the setup with no diffusers. Higher frequencies felt a bit dissonant and overall the sound felt very uneven over all tones. Participant 5 said that certain tones gave resonances, while others did not for the setup of no diffusers. For one diffuser the liveness was more pleasant and felt more natural for the higher pitched tones but participant 5 maintained that something was off with the timbre. When changing the setup to three diffusers participant 5 noticed a major difference for the better. Participant 5 thought that the sound became very dry, but said that the dryness of the sound was also suitable and expected for a room of this size. Participant 5 said that with three diffusers the room felt pleasant and there was more control over the voice and the acoustics. Participant 5 preferred the setup with three diffusers.

Participant 6 - Song and Guitar

Participant 6 perceived the room with three diffusers as very good. Participant 6 said that the room was very dry with this setup, but that it was also very pleasant to practice in. When changing to the setup with one diffuser participant 6 said that the room felt more live, but also more "boomy" in the lower bass region. The definition in the higher frequencies felt cluttered, making it very difficult to perceive the voice for this setup according to participant 6. Finally, when changing the setup to no diffusers participant 6 said that the issues got even more prominent. The lower frequency region was even more amplified, making it even more difficult to sing and play the guitar at the same time. Participant 6 said that the room felt very unbalanced and that it was necessary to restrain the guitar playing in order to get good feedback of the voice. Participant 6 preferred the setup with three diffusers.

Participant 7 - Flute

Participant 7 perceived the room with three diffusers to be a little bit too dry. This was especially prominent when practicing staccatos. Participant 6 said that the room felt fairly balanced and that no tones distinctly stood out with the setup of three diffusers. When changing the setup to one diffuser, participant 7 said that the room felt more loud and more live, and changing the setup to zero diffusers made the room even more live. Participant 7 preferred the setup with one diffuser.

Participant 8 - Song

For the setup with three diffusers participant 8 perceived the higher pitched tones to stand out but said that the room otherwise felt very pleasant to practice in. When changing the setup to one diffuser participant 8 said that the room felt a little bit exposed, but that there was not a huge difference in comparison to the setup with three diffusers. For zero diffusers the difference was substantial in comparison to one diffuser, and participant 8 said that the room was a lot more live for this setup. Participant 8 perceived the room to be a little bit too live for no diffusers and that the character of the liveness was "sudden" in an unpleasant and harsh way.

Participant 8 compared the unpleasantness of the character of the liveness to when one is talking on the phone and suddenly hears their own voice from the other end.

4.2 Subjective Listening Test

In the following section the results from the subjective listening test is presented. The test consisted of two parts, where part one was a comparison test and part two was a preference test. The subjective listening test was performed in Artemis sQala using violin recordings made in the small practice room from a binaural head. The purpose of the comparison test was to investigate if there were any audible differences between recordings when using different diffuser setups and to remove any visual impression of the diffusers. The purpose of the preference test was to compare with the subjective listening assessment on-site. There were 21 participants in total, all with various music backgrounds.

4.2.1 Comparison test

For the comparison test the participants were asked to listen to 12 comparisons. Each comparison comprised of one reference recording and two recordings to compare with the reference recording. One of the comparison recordings had the same amount of diffusers as the reference recording. The participants were not disclosed how many diffusers the reference recording had and the order in which they listened to the recordings was randomized.

In Table 4.1 the results from the comparison test is presented for all 12 comparisons and shows the percentage of answers of which comparison recording was perceived as being the same as the reference recording.

Table 4.1: The results of the 12 different comparisons with reference recordings (rows) and the two recordings being compared (column).

	0D,R.1	**0D,R.2**	**1D,R.1**	**1D,R.2**	**3D,R.1**	**3D,R.2**
1. 0D,R.1	-	**81%**	19%	-	-	-
2. 0D,R.1	-	**57%**	-	-	43%	-
3. 0D,R.2	**71%**	-	-	29%	-	-
4. 0D,R.2	**62%**	-	-	-	-	38%
5. 1D,R.1	48%	-	-	**52%**	-	-
6. 1D,R.1	-	-	-	**38%**	62%	-
7. 1D,R.2	-	76%	**24%**	-	-	-
8. 1D,R.2	-	-	**57%**	-	-	43%
9. 3D,R.1	43%	-	-	-	-	**57%**
10.3D,R.1	-	-	52%	-	-	**48%**
11.3D,R.2	-	52%	-	-	**48%**	-
12.3D,R.2	-	-	-	38%	**62%**	-

Figure 4.9 is a graphical representation of Table 4.1 depicting the percentage of responses for participants who perceived that the comparison recording with the same amount of diffusers as the reference recording to be the most similar. The result shows that the percentage of correct answers is highest when comparing zero diffusers with one diffuser when recording 0.1 is used as the reference recording compared with 0.2 and 1.1. The lowest percentage of correct answers is when one diffuser is compared with zero diffusers when recording 1.2 is used as the reference recording and recordings 1.1 and 0.2 are used as the comparison recordings. A chi-square goodness-of-fit test was also done, with the assumption that the expected result would be 50% if participants could hear no difference. The results show that the null-hypothesis is not fulfilled meaning that the results are statistically significant.

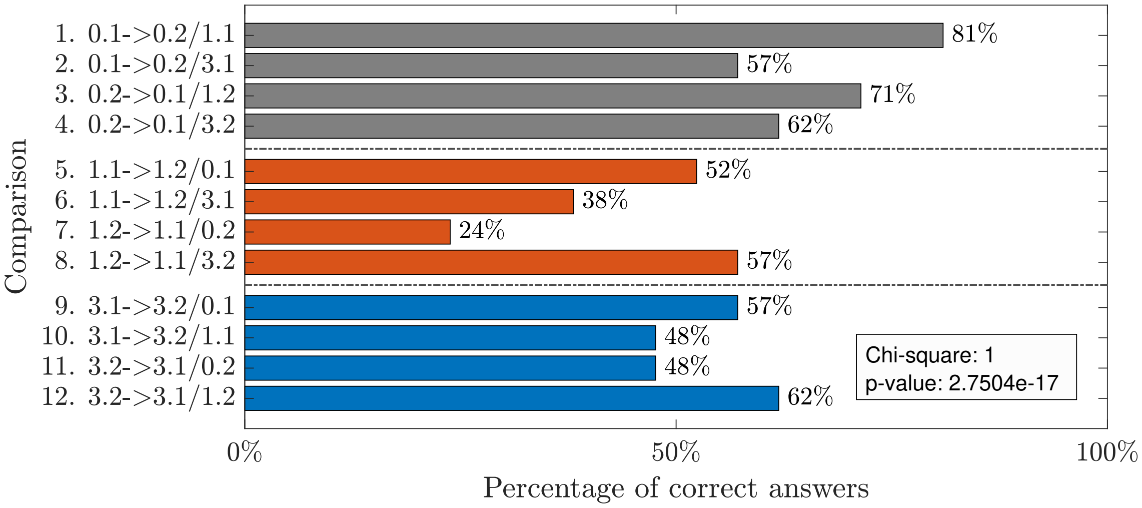


Figure 4.9: Graphical representation of table 4.1. Shows the percentage of correct answer for each comparison. (Abbreviation 0.1 reads "0 Diffusers, Recording 1" etc).

Figure 4.10 depicts the total percentage of correct answers when combining the recordings with the same amount of diffusers. The result shows that there is no clear indication that the participants could hear a difference between recordings with different amount of diffusers. The comparisons which yields the highest percentage is the comparison between zero and one diffuser and the lowest percentage is when comparing one and zero diffusers, which is contradictory. If the participants would not be able to hear a difference the result would be close to 50%. A result much higher than 50% would indicate that the participants can hear a difference, and a result much lower than 50% would indicate that the participants could hear a difference, but not correlating to number of diffusers.

