Major Project for BSc (Hons) in Audio Production

Creating a professional video studio with appropriate acoustic treatment

Submission Code:	CMN6302.1
Submission Date:	04/10/2020
Student ID:	5-AMS-505575
Word Count:	14,412 words

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Amsterdam, October 4th 2020 Signature

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ABBREVIATIONS

α	Absorption coefficient
Σ	Sum of
CFL	Compact Fluorescent Light
cm	Centimeter
CPU	Central Processing Unit
dB	Decibel(s)
DAW	Digital Audio Workstation
DMX	Digital Multiplex
DoP	Director of Photography
ft	Feet
GPU	Graphics Processing Unit
h	Hour(s)
HVAC	Heating, Ventilation and Air-Conditioning
Hz	Hertz
kg	Kilogram(s)
kHz	Kilohertz
kWh	Kilowatt-hour(s)
LED	Light Emitting Diode
m	Meter
ms	Millisecond(s)
NC	Noise Criteria
REW	Room EQ Wizard
RT_{60}	Reverberation Time
s	Second(s)
SNR	Signal-to-Noise Ratio

SPL	Sound Pressure Level
STC	Sound Transmission Class
STL	Sound Transmission Loss
TRS	Jack cable with 3 connectors, “Tip, Ring, Sleeve”
UPS	Uninterruptible Power Supply
V	Volt(s)
VAT	Value Added Tax
W	Watt(s)
Wh	Watt Hour
XLR	Connector type X with Latch and Rubber ring

ABSTRACT

Creating videos is nowadays made easier and easier, and is a mass consumption product. In professional video productions, multiple departments work hand in hand to create videos. However, the sound department's work seems to be misunderstood, leading to the omission of acoustics on set and audio post-production considerations in the filmmaking process by other departments. It is therefore important to create a good sounding space and practical audio workstation for recording and making videos.

This thesis thus addresses the acoustical considerations and applications, alongside audiovisual equipment usage, in a video recording studio. More specifically, the application of the research is done on a medium-scale studio space created in an existing room and for a maximum total budget of 80,000€.

The literature review informed us about the different types of acoustic treatment through absorptive, diffusing and isolating solutions. We also learned about the equipment needed for professional filmmaking. Thereafter, the implementation of the acquired knowledge was made to an existing room based in an office building in northern Amsterdam. The room was divided into 3 spaces: a small entrance hall, a control room and a live room. Both rooms were acoustically treated, based on their respective original boundaries and frequency responses, environmental noise assessments, total absorptions and reverberation times. The rooms were successfully treated for a more even frequency response and for a reverberation time below 500ms. The building of and incorporation of equipment in said studio can be accomplished for less than 80,000€.

A final note was made that the application of the research would have to be reviewed and adapted for large-scale studios and sound stages with different approaches to acoustic treatment and equipment choice, and would therefore require a larger budget.

INTRODUCTION

The world of filmmaking encompasses a wide range of departments and professionals that need to cooperate with each other in order to create quality products. One of those sections is the sound department, which is in charge of recording and processing audio for the videos. Often, their work is misunderstood by the other actors of filmmaking. John Coffey, in his *Open Letter from your Sound Department* (n.d.), lays out the issues the sound crews regularly experience with other departments on film sets. He addresses the location department and mentions that the set's location plays an important role in determining whether the recorded sound will already be of good quality or not. Reducing environmental noise factors highers the sound quality of the film. It can hence be inferred that, when building one's own video recording studio, close attention should be paid to acoustics.

Upstream literature research found there were theses written about filmmaking studio building, such as the work of Pratik L. Shrestha (2014), from Nepal Engineering College, in her *Film Studio Design* thesis or Rohit A. Digra's *Study of a Recording Studio* (2015), written during his time at Dr. Baliram Hiray College of Architecture. Moreover, books have been written about acoustics (Everest and Pohlmann, 2013 and 2015), audio recording and post-production (Alten, 2014), lighting (Box, 2013) and film production (Honthaner, 2010), as well as videos about those topics. Thus, they only focus on one aspect or department of the filmmaking process, often in a lengthy form and rarely mentioning budget considerations, and do not combine all of those aspects into one piece of writing.

Therefore, it was deduced that assembling a single, shorter and simple scientific guide to filmmaking studio construction would be useful. The main question we can then address is: How can a professional video studio be designed?

It is a very long and tedious work to join all the departments' considerations, and thus too ambitious for this thesis. For this reason, it was decided to narrow down the scope of such a project to produce a small guide to studio construction, focusing mainly on the audio aspect of the design process, as well as making the studio a more affordable product for smaller-scale production companies. Then, what is needed to acoustically treat this studio and make it a multi-usage space, and how can one incorporate this knowledge in an existing office building room in the most cost- and energy efficient way?

To answer this question, we will first look at the existing literature about acoustics and sound-related considerations in the process of filmmaking, as well as have an overview of video considerations. In a second phase, we will apply this knowledge to an existing room and discuss the results of this implementation. The specific uses of the studio were established for a more concrete application of the research: the studio would be used for video recording with sound, streaming and audio post-production and would include the author's audiovisual equipment.

For this research, an "affordable" budget had to be determined. It was decided for it to be of 80,000€, excluding VAT and room acquisition costs, which is around the starting price for a professional audio recording studio (Recording Connection, n.d.). It is expected for this budget to be entirely used because of the usual expensiveness of acoustic treatment, especially if the original room has poor acoustics, and of the audiovisual equipment. Additionally, one can await the energy consumption to be consequent in regards to the quantity of electrical equipment needed for such a studio.

LITERATURE REVIEW

This chapter will help us understand the aspects that need to be considered in order to build a small video studio with appropriate acoustics. Those considerations regard different room acoustics, equipment choice and energy consumption options.

a. ACOUSTICS IN STUDIO CONSTRUCTION

When building a studio, it is important to understand the behavior of sound waves in a closed space. Acoustics is the field taking care of that: it is looking at the properties of a given space in order to determine how the sound will travel and behave in it (Definition of Acoustic by Oxford Dictionary, 2020).

When a sound wave encounters a boundary, it can either be diffracted, refracted, reflected, or absorbed. Diffraction happens when the wave hits a small object or small opening, compared to the value of their wavelength, and evenly spread out past said object or opening. When the sound wave changes direction when passing through a different medium, refraction happens (Wave Behaviour, 2020). We will discuss reflection and absorption more in detail below.

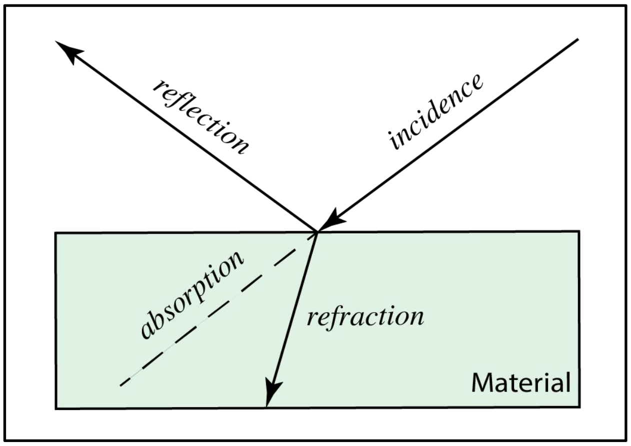


Fig. 1: Sound waves behavior with boundary (Meissonnier, 2020)

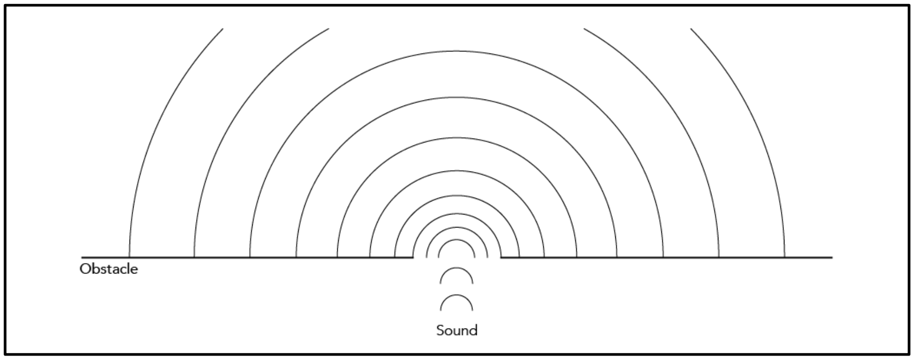


Fig. 2: Sound wave diffraction (Meissonnier, 2020)

i. Reflection and Diffusion

Reflection happens when a sound wave hits a boundary and is returned with the same properties as its incidence. For the wave to be reflected, the boundary has to be larger than the signal's wavelength. Depending on the type of surface it hits, the reflection will take different paths (Wave Behaviour, 2020). The scheme below details those.

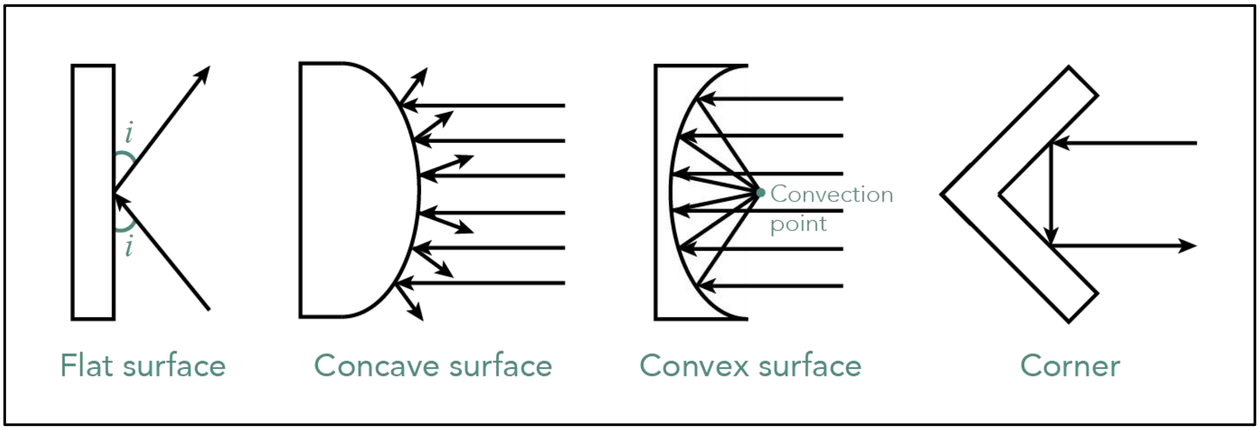


Fig. 3: Reflection of sound waves on different surfaces (Meissonnier, 2020)

Sound waves reflecting against boundaries in a room can cause comb filtering, which is the result of interferences between said waves. Peaks and dips are created in the frequency response of the room, which causes acoustic distortion during sound recording and processing, in the case of a studio (White, 2020).