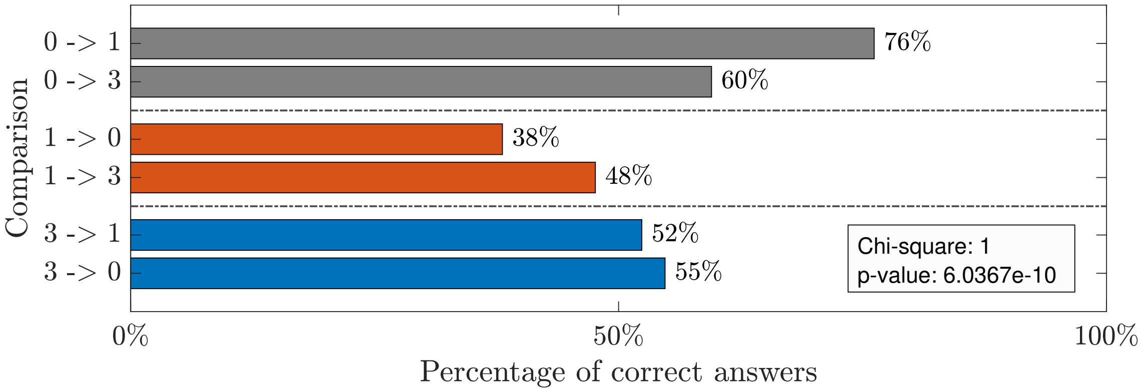


Figure 4.10: Simplified version of Figure 4.9 combining the recordings with same amount of diffusers.

4.2.2 Preference recordings

In addition to being asked to compare the different recordings, each participant was also asked to rate the recordings for how much they preferred the recording. The participants were asked to rate the recording as if they were the violinist practicing in the small practice room. The arithmetic mean as well as the confidence intervals using a students t-distribution is presented in Figure 4.11.

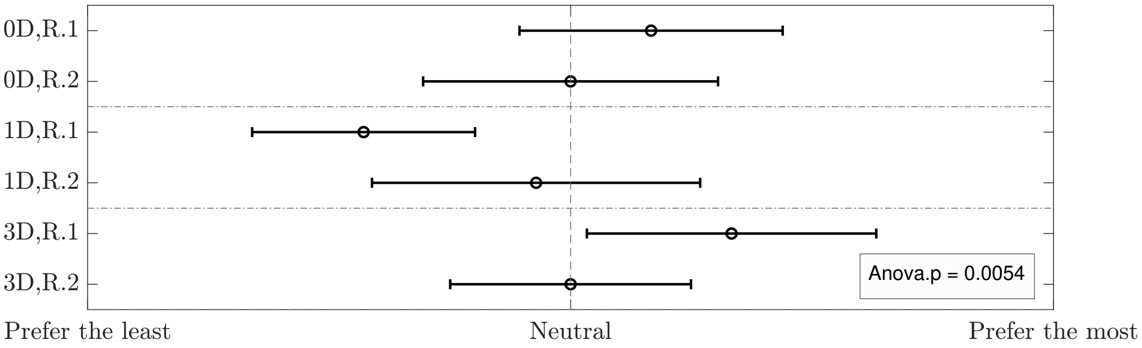


Figure 4.11: Arithmetic mean and confidence intervals according to a students t-distribution indicating preference of each recording. The participants were asked: "Imagine that you are practicing in the small practice room. How would you rate the different recordings?"

The result shows that the participants preferred recording 3D,R.1 the most and recording 1D,R.1 the least. Recording 0D,R.2, 1D,R.2 and 3D,R.2 were all rated neutral, with 1D,R.2 being slightly less preferred. The overall result indicates that the participants preferred the recordings with the setup with zero diffusers and three diffusers the most, and the setup with one diffuser the least. No trend can be seen that preference correlates with amount of diffusers. There is also a great variability between the recordings of the same setup.

4.3 Room acoustic parameters

Room acoustic parameters were obtained in the small practice room using a sine sweep and the measurement system IRIS. Six microphone positions and two source positions were used and averaged over positions for each setup of diffusers. The signal-to-noise ratio for the system is shown in figure 4.12. The signal-to-noise ratio >45dB for all octave bands which is sufficient according to ISO 3382-2:2009 [27].

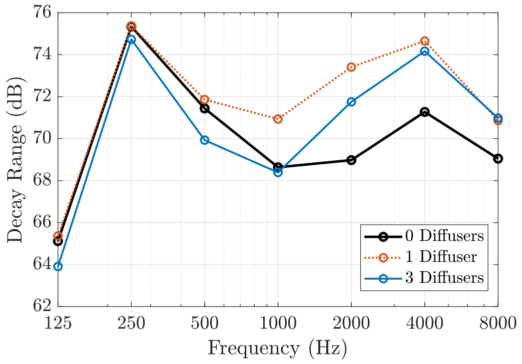


Figure 4.12: Dynamic range of the decay curve, which is the signal-to-noise ratio of the impulse response.

In Figure 4.13 the early decay time and the reverberation time (T20) is shown for zero, one and three diffusers. The result shows that the EDT has a peak at 250 Hz for zero diffusers and that the peak disappears when adding diffusers. The EDT is lower for all frequencies with added diffusers, but the most significant attenuation is for frequencies below 1000 Hz, and especially for 250 Hz. When studying the reverberation time (T20) a significant decrease can be seen for all frequencies when increasing amount of diffusers, but especially for the octave bands ranging from 250 to 4000 Hz, with the octave band for 1000 Hz being the most attenuated.

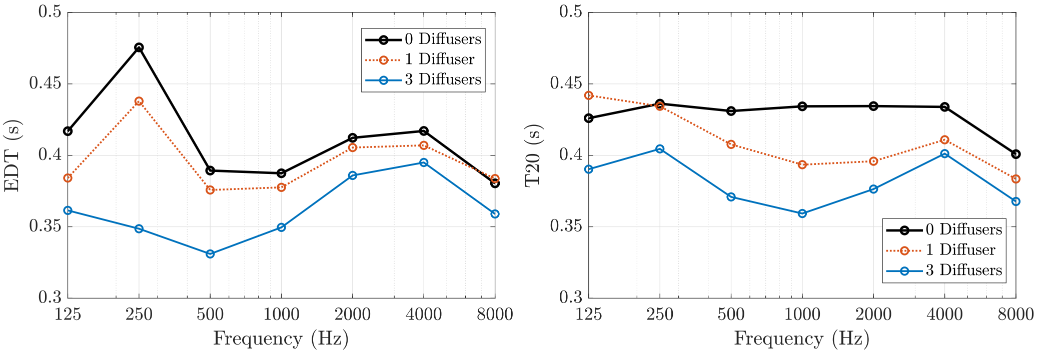


Figure 4.13: Early decay time (left) and Reverberation time, T20 (Right) of the small practice room.

In Figure 4.14 the clarity (C50) and the definition (D50) is shown. The clarity and definition increases with added diffusers and the most significant increase is for the octave bands 125 Hz, 250 Hz and 500 Hz.

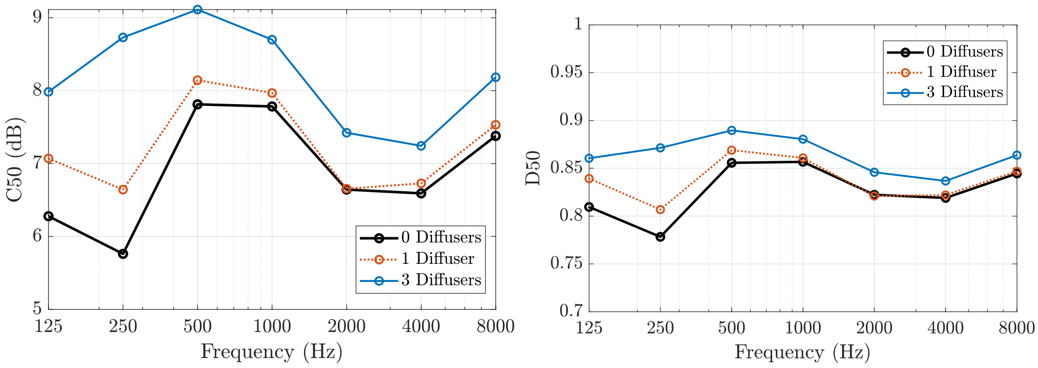


Figure 4.14: Clarity (left) and Definition (right) of the small practice room.