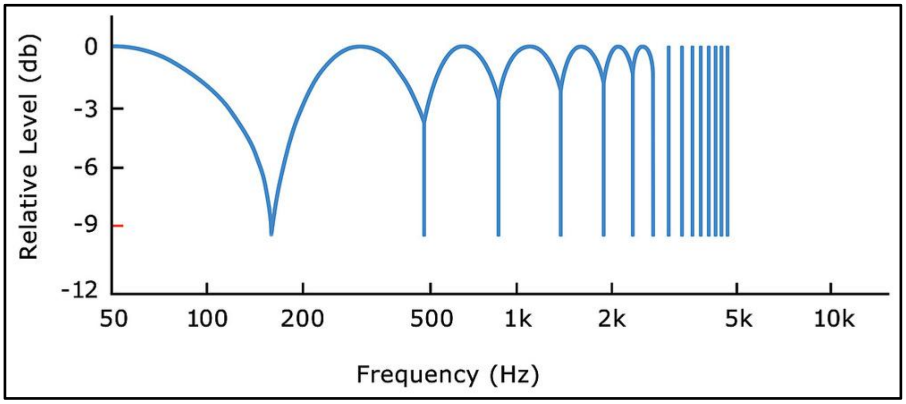


Fig. 4: Graphic representation of comb filtering (soundonsound.com, 2013)

Reflections also cause standing waves, called "room modes". The sound waves hit one or more boundaries in a cyclic way. Their particle velocity is then always highest and lowest at the same points in the room. Rooms modes can either be axial, which are usually the strongest and hence the priority of treatment, tangential or oblique (GIK Acoustics, 2020).

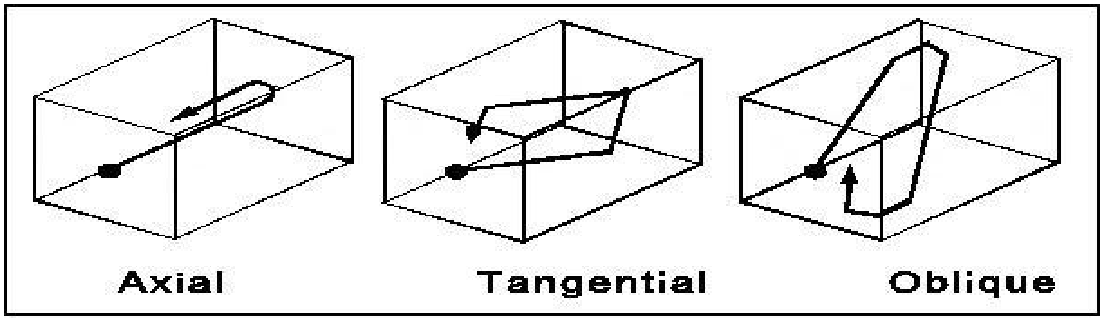


Fig. 5: Room modes types (gikacoustics.com, 2020)

In order to control reflections, reflectors and diffusers are used. They distribute the sound through the space in order to even the frequency response throughout the room. They also help improve speech intelligibility in studios and reduce the comb filtering effect. To be efficient though, diffusing elements should present a randomness in the way they diffuse signals. This way, wide-frequency diffusion can be applied (INS Acoustics. n.d).

PHASE-GRATING DIFFUSERS

Phase-grating diffusers diffuse sound very effectively. They can act as diffusers and simultaneously as specular reflectors, depending on how they are designed and placed in the room. Such diffusers spread the sound waves' energy over time with the different depth of wells, they attenuate by about 8 to 10 dB the amplitude of the wave compared to the incident one, and they scatter the sound through a half circle around the diffuser. The depth of the wells determines the lowest frequency that can be diffused and the width of the wells defines the highest diffused frequency. Wavelength below the low frequency limit can partly be absorbed by the diffuser's structure (Everest and Pohlmann, 2015).

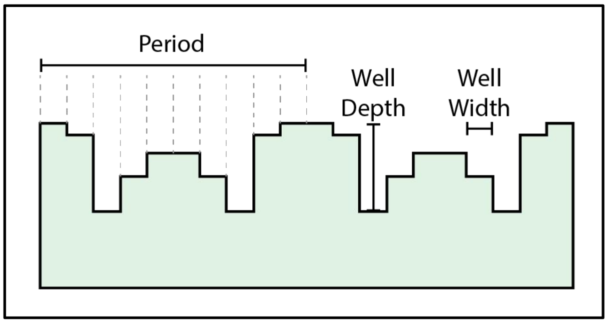


Fig. 6.a: Graphical definition of terms used to specify a phase-grating diffuser (Everest and Pohlmann, 2015)

Fig. 6.b: Phase-grating diffuser (arqen.com, 2020)

Phase-grating diffusers can be designed using a quadratic-residue sequence, which is determined by calculations to find the values for the wells' depths that will provide the most appropriate sound diffusion (Razorblade Science - Primacoustic, n.d.).

Quadratic diffusers can be used vertically or horizontally, as well as in a combination of both that will diffuse sound in a two-dimensional way (Foley, 2013).

POLYCYLINDRICAL DIFFUSERS

One type of absorber is polycylindrical diffusers. They also are absorbers and will be detailed later on in this chapter.