In Figure 4.15 the centre of gravity in time is shown as well as the early strength of the small practice room. The centre of gravity in time is lower for all octave bands when adding diffusers. However, the 250 Hz octave band is slightly more decreased than other octave bands when comparing three diffusers with no diffusers. When studying the early strength a decrease in lower frequencies can be seen when adding diffusers. Both the 250 Hz octave band and the 125 Hz octave band is attenuated. Frequencies at 500 Hz, 1000 Hz, 2000 Hz, and 8000 Hz are also slightly amplified, while 4000 Hz is slightly attenuated.

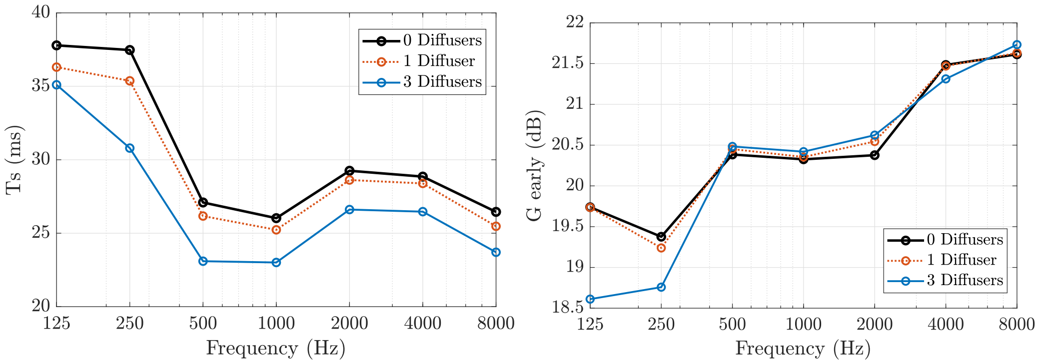


Figure 4.15: Centre of gravity in time (left) and Strength (right) of the small practice room.

4.4 Binaural measurements

A binaural impulse response has been measured in the small practice room using the same source and receiver positions as the recordings used for the subjective listening test. These measurements aims at investigating early reflections and any visible indications of coloration due to comb-filtering. As previously established, early reflections above -20 dB and within 35 ms of the of the direct sound may have coloration effects due to comb-filtering. The results are presented for both left ear and right ear. The right ear is facing the wall with two diffusers and the left ear is facing the wall with no diffusers, see Figure 3.6 for diffuser position as well as source and receiver positions.

4.4.1 Coherence

Figure 4.16 depicts the coherence for both input signals (left and right ear of the binaural recording head HMS V). The signals have a strong coherence in the range 100 Hz to 16 kHz. The loudspeaker used was however limited to be omnidirectional between 50 Hz and 6300 Hz, which further restricts the valid frequency range to 100 Hz - 6300 Hz.

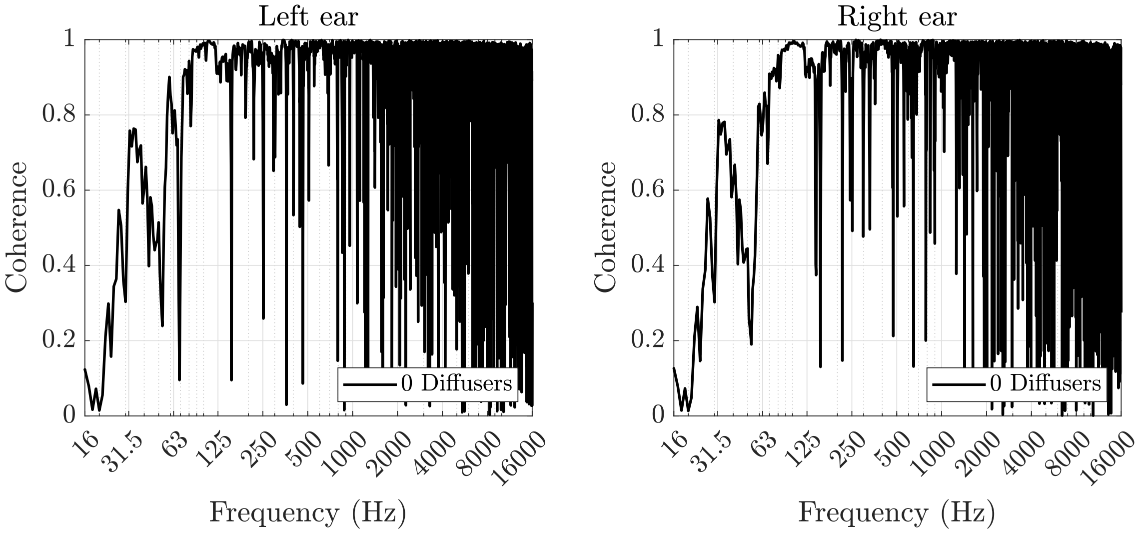


Figure 4.16: Coherence of impulse response measurement for binaural recordings.

4.4.2 Impulse response

Figure 4.17 depicts the impulse response of the room for the left and right ear of the binaural head at the measurement position. From Figure 4.17 it is evident the reverberation time is shorter for three diffusers than for no diffusers.

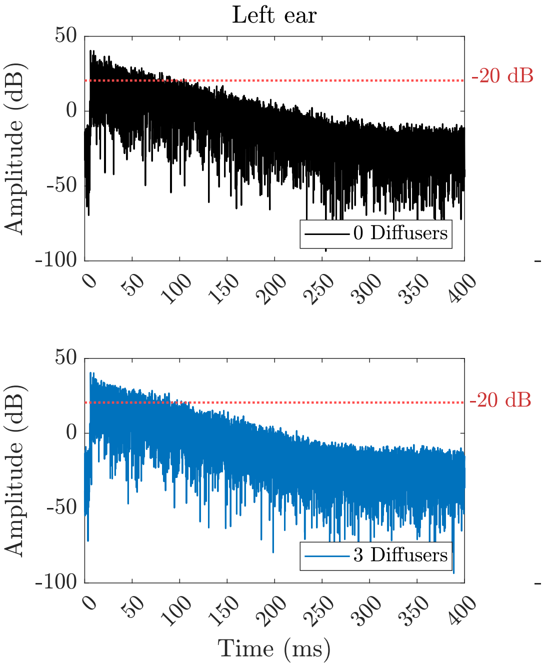


Figure 4.17: Impulse response (dB) of binaural measurement for no diffusers compared with three diffusers. The red dotted line marks the -20 dB of direct sound threshold.

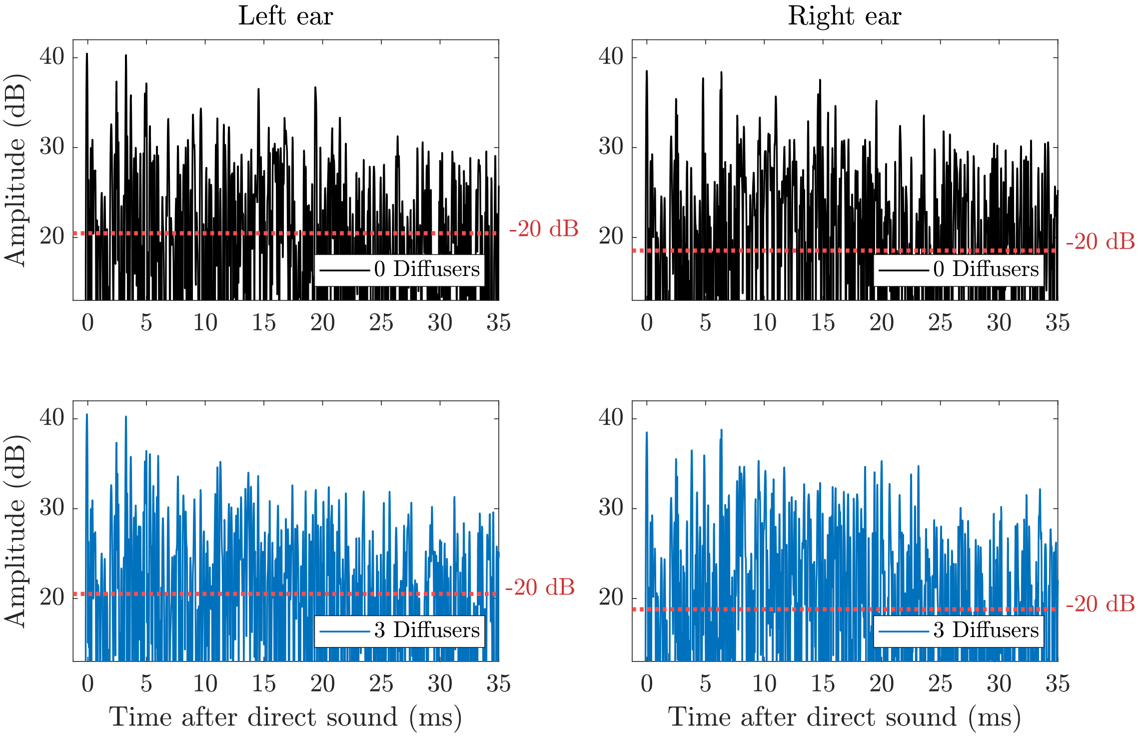


Figure 4.18: Impulse response (dB) of binaural measurement for the first 35 ms for the setup with no diffusers compared with three diffusers. The red dotted line marks the -20 dB of direct sound threshold.