Fig. 7: Polycylindrical diffuser (soundproofdirect.com, 2020)

ii. Absorption

One of the most used techniques to control sound in a room is absorption. It is used more specifically to control echoes and the sound level in a room. This phenomenon is "the measure of the amount of energy removed from the sound wave as the wave passes through a given thickness of material". Absorption is indispensable when it comes to soundproofing a room (Shrivastava, 2020). Absorption is closely related to the RT60 as increasing the total absorption proportionally decreases the reverberation. It is however important to control which frequencies are being absorbed. If some frequencies are too attenuated, the reverberation and room response might become too bright or too muddy.

The amount of absorption provided by a material is qualified by an absorption coefficient, named α, that represents the absorbed fraction of incident sound hitting said material per m^2. If α is lower than 0.2, the material is said to be reflective. If α is higher than 0.5, the material is then considered as absorbent. When choosing components for acoustic treatment, it is good to note that the difference in absorption between two materials becomes noticeable if their absorption coefficients vary by at least 0.3.

When designing acoustics for a room, it is needed to multiply the absorption coefficients of each material by their respective total surface area in order to know the total room absorption. Therefore, it can be calculated as follows:

$$A = \sum S\alpha$$

S, surface area (in m^2)
α, sound absorption coefficient

There are different types of equipment that provide sound absorption, that are called "absorbers". The depth of their cavity is ideally at a quarter of the wavelength of the frequency of interest for the most efficient absorption. The particle velocity is indeed highest at that proportion of the wavelength. They are most efficient when placed where the pressure is at its maximum (Everest and Pohlmann, 2013).

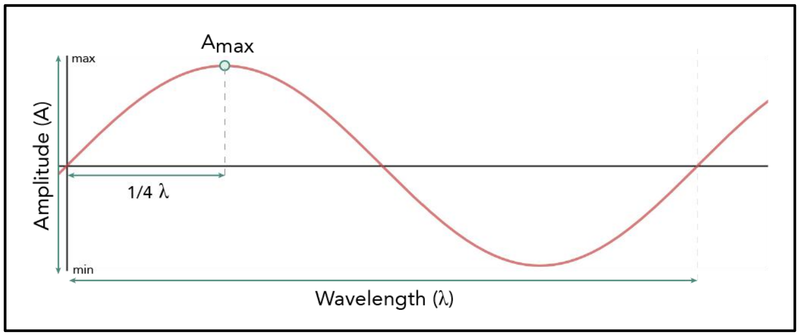


Fig. 8: Wavelength versus amplitude (Meissonnier, 2020)

Original Materials	Frequency					
	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz
Smooth concrete, unpainted	0.01	0.01	0.02	0.02	0.02	0.05
Gypsum on solid backing	0.03	0.03	0.02	0.03	0.04	0.05
Linoleum stuck to concrete	0.02	0.02	0.03	0.04	0.04	0.05
Other Materials	Frequency					
	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz
Plasterboard on battens	0.3	0.2	0.15	0.05	0.05	0.05
Glasswool (16kg/m^3)	0.12	0.28	0.55	0.71	0.74	0.83
Gypsum tiles (22mm, 17% perforated)	0.45	0.70	0.8	0.8	0.65	0.45
Fiberglass bonded mat	0.1	0.35	0.5	0.55	0.7	0.7
Melamine-based foam 15mm	0.09	0.22	0.54	0.76	0.88	0.93
10mm plywood on battens (50mm airspace filled with glasswool)	0.8	0.7	0.4	0.3	0.1	0.1
Chipboard on battens	0.2	0.25	0.2	0.2	0.15	0.2
Vinyl	0.02	0.02	0.03	0.04	0.04	0.05
Plasterboards on battens (18mm airspace filled with glasswool)	0.3	0.2	0.15	0.05	0.05	0.05

Table 1: Examples of absorption coefficients (Web Absorption Data Eng., n.d.)

Absorbers are usually built in a visually neutral or appealing design. Depending on their specifications, they can be used to treat specific frequencies or frequency ranges. They can be classified into different categories.

OPEN-CELL FOAM

Those absorbers are usually seen in professional and home studio acoustic treatment. Their pores are interconnected, facilitating the dissipation of sound into heat. They are good absorbers but poor isolators; they are made of lightweight materials, hence the sound passing more easily through (Everest and Pohlmann, 2015).

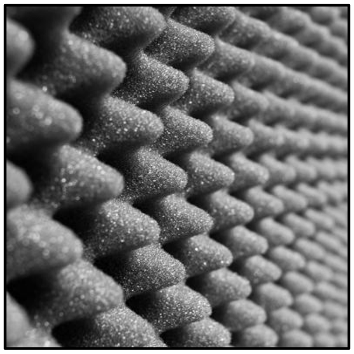


Fig 9: Open-cell foam (AK Rubber & Industrial Supplies Ltd, 2020)

BASS TRAPS

Bass traps are absorbers meant to treat approximately the two lowest octaves of the audible range, which are also the most difficult ones to absorb. A bass trap's cavity should ideally be one quarter of the wavelength of the frequency that needs to be absorbed. Since low frequencies have long wavelengths, bass traps tend to be spacious. Therefore, they are often implemented in unused spaces in the room such as its rear and above its inner shell's ceiling (Everest and Pohlmann, 2015).

PANEL ABSORBERS

Those absorbers can also be called “diaphragmatic” or “membrane” absorbers as they use the vibration of a membrane to turn acoustical energy into heat. It is possible to add some glass fiber inside the airspace. This results in a broader frequency band being absorbed but a lower absorption peak (Everest and Pohlmann, 2013).