Figure 4.18 shows the sound pressure level of the first 35 ms after the direct sound. Reflections within 35 ms of the direct sound in the impulse response are important parameters since the reflections within this time interval may contribute to coloration (see Figure 2.5). The results show that within 35 ms after the direct sound most of the reflections for both setups have an amplitude above -20 dB of the direct sound. When increasing the number of diffusers, the amount of reflections seems to increase, while simultaneously attenuating the amplitude of certain strong reflections. This causes the reflections to be more even and more steadily decaying for three diffusers than for zero diffusers. This is especially visible for the left ear in the region between 3 ms - 30 ms. Studying the right ear the same can be seen, although this change is less obvious than for the left ear.

In order to distinguish strong reflections, the impulse response was also plotted for sound pressure, see Figure 4.19. Figure 4.19 shows similarly to Figure 4.18 that increasing the amount of diffusers introduces more reflections. A general trend is seen for both left and right ear in that most amplitudes are reduced for strong reflections. With an increase in reflections, the impulse response generally exhibits a denser, but also more steadily decaying pattern. This is especially apparent for the left ear. However, for the right ear at the range of 4 ms - 5 ms, and at the range of 18 ms - 23 ms, the reflections are only decreased slightly in amplitude when increasing number of diffusers. Instead, new reflections are introduced almost equal in strength to the already existing amplitudes at these ranges. However, the impulse response also exhibits less of a periodic pattern when introducing diffusers, which is especially evident for the right ear. A clear periodic pattern emerges in the range 15 ms - 25 ms for no diffusers, which is then removed for three diffusers.

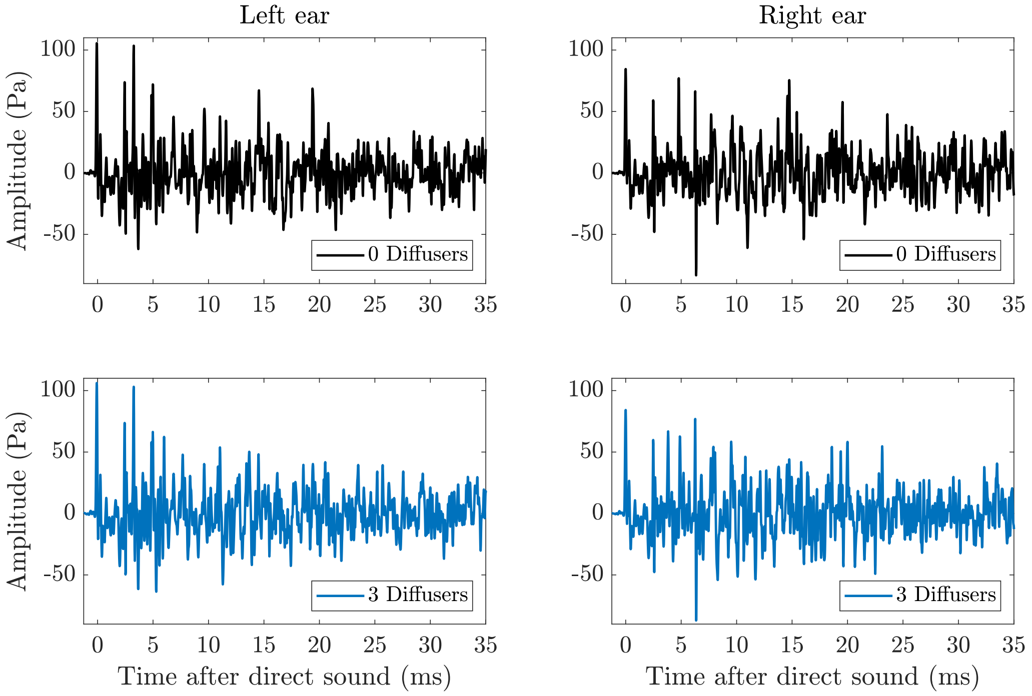


Figure 4.19: Impulse response of binaural measurement for the first 35 ms for the setup with 0 diffusers compared with 3 diffusers.

4.4.3 FFT of early reflections

The FFT of the impulse responses has been plotted in Figure 4.20 for the first 35 ms in order to spot any indication of comb-filtering according to the method introduced by Halmrast (that coloration due to comb-filtering is best discerned for the FFT of early reflections). The impulse response in Figure 4.18 showed that more reflections were introduced with an increasing amount of diffusers, and that most reflections within 35 ms were above -20 dB of the direct sound. The reflections were however more steadily decaying and even for three diffusers than for zero diffusers. The reflections also exhibited a less periodic pattern when adding diffusers.

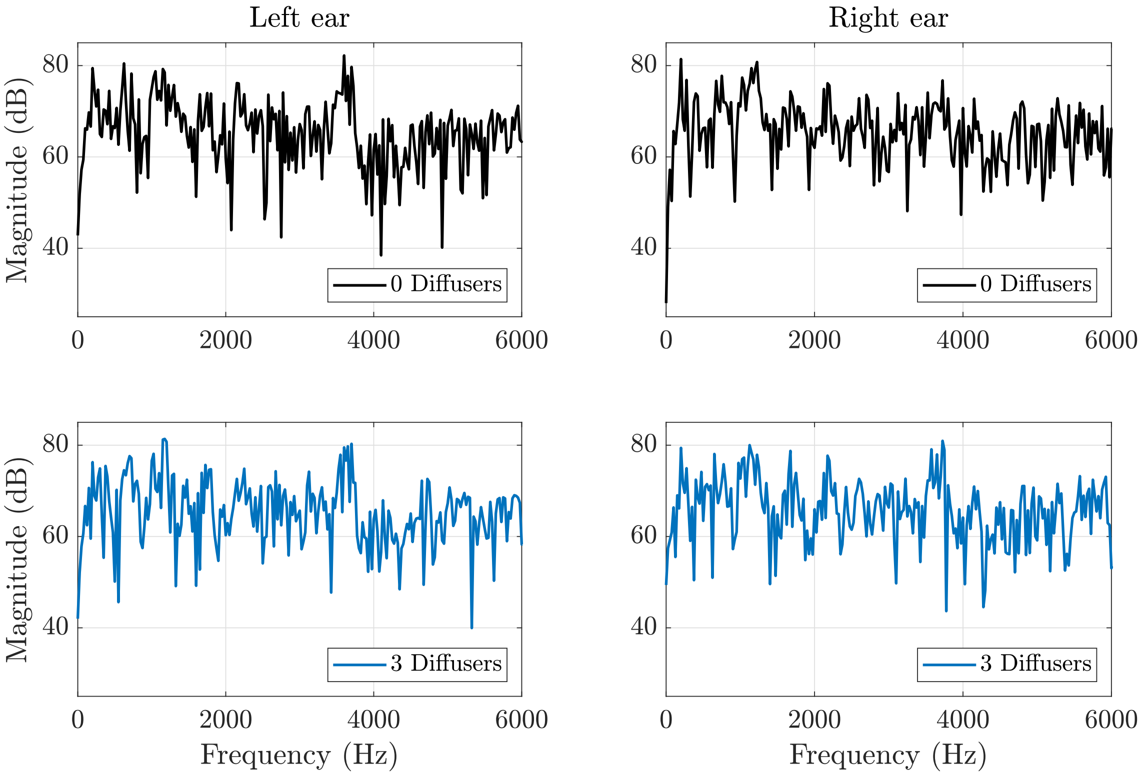


Figure 4.20: FFT of the impulse response of binaural measurement for the first 2048 samples which corresponds to the first 0.4 seconds.