The thinner the membrane and the wider the airspace behind it, the lower the frequency that can be absorbed by the panel, as can be deduced by the frequency of resonance of this absorber formula below:

$$f = \frac{60}{d\varrho_M} \text{ (Ballivian, n.d.)}$$

d, *depth of air space (in m)*

ϱ_M, *mass density of the membrane (in kg/m^3)*

Using panel absorbers can help bring down the costs of acoustic treatment for a room as they are quite simple to build.

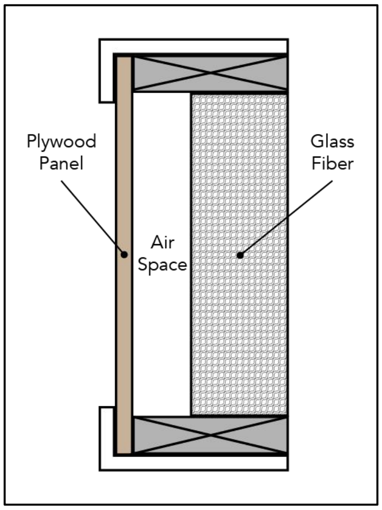


Fig 10: Panel absorber structure (Meissonnier, 2020)

POLYCYLINDRICAL ABSORBERS

Polycylindrical absorbers work similarly to panel absorbers. The difference is that the hardboard cover is here bent between strips and optionally on top of bulkheads. Each cavity is air-tight and isolated from the other cavities. The cavities can also be filled with glass fiber bulkheads in order to increase its performance. Polycylindrical absorbers can also diffuse the sound above 120° of incidence.

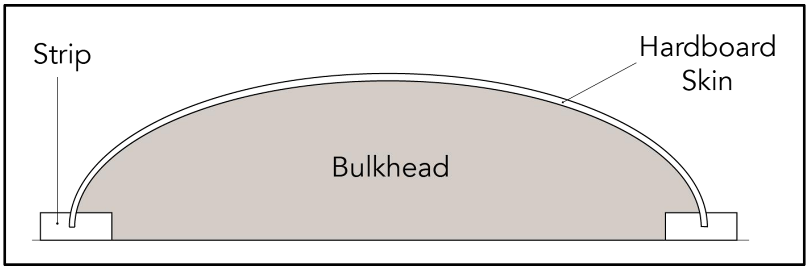


Fig 11: Polycylindrical absorber structure (Meissonnier, 2020)

HELMHOLTZ RESONATORS

The principle on which Helmholtz resonators rely can easily be demonstrated by blowing in an empty bottle. The cavity will resonate at the bottle's resonant frequency. Helmholtz resonators act as absorbers by dissipating the sound waves' energy through the friction of the waves with the air at the resonator's mouth, the reflections inside the cavity and, optionally, porous material placed in the neck of the resonator. Like for panel absorbers, adding porous material results in a broader frequency band of effectiveness with a lowered absorption peak. All frequencies that are not absorbed by the resonator come back out of the resonator, diffused in the room through the diffraction of said frequencies by the mouth of the cavity. Helmholtz resonators work best for low frequencies.

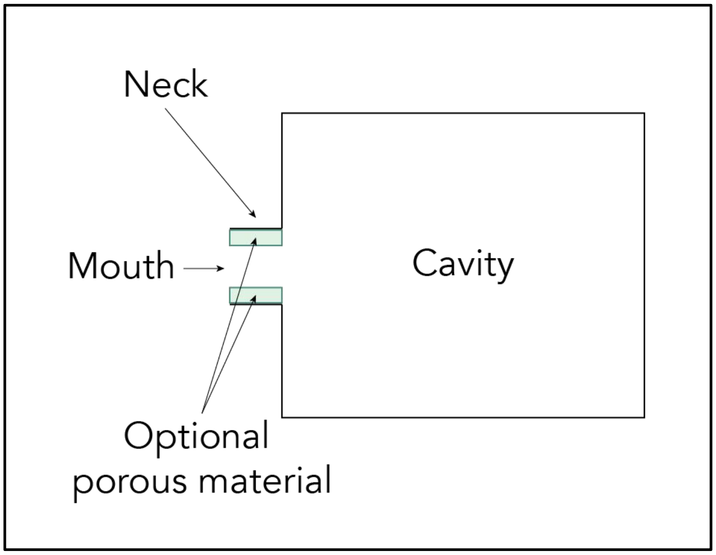


Fig. 12: Helmholtz resonator structure (Meissonnier, 2020)

If the resonator’s mouth is square, the cavity’s resonant frequency can be determined as follows:

$$f_{square} = \left(\frac{C}{2\pi}\right)\sqrt{\frac{S}{V\,(l+2\Delta l)}}$$

c, speed of sound (in m/s)

S, cross-sectional area of the resonator opening (in m^2)

V, volume of the resonator (in m^3)

l, length of the resonator opening (in m)

$2\Delta l$ *, resonator mouth correction factor: 0.9a, where a is the edge length of the square opening*

If the resonator’s mouth is circular, one can use the formula below to determine the cavity’s resonant frequency:

$$f_{circular} = \frac{100}{\sqrt{V\,(l+1.6R)}}$$

V, volume of the resonator (in m^3)
l, length of the resonator opening (in m)
R, radius of the circular opening (in m)

Helmholtz resonators, when incorporated into concrete masonry structures can provide good isolation, provided that the concrete’s mass is high enough (Everest and Pohlmann, 2015).

In fact, Helmholtz resonators have been in use for a long time. Ancient Greek and Roman theatres were using jars, usually bronze ones, placed under the audience’s seat to improve the sound of the actors’ voices. It would become richer when resonating in the vase, hence becoming more intelligible and pleasant for the audience (Godman, n.d.).

PERFORATED PANEL ABSORBERS

Perforated panel absorbers work on the same principle as the Helmholtz resonators, although they do not have the same appearance: The sound energy is dissipated by the friction of air by the opening of the panel. The panel’s holes act like the neck of a Helmholtz resonator would. The perforated panel can be mounted over a box. That structure can hence be assimilated to a host of coupled resonators. The resonant frequency of such a panel can be determined by this formula:

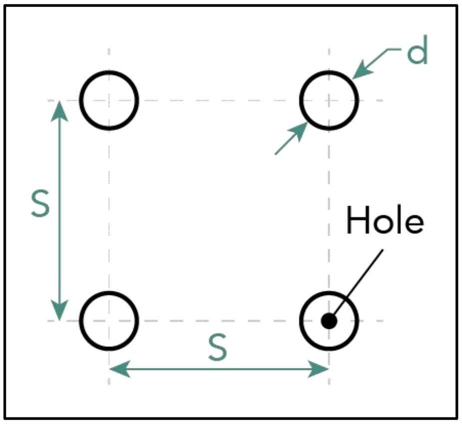
$$f = 200\sqrt{\frac{p}{d \times t}}$$

p, perforation percentage

t, effective hole length (t (in inches) = panel thickness + 0.8 x hole diameter)

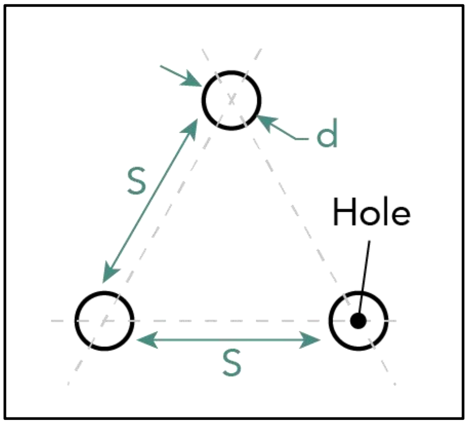
d, depth of airspace (in inches)

The number of holes per area unit, which is called the perforation percentage, and their shape influence the absorption amount. The higher the perforation percentage, the better the high-frequency absorption, and the lower the perforation percentage, and hence the higher the solid area, the more reflective the panel is. Depending on the layout of the holes, the perforation percentage can be calculated as below:



$$Perforation\ \% = 78.5\left(\frac{d}{S}\right)^2$$

Fig. 13.a: Square layout (Everest and Pohlmann, 2015)



$$Perforation\ \% = 90.6\left(\frac{d}{S}\right)^2$$

Fig. 13.b: Triangle layout (Everest and Pohlmann, 2015)

It is very usual to add absorbent material behind the panel, preferably right behind it for the best performance, to broaden the absorption bandwidth. This comes at the cost of diminishing the high-frequency absorption capabilities of that material. Porous absorbers should not be used only if there is the need to treat a specific frequency (Everest and Pohlmann, 2013).

SLAT ABSORBERS

Slat absorbers are comparable to Helmholtz resonators as well. They are made out of narrow wooden strips, called "slats", placed over an air cavity, the slats acting like the neck of the resonator. The absorbers' dimensions can be constant, treating a specific frequency region, or varied and optionally completed with glass fiber, broadening the absorption peak. The slats' surface can either be flat or uneven, then providing some high-frequency diffusion.

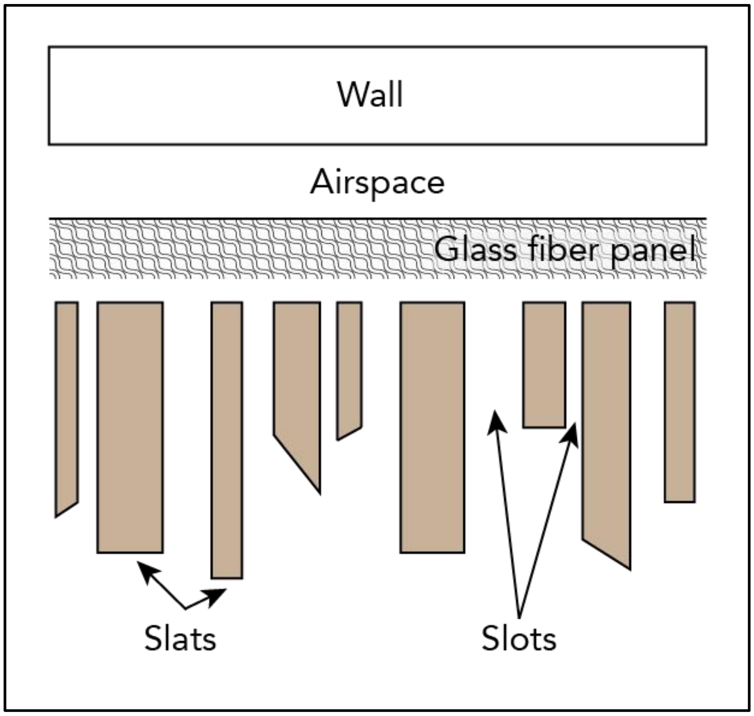


Fig .14.a: Salt absorber structure (Meissonnier, 2020)