The FFT of both ears suggests that coloration has not been reduced by the diffusers, and there is some minor indication that coloration instead might have been slightly increased. This is most apparent for the right ear, which faced the diffuser wall. Some indication of coloration due to comb-filtering can be seen since the peaks at 1800 Hz, 2200 Hz, and 3700 Hz are stronger for three diffusers than for no diffusers. The stronger peak at 3700 Hz makes the FFT of the right ear and the left ear more similar for three diffusers however, which might suggest that the sound field is more diffuse at the position of the binaural head for three diffusers. For the left ear there is some indication that coloration might have slightly been reduced in the area between 1500 Hz - 3000 Hz. However, the area above 4000 Hz instead seems to exhibit a slightly stronger comb-filtering pattern for three diffusers than for zero diffusers.

4.4.4 Transfer function of the full signal

Comments by Mendel and Tichy was that sixth octave bands is a good representation for the human ear. The transfer function of the full impulse response of the room has therefore been plotted in sixth-octaves with a window length of 51200 samples, see Figure 4.21. The transfer function takes into consideration reflections occurring for the full signal length of one second.

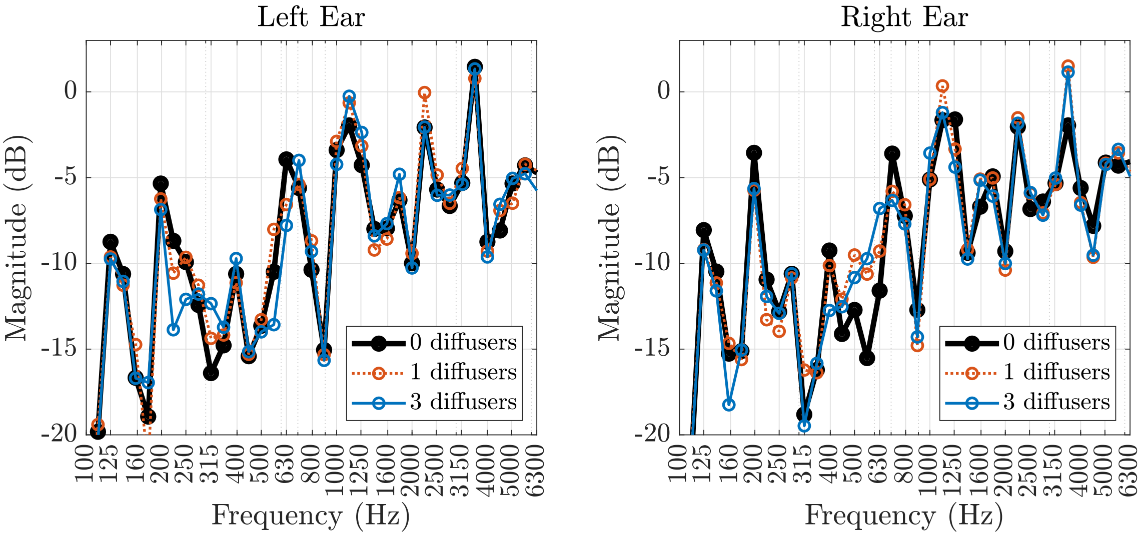


Figure 4.21: Transfer function of the full signal in sixth octaves.

The result shows that by adding diffusers the magnitude is generally reduced at lower frequency bands and increased at higher frequency bands. At mid frequencies certain frequency bands are amplified while other frequency bands are attenuated. This can be seen at 400 Hz and 800 Hz where the magnitude for more diffusers are attenuated, while amplified at 550 Hz.

5

Discussion

5.1 Discussion on Results

The results has been obtained from the investigations for the subjective assessment on-site, subjective listening test, room acoustic parameters, and binaural measurements. This section will discuss the results of each individual investigation, followed by a discussion on the implications of the overall findings.

5.1.1 Subjective assessment on-site

The subjective assessment on-site involved eight musicians with varying levels of music experience and asked each participant to answer a survey on how they perceived the acoustics when practicing their instruments with the different diffuser setups. When asked about their preferred setup, an equal number of musicians answered one diffuser and three diffusers, as shown in Figure 4.7. However, each participant was also asked to rate how good each current setup was for rehearsal when they were playing. This result clearly indicated that the setup with three diffusers provided the best acoustics for rehearsal. The result is supported by a low p-value (p«0.05) from the ANOVA test, suggesting that the result is also statistically significant. However, it is important to consider the limited number of participants, instruments, and the varying levels of music experience among the participants when interpreting these results.

The results regarding perceived loudness, liveness and balance, seen in Figures 4.1, 4.3, 4.2, demonstrated that the setup with 3 diffusers was the most neutral overall. However, only the perceived liveness may be seen as statistically significant since this result was the only result that had a p-value below 0.05. This suggests that the participants were less in agreement in their responses regarding perceived loudness and perceived balance. Having more participants might have made these results more reliable. The higher p-values for perceived loudness and perceived balance might also be a consequence of the participants being unsure of what to listen for, or having a different perception of what the different parameters would sound like.

The participants were also asked to answer a question regarding whether they perceived the sound as even over all frequencies. This question evaluated balance, similar to the assessment in Figure 4.2, but with a different approach. The participants were informed that unevenness of sound meant that certain tones would be accentuated, sounding peculiar or even abnormal. Although there were no consensus among the participants regarding at which frequencies the sound seemed uneven, an evident pattern emerged indicating that participants perceived the sound as more even overall with added diffusion.

The participants were also asked if they could perceive any difference between setups, as shown in Figure 4.8. The results show that the mean values for perceived improvement of adding one diffuser from a setup without any diffusers was slightly greater than the improvement observed when adding two diffusers to an already existing setup with one diffuser. This implicate that participants perceive the greatest difference for the first diffuser added, and that the change may be seen as less with an increasing amount of diffusers. However, this the result had a p-value of 0.63, which is much greater than 0.05, and more participants would have been needed to truly assess whether this is accurate or not.

When comparing the results of the survey with the qualitative interviews of each participant it is evident that while the consensus was that three diffusers sounded very good, participants also perceived this setup as slightly too dry. However, more diffusers seemed to remove an unpleasant liveness present in the room for zero diffusers and for one diffuser. The participants described this in different ways, but most participants seemed to agree on that certain tones sounded peculiar or abnormal and that the liveness was "too sudden" or "too strong" making it strenuous and unpleasant to practice in the room with zero diffusers.

5.1.2 Subjective listening test

The objective of the subjective listening test was to remove the visual stimuli of the room and to investigate if differences between diffuser setups were audible from binaural recordings. The binaural head was placed in front of the violinist and the participants listened to the recordings as if they were standing in front of the violinist. For the recordings a violinist played a piece from Bach BWV 1005 - III. Largo and tried to play as similarly as possible for all recordings. Six recordings were made in total, with two recordings for each setup of zero, one, and three diffusers. Each participants performed the listening test in the audio listening environment software Artemis sQala for both a comparison test and a preference test. In order to interpret the results from the comparison test a chi-square goodness-of-fit test was performed to investigate the statistical reliability of the results. If participants were unable to hear a difference between recordings the percentage of correct answers would be close to 50%. The chi-square goodness-of-fit test was conducted to test this hypothesis and the result indicated that the null-hypothesis could be rejected at the 5% significance level. This suggests that that there was an audible difference between recordings. The result was also statistically significant with a p-value « 0.05.

When interpreting the results, see Section 4.2, there was no clear indication that participants could hear a difference between different diffuser setups. The highest amount of correct answers was when zero diffusers was used as a reference recording and compared with one diffuser, but when one diffuser was used as a reference recording and compared with zero diffusers a strong negative correlation was obtained. The expected result would be that these would yield similar amount of correct answers. Furthermore, if participants could hear a difference between diffuser setups, the percentage of correct answers when comparing zero and one diffusers, as well as one and three diffusers would be smaller than the percentage of correct answers when comparing zero and three diffusers. However, no such findings could be seen, indicating that the result was heavily influenced by other contributing factors. One such influence may have been differences in how the violinist is playing. This is further evident when interpreting the results for preference. Figure 4.11 demonstrated that the difference in correct answers between recordings with the same amount of diffusers was larger than the difference in correct answers between recordings of different diffusers, indicating that the violinist was indeed playing differently.