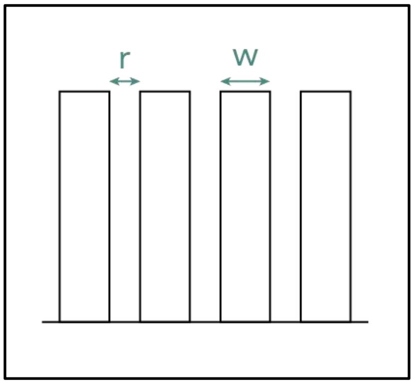
The frequency of maximum absorption reduces as the width of the slots and the depth of the cavity increase (Everest and Pohlmann, 2015):

$$f = 216\sqrt{\frac{p}{d \times D}}$$

p, perforation percentage

d, depth of airspace (in inches)

D, thickness of slat (in inches)



$$Perforation\ \% = 100\left(\frac{r}{w+r}\right)$$

Fig 14.b: Simple slat absorber scheme (Everest and Pohlmann, 2020)

CEILING-MOUNTED ABSORBERS

The advantage of the room having a high ceiling is the possibility of hanging absorbers from it, optimizing the exposed absorptive area. Moreover, the use of multiple panels enables sound to be better absorbed: if some sound energy is not absorbed by a first panel, it will reflect and be absorbed by the next panel it encounters (Everest and Pohlmann, 2013).

Fig. 15.a: RenAcoustic Baffles (Renhurst, 2020)

Fig. 15.b: Hush Absorber 50A (Hush Acoustics, 2020)

ACOUSTICAL TILES

Often seen in offices, acoustical tiles can be placed on walls and ceilings, providing good absorption above 500Hz. They are also cost-effective.

Fig. 16: Modern conference room interior (@grooveriderz on freepik.com, 2019)

ADJUSTABLE ACOUSTICS

There are alternatives to fixed absorbent, reflecting or diffusing units. Those are adjustable acoustic solutions.

Draperies can be used to absorb some midrange and high frequencies. They are not as efficient as the absorbers mentioned above, but they can in some cases provide the right amount of absorption needed. They can be hung from the ceiling or placed in front of walls in the form of curtains, and can be retractable. This way, the amount of reflection and absorption can be modulated.

There are movable absorptive panels as well. They are panel absorbers designed to be moved around. They can simply have handles, or have hooks to be hung in different places or larger panels can be put on wheels.

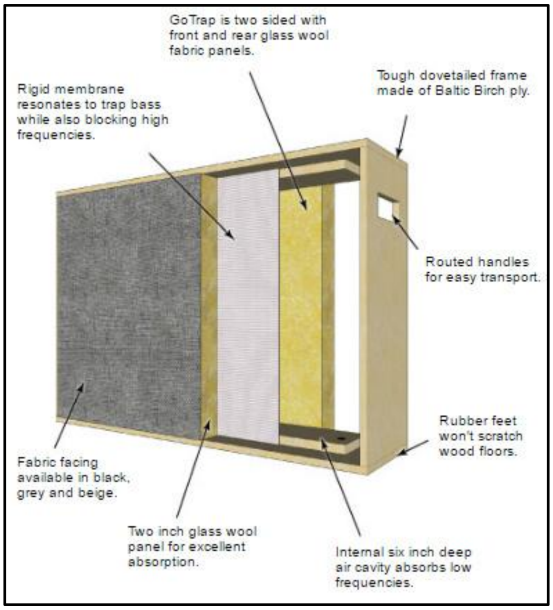


Fig. 17.a: GoTrap design (Primacoustic, 2020)

Fig. 17.b: FreeStand acoustic panel (Gik Acoustics, 2020)

Rotating elements are also an option. They have multiple faces, each of which provide a different type of acoustic treatment. The Triffusor®, for example, has a diffusing side, an absorptive side and a reflecting side. Multiple Triffusors® can be aligned and pivoted differently to provide all three treatments simultaneously on a relatively small area. The biggest inconvenience from using such adjustable acoustics is the larger space it requires to be implemented (Elwasife, n.d.).

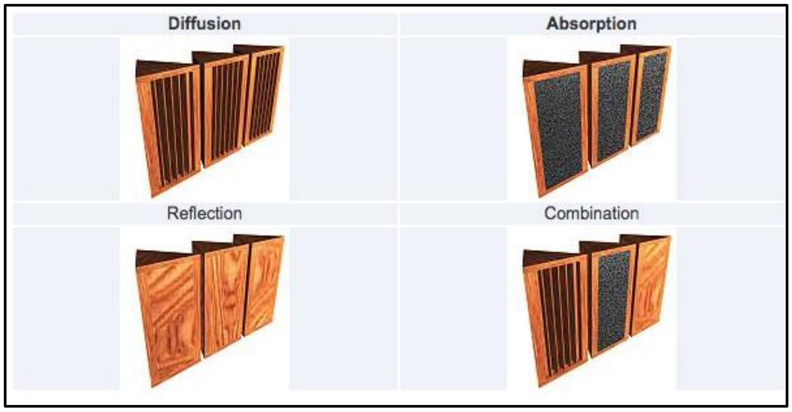


Fig. 18: RPG Triffusor® arrangements (RPG Europe, 2020)

iii. Sound Isolation

Regarding the construction of a studio dedicated to video recordings, acoustics need to be built in order to isolate the room from outside noises and control the RT60. The noise existing inside of the studio, coming from the equipment or the air conditioning for example, need to be treated as well because they will become more noticeable in a quiet environment. This noise level should not exceed 15dBA and should be analyzed quantitatively and qualitatively. (Corelli, Felici and Martinelli, 2006)

When insulating a room from outside noise, and when isolating the surroundings from sounds made in the room, focus has to be drawn to the transmission loss (TL). It is a material's ability to keep sound from going through a medium, of the room's boundaries (Everest and Pohlmann, 2015) and can be calculated as follows:

$$TL = 20log_{10}(m_s f) - 48$$ (Warnock, 1985)

m_s, *mass per unit area (in kg/m²)*

f, *frequency of the sound wave (in Hz)*

We can note that every time a boundary's surface mass doubles, transmission loss through said material increases by 5dB. Some common construction material's mass can be found in table 2.