5.1.3 Room acoustic parameters

The room acoustic parameters were obtained using an omni-directional loudspeaker and an ambisonic microphone averaged over multiple measurement positions. The decay range showed a signal-to-noise ratio above 45 dB, indicating that the results were not affected by background noise. The measurements were made in accordance with ISO 3382-2:2009 [27]. When analyzing the results in Figure 4.13 for EDT and T_{20} it can be interpreted that the diffusers are mainly absorptive in the region of 250 Hz, while being primarily diffusive in the region around 1000 Hz. This is evident since the 250 Hz octave band is notably attenuated for EDT, while remaining longer for T_{20}. For T_{20} the 1000 Hz and nearby octave bands are instead the most attenuated. T_{20} takes into consideration reflections for a longer time-frame than EDT which would make the influence of a shorter mean-free-path apparent, which diffusion contributes to. This result is predicted from literature, where a semi-cylinder diffuser of this size would act as a membrane absorber at lower frequencies and a spatial diffuser at higher frequencies around 1000 Hz.

Parameters relating to perceived clarity of sound is clarity, definition, and centre time. Each of these parameters were investigated as seen in Figures 4.14 and 4.15. The result showed that the diffusers added clarity and definition and reduced the centre time for all octave bands, but most notably at 250 Hz. This octave band is where the membrane absorption of the diffusers seems to be the most effective. When investigating early strength an attenuation could likewise be seen at lower frequencies, specifically at the octave bands 125 Hz and 250 Hz. The result suggests that the diffusers are effective in increasing clarity for all frequencies, but that this clarity is most likely attributed to an increase in absorption.

5.1.4 Binaural measurements

The binaural measurements were made to investigate comb-filtering effects and to see if there were any indication of severe coloration. The measurements had a good coherence from 100 Hz and the omni-directional speaker had a valid frequency range up to 6300 Hz, making the measurements valid in the frequency range of 100 Hz -

6300 Hz. When investigating coloration, early reflections are the most important. The measurements which looked at the first 35 ms of the impulse response suggests that when increasing the number of diffusers the amount of reflections increased while also attenuating strong reflections, see Figures 4.18 and 4.19. This is supported by literature, and is the primary objective of spatial diffusers, where spatial diffusers scatters the incoming sound wave into many smaller reflections. However, while some strong reflections were certainly attenuated, the question remains if they were attenuated enough in order to reduce coloration.

The impulse response demonstrated that reflections at the time interval of the first reflections from the semi-cylinder diffuser position created more reflections almost equal in strength to the reflection without any diffusers, and the attenuation of the existing reflection at this time interval was only minor. The FFT of the impulse response, seen in Figure 4.20, indicated a higher magnitude for the right ear for frequencies around 1800 Hz, 2200 Hz, and 3700 Hz when adding diffusers, which points towards the energy of the reflections beings greater around these frequencies. The peaks evident at 1800 Hz, 2200 Hz and 3700 Hz, increases the comb-filtering pattern slightly, and may therefore indicate an increased coloration effect. This may suggest that while the amplitude of the reflections in the time domain was attenuated slightly, the new reflections might have added to the comb-filtering pattern since they were almost equal in strength to the already existing reflection, making the comb-filtering pattern slightly more prominent. It is worth noting however, that a periodic pattern which could be seen for the right ear with zero diffusers at 15 ms - 25 ms, seemed to have been reduced with increasing diffusers. This might indicate that flutter echo has been treated using the diffusers. Flutter echo within 35 ms of the direct sound would appear as a comb-filtering pattern in the FFT however, and it is curious that there is no apparent visible improvement in the FFT for this when it was visible in the impulse response.

The peak at 3700 Hz is also evident for zero diffusers, but only for the left ear, and it is only when adding diffusers that this peak also is introduced for the right ear. When studying the FFT of the left and right ear and comparing for zero and three diffusers, the FFT of both ears seems to be more symmetrical for three diffusers. This may be an indication that the diffusers makes the sound field in the room more diffuse, so that the sound is more even at all positions. Studying the transfer function in Figure 4.21 it can likewise be seen that the transfer function with three diffusers for left and right ear are more similar than the left and right ear for zero diffusers. However, this may also be a consequence of a stronger comb-filtering effect from the energy of the higher frequencies being being amplified at the right ear. Since the absorption was likewise increased, it is unlikely that the sound field would be more diffuse overall over a longer time window.

5.1.5 Findings and implications derived from the results

The findings and implications derived from the results suggests that while participants preferred diffusers in the small practice room, the preference for diffusers may or may not be related to any diffusive qualities, but rather to absorptive qualities.

This is suggested since the comb-filtering pattern in the frequency domain, which diffusers are supposed to improve, was not improved when introducing the diffusers into the small practice room. It could instead be argued that it appeared to be slightly worse, indicating more coloration. This might have been a consequence of strong reflections being introduced while the already existing strong reflections were not attenuated enough, which would be a consequence of the small volume of the room. The semi-cylinder diffusers was however shown to increase absorption across all octave bands, which is possibly attributed to membrane absorption in lower frequencies and a decrease in the mean-free-path for mid to higher frequencies where the diffuser would be effective.

Any change in the frequency domain introduced by increasing diffusers was not audible so that participants would prefer the setup with zero diffusers over one or three diffusers. In the listening test in Artemis participants could not differentiate between recordings and in the subjective assessment on-site participants preferred more diffusers. With no diffusers, participants complained on-site that the reflections of the room was harsh, sudden, and unpleasant, while being balanced and pleasant, although a bit dry, with more diffusers. It is difficult to truly access if the reflections changed subjectively in character since these reflections were also likely less noticeable due to the higher absorption. The FFT suggests that coloration might have increased slightly, however, a less periodic pattern was also observed in the impulse response of the binaural measurements, which might have improved the sound quality by removing flutter echo. An additional observation by an earlier master thesis by Sandaker, was that participants preferred rooms with low reverberation times and more evenness in amplitude for the first 15 ms of the impulse response. The diffusers did increase the evenness in this range, and the result correlates with Sandaker's conclusion, that participants would prefer this.

The listening test in Artemis suggests that changes in how the violinist was playing had a greater impact on sound quality in the small practice room than the setup of diffusers when participants listened to recordings made in the room. There were no indications that participants could hear a difference between different diffuser setups for this test, and the results suggests that participants instead based their comparisons on small changes in how the violinist was playing. The violin piece was cut short immediately after the last tone, removing any indications of reverberation. Since the reverberation time was indeed shorter when introducing more diffusers, this might suggest that it was partly the lowered reverberation time that participants preferred when they were practicing on-site, but could not perceive when listening to the recordings. However, more research would be needed to access this, particularly comparing diffusion directly with absorption.

5.2 Discussion on Method

The aim of the master's thesis was to investigate if general principles of diffusers could be applied in a small practice room and if diffusers made an improvement in these both subjectively and objectively. The method used in this master's thesis have provided some clarity to these questions. However, there are certain limitations which were introduced by the method, which should be taken under consideration when interpreting the results.

The subjective assessment on-site was highly restricted in amount of participants, their level of music expertise and the amount of different instruments used. For a statistical reliable result a larger amount of participants would have been needed. The results of this master's thesis may now be seen as guiding or suggesting, rather than definite. The subjective listening test had more participants however and the p-values of the ANOVA test suggests that these results are statistically significant and are not by mere chance. The listening test was shortened by using only one instrument and in order to make the listening test more statistically reliable and general for practice rooms more instruments and more comparisons could have been made.

When designing the subjective listening test two approaches were considered. Either record a live musician in the small practice room, or use a loudspeaker and play back an anechoic recording. Both approaches had different drawbacks and ultimately it was decided to record a live musician. When interpreting the results from the subjective listening test it was evident that the participants perceived differences in how the musician was playing. It may have been beneficial to use a recording instead so that small variations in how the musician is playing does not affect the result. However, this would have made the recordings that the participants listened to less accurate to how it sounded in the small practice room. It was further decided to use a binaural head in front of the participant instead of a binaural microphone headset placed on the participant's head. This was done to increase the playback quality. For a more accurate representation of a single student rehearsing in a small practice room, a binaural microphone placed on the student could have been used.

When deciding on what type of diffuser to investigate it was decided to use semi-cylinder diffusers for the investigation due to accessibility. These diffusers have inherit absorption, and previous investigations suggests that these do not remove coloration due to their lack of temporal dispersion. For a result providing better understanding of diffusers in general for small practice rooms another diffuser such as the Schroeder diffuser could have been used instead. However, using semi-cylinders provided a great understanding in the behavior of spatial diffusers in a small confined space and was relevant considering their widespread use around music facilities in Gothenburg.

5.3 Further research

This master's thesis has investigated the usage of semi-cylinder diffusers in small practice rooms, and some effects of adding semi-cylinder diffusers in a small practice room has been apparent. However, general principles for spatial diffusers such as this semi-cylinder diffuser may not be applicable for all spatial diffusers. Further research would be needed to ensure that the right diffusers are used and applied where they are needed. The results of this master's thesis indicate that any improvement in sound that participants may perceive in a small practice room using semi-cylinder diffusers may be attributed to an increase in absorption. Further investigations would be needed to investigate the audibility of any improvements that diffusers may yield in comparison to absorption alone.

The results were also exclusive for spatial diffusers, and further research on temporal diffusers would further ensure that diffusers are applied and used correctly to ensure satisfactory acoustical results. The sound field is also highly dependent on type of instruments and usage of the room. Further research is needed to investigate the effects of diffusers for different types of instruments and frequency ranges.

From the results it was apparent that the setup with three diffusers seemed to exhibit a more similar frequency response for both ears than for no diffusers, when using a short time window. There was some reasoning that this might have been due to the sound field being more diffuse for this setup, having introduced more reflections. In the literature study it was found in an earlier master's thesis that participants preferred rooms that were less diffuse according to a method called IACC, which measures the cross correlation between the ears. It would have been interesting to further analyze the results using this cross correlation, however, time did not permit for this, and will be left for future studies. Additional research which would greatly enhance the understanding of diffusers in small practice rooms would also be to study more specifically how comb-filtering changes when increasing the amount of reflections within the time interval contributing to comb-filtering.

6

Conclusion

The aim of this master thesis was to investigate diffusers in small music practice rooms. It did this by limiting its investigation to semi-cylinder diffusers and investigating the subjective experience using both an on-site investigation and a subjective listening test. Two objective analysis was also performed to investigate any differences on the impulse response and on other acoustical parameters. The conclusion will be summarized by answering the questions asked in the introduction.

- *Can the general principles and applications of diffusers be applied to small practice rooms?*

The results showed that the semi-cylinder diffusers behaved somewhat predictably for a small practice room. The semi-cylinder diffusers, which measured 1.2 m x 1.2 m, provided absorption in the lower frequency region and diffusion in the frequency region around 1000 Hz. The impulse response was more smooth, evenly dispersed and more steadily decaying having removed some strong reflections for a setup using three diffusers in comparison with zero diffusers. The reducing of coloration due to comb-filtering is stated to be the primary objective of diffusers in small practice rooms. Even though a periodic pattern indicating flutter echo was smoothed out in the impulse response, it could be seen in the frequency response that a comb-filtering pattern was not reduced by using the diffusers. This might have been due to added strong reflections in the early impulse response from the diffusers and that the already existing reflections was not attenuated enough. Some indication was also seen in that the frequency response was amplified at even higher frequencies by the added diffusers, which contributed to the frequency response exhibiting a slightly more prominent comb-filtering pattern. The findings from this report and this setup therefore suggests that general principles and applications of spatial diffusers may not be applied in small practice rooms, since their primary function was not achieved. Their function seems to be severely limited by the small sizes of these rooms, causing the introduced reflections to be too strong and the already existing reflections to not be attenuated enough.

- *How does the acoustical sound field change objectively and subjectively in a small practice room when increasing the amount of diffusers?*

The acoustical sound field of the room when introducing semi-cylinder diffusers mainly changed objectively by an increase in absorption as well as what could be interpreted as a slight increase in coloration due to comb-filtering. However, the increase in coloration may be seen as minor as there were no indications from the result of the subjective investigations that any coloration was heard. From the results of the subjective investigation-on site an improvement was seen in the acoustical quality of the room when adding semi-cylinder diffusers. The result demonstrated that while the semi-cylinder diffusers increased the perceived dryness, they also improved the perceived balance of the room. An increased evenness could also be seen in the impulse response for the first 15 ms when increasing the number of diffusers and earlier an master thesis have correlated this evenness for early reflections with an improved quality of sound.

- *Does the usage of diffusers yield favorable results compared to other acoustical treatment solutions in a small practice room?*

The results from the subjective investigation on-site showed that participants preferred diffusers. However, it was proven difficult to truly access if the character of the reflections changed subjectively since these reflections were also likely less noticeable due to higher absorption. Since the subjective assessment on-site favored diffusers, and that these diffusers were proven to be very effective in lowering the reverberation time, it might be implied that the preference of diffusers may have depended on an increase in absorption. This suggests that other acoustical treatment solutions with the primary objective of providing absorption may likely be used in favor of semi-cylinder diffusers in small practice rooms. More studies would need to be conducted where diffusion is compared directly with purely absorption to fully access this. However, what can be concluded is that the main function of a diffuser - to reduce coloration due to comb-filtering without removing sound energy from the room - seems to not be achieved for a semi-cylinder diffuser in this particular small practice room and with this setup.

Bibliography

[1] J. Ashbourn, “The Physics of Sound,” in *Audio Technology, Music, and Media From Sound Wave to Reproduction*, Cham, Switzerland: Springer International Publishing, 2021, ch. 4, pp. 15–21. DOI: `10.1007/978-3-030-62429-3`.

[2] M. Kleiner and J. Tichy, “Physics of Small Room Fields,” in *Acoustics of Small Rooms*, Boca Raton London New York: CRC Press, 2014, ch. 1, pp. 163–185, ISBN: 9780415779302.

[3] A. F. Everest and K. C. Pohlmann, “Fundamentals of Sound,” in *Master Handbook of Acoustics*, 5th ed., United States: McGraw-Hill, 2009, ch. 1, pp. 1–17.

[4] A. Everest and K. Pohlmann, “Modal Resonances,” in *Master Handbook of Acoustics*, 7th ed., United States: McGraw-Hill, 2022, ch. 13, pp. 241–276, ISBN: 9781260473599.

[5] L. Beranek, “The Language of Musical Acoustics,” in *Concert Halls and Opera Houses*, 2nd ed., New York: Springer, 1996, ch. 2, pp. 20–35.

[6] M. Kleiner and J. Tichy, “Geometrical Acoustics,” in *Acoustics of Small Rooms*, Boca Raton London New York: CRC Press, 2014, ch. 3, pp. 99–118, ISBN: 9780415779302.

[7] Kleiner and Tichy, “Sound fields in Enclosed Spaces,” in *Acoustics of Small Rooms*, Boca Raton London New York: CRC Press, 2014, ch. 2, pp. 99–118, ISBN: 9780415779302.

[8] A. F. Everest and K. C. Pohlmann, “Comb-Filter Effects,” in *Master Handbook of Acoustics*, 7th ed., United States: McGraw-Hill, 2022, ch. 10, pp. 143–160, ISBN: 9781260473599.

[9] T. J. Cox and P. D’Antonio, “Applications and principles of diffusers,” in *Acoustic Absorbers and Diffusers*, New York: Spon Press, Taylor Francis Group, 2004, ch. 2, pp. 23–57, ISBN: 0-415-29649-8.

[10] T. Halmrast, “Sound coloration due to reflections - further investigations,” *akuTEK*, 2013.

[11] A. F. Everest and K. C. Pohlmann, “Reflection,” in *Master Handbook of Acoustics*, 7th ed., United States: McGraw-Hill, 2022, ch. 6, pp. 101–113, ISBN: 9781260473599.