Material	m_s (kg/m²)	A (Hz)
Aluminium	2.7	12,900
Concrete, dense poured	2.3	18,700
Hollow concrete block (nominal thickness, 150 mm)	1.1	20,900
Fir timber	0.55	8,900
Glass	2.5	15,200
Lead	11.0	55,900
Plexiglas or Lucite	1.15	30,800
Steel	7.7	12,700
Gypsum board	0.82	39,000
Plywood	0.6	21,700

Table 2: Surface Mass, ms, for 1 mm Thickness and Constant, A, for Calculation of Critical Frequency, fc, of Some Common Building Materials (Warnock, 1985)

Based on its transmission loss properties, materials can be categorized using sound transmission class (STC) standard rates.

STC Range	Intrusion between rooms
0-20	Voices clearly heard
20-40	Voices heard in low background noise
40-55	Only raised voices heard in low background noise
55-65	Only high-level noise heard in low background noise
70	Practical limit

Table 3: Sound intrusion between rooms according to STC ratings (Everest and Pohlmann, 2015)

WALLS

An effective isolating wall needs to have a high STC rating. The wall's materials hence have to be massive, but not only. The arrangement of the different materials is important as well. Separating and combining masses within the wall's construction proves to increase the transmission loss through said wall (Everest and Pohlmann, 2013). Some examples are found below.

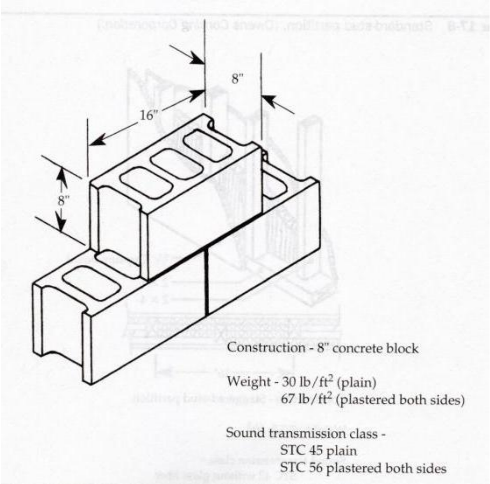


Fig. 19.a: Concrete block (8-in) call construction (Everest and Pohlmann, 2015)

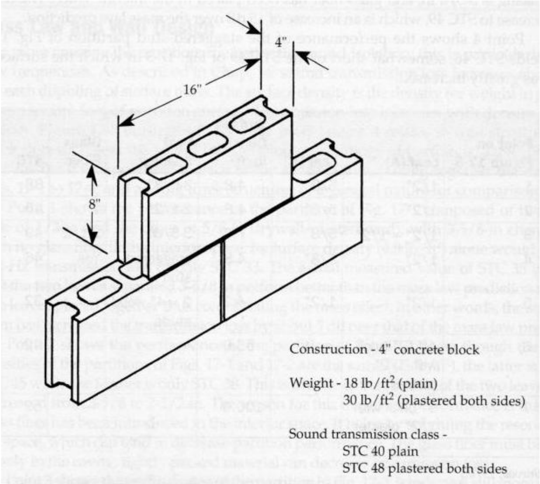


Fig. 19.b: Concrete block (4-in) call construction (Everest and Pohlmann, 2015)

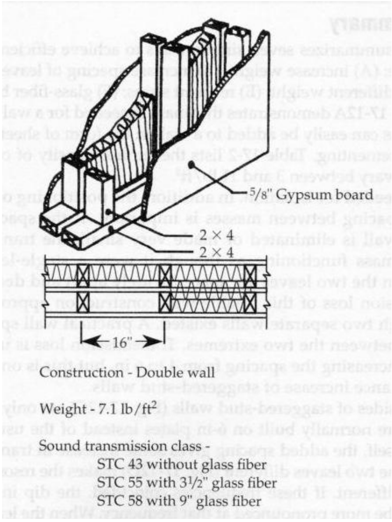


Fig. 19.c: Double-wall partition (Everest and Pohlmann, 2015)

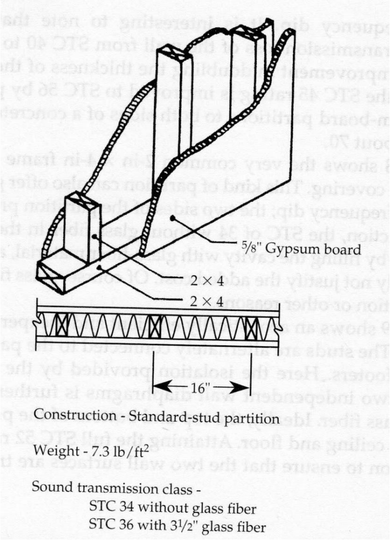


Fig. 