[12] T. J. Cox and P. D’Antonio, “Applications and principles of absorbers,” in *Acoustic Absorbers and Diffusers*, New York: Spon Press, Taylor Francis Group, 2004, ch. 1, pp. 6–22, ISBN: 0-415-29649-8.

[13] A. F. Everest and K. C. Pohlmann, “The Perception of Sound,” in *Master Handbook of Acoustics*, 7th ed., United States: McGraw-Hill, 2022, ch. 4, pp. 43–72, ISBN: 9781260473599.

[14] M. Kleiner and J. Tichy, “Diffusion,” in *Acoustics of Small Rooms*, Boca Raton London New York: CRC Press, 2014, ch. 5, pp. 163–185, ISBN: 9780415779302.

[15] T. J. Cox, “Acoustic diffusers: the good, the bad and the ugly,” *Proceedings of the Institute of Acoustics*,

[16] M. Kleiner and J. Tichy, “Small Rooms for Voice and Music Practice,” in *Acoustics of Small Rooms*, Boca Raton London New York: CRC Press, 2014, ch. 12, pp. 359–376, ISBN: 9780415779302.

[17] G. Ciaburro, G. Iannace, I. Lombardi, and A. Trematerra, “Acoustic design of ancient buildings: The odea of pompeii and posillipo,” *Buildings*, vol. 10, no. 12, pp. 1–16, Dec. 2020.

[18] L. L. Baranek, *Concert and Opera Halls: How they sound.* Acoustical Society of America, 1996, pp. 69–74.

[19] T. J. Cox and P. D. ’. Antonio, “A Brief History of Room Acoustic Diffusers,” *Acoustics Today*, 2006.

[20] A. H. Marshall and J. R. Hyde, “Some Preliminary Acoustical Considerations in the Design for the Proposed Wellington (New Zealand) Town Hall,” *Journal of Sound and Vibration*, vol. 63, no. 2, pp. 201–211, 1979.

[21] W. Fehlhaber, *Does the type of Diffuser matter?* 2015.

[22] A. F. Everest and K. C. Pohlmann, “Diffusion,” in *Master Handbook of Acoustics*, 7th ed., United States: McGraw-Hill, 2022, ch. 9, pp. 133–142, ISBN: 9781260473599.

[23] V. Sandaker, *Rehearsal Rooms for Acoustical Instruments-Comparing Measurements and Subjective Experiences*, Gothenburg, 2018.

[24] O. Olsson and D. Söderström Wahrolén, *Perceived Sound Qualities for Trumpet Players in Practice Rooms*, 2010.

[25] International Standard, *ISO 23591:2021, Acoustic quality criteria for music rehearsal rooms and spaces*, 2021.

[26] Standard Norge, *NS 8178:2014, Acoustic criteria for rooms and spaces for music rehearsal and performance*, 2014.

[27] Swedish Standard Institute, *ISO 3382-2:2008 - Acoustics-Measurement of room acoustic parameters-Part 2: Reverberation time in ordinary rooms*, 2008.

A

Appendix

A.1 Survey from Subjective Assessment On-site

Survey investigating the effects of diffusers

The purpose of this survey is to investigate how diffusers affect the acoustics of a small practice room. The result will be used anonymously in conjunction with other data in order to determine how many diffusers should be used in a practice room of this size.

This study only encompasses the audible effects of diffusers. Try to listen to differences in the sound with different amount of diffusers without focusing too much on other visual aspects.

Thank you for your participation!

Name:____ **Age**:_________ **Date**:_______________

Occupation:___________________________________ **Instrument:**_______________________________

In what type of room do you normally rehearse?____

How many hours a week do you rehearse your instrument?____

0 / 3 diffusers

Answer the following questions on how you perceive the acoustics of the room. There are no right or wrong answers. Try to answer as intuitively as you can.

1. How do you perceive the strength?

☐-4	☐-3	☐-2	☐-1	☐0	☐1	☐2	☐3	☐4
Too quiet				**Neutral**				**Too loud**

2. How do you perceive the liveness?

☐-4	☐-3	☐-2	☐-1	☐0	☐1	☐2	☐3	☐4
Too dry				**Neutral**				**Too live**

3. How do you perceive the balance?

☐-4	☐-3	☐-2	☐-1	☐0	☐1	☐2	☐3	☐4
Too warm				**Neutral**				**Too brilliant**

Comment:

4. Do you perceive the sound as even over all frequencies?

☐ **Yes** ☐ **No**

If no, for what frequencies is the sound uneven?

☐ **Lower pitch** ☐ **Middle pitch** ☐ **Higher pitch** ☐ **Can not tell**

Comment:

5. What is your overall impression of the room with this setup?

☐-4	☐-3	☐-2	☐-1	☐0	☐1	☐2	☐3	☐4
Very bad				**Neutral**				**Very good**

Comment:

1 Diffuser

Answer the following questions on how you perceive the acoustics of the room. There are no right or wrong answers. Try to answer as intuitively as you can.

a. Do you perceive a difference compared to the previous setup?

☐ **Yes** ☐ **No**

b. How do you perceive the acoustics in comparison to the previous setup?

☐-4	☐-3	☐-2	☐-1	☐0	☐1	☐2	☐3	☐4
Much worse				**Can not tell**				**Much better**

Comment:

1. How do you perceive the strength?

☐-4	☐-3	☐-2	☐-1	☐0	☐1	☐2	☐3	☐4
Too quiet				**Neutral**				**Too loud**

2. How do you perceive the liveness?

☐-4	☐-3	☐-2	☐-1	☐0	☐1	☐2	☐3	☐4
Too dry				**Neutral**				**Too live**

3. How do you perceive the balance?

☐-4	☐-3	☐-2	☐-1	☐0	☐1	☐2	☐3	☐4
Too warm				**Neutral**				**Too brilliant**

Comment:

4. Do you perceive the sound as even over all frequencies?

a) ☐ **Yes** ☐ **No**

b) ☐ **Better than previous setup** ☐ **Worse than previous setup**

c) **If no, for what frequencies is the sound uneven?**

☐ **Lower pitch** ☐ **Middle pitch** ☐ **Higher pitch** ☐ **Can not tell**

Comment:

5. What is your overall impression of the room with this setup?

☐-4	☐-3	☐-2	☐-1	☐0	☐1	☐2	☐3	☐4
Very bad				**Neutral**				**Very good**

Comment:

3 / 0 Diffusers

Answer the following questions on how you perceive the acoustics of the room. There are no right or wrong answers. Try to answer as intuitively as you can.

a. Do you perceive a difference compared to the previous setup?

☐ **Yes** ☐ **No**

b. How do you perceive the acoustics in comparison to the previous setup?

☐-4	☐-3	☐-2	☐-1	☐0	☐1	☐2	☐3	☐4
Much worse				**Can not tell**				**Much better**

Comment:

1. How do you perceive the strength?

☐-4	☐-3	☐-2	☐-1	☐0	☐1	☐2	☐3	☐4
Too quiet				**Neutral**				**Too loud**

2. How do you perceive the liveness?

☐-4	☐-3	☐-2	☐-1	☐0	☐1	☐2	☐3	☐4
Too dry				**Neutral**				**Too live**

3. How do you perceive the balance?

☐-4	☐-3	☐-2	☐-1	☐0	☐1	☐2	☐3	☐4
Too warm				**Neutral**				**Too brilliant**

Comment:

4. Do you perceive the sound as even over all frequencies?

a) ☐ **Yes** ☐ **No**

b) ☐ **Better than previous setup** ☐ **Worse than previous setup**

c) **If no, for what frequencies is the sound uneven?**

☐ **Lower pitch** ☐ **Middle pitch** ☐ **Higher pitch** ☐ **Can not tell**

Comment:

5. What is your overall impression of the room with this setup?

☐-4	☐-3	☐-2	☐-1	☐0	☐1	☐2	☐3	☐4
Very bad				**Neutral**				**Very good**

Comment:

Comparison between the different setups

1. In what order did you perform the test?

☐ 0 -> 1 -> 3 ☐ 3 -> 1 -> 0

2. What setup did you like the most?

☐ 0 Diffusers ☐ 1 Diffuser ☐ 3 Diffusers ☐ No preference

Comment:____

3. What was your impression with and without diffusers? What comments do you have on what makes a good practice room?

Thank you for your participation!

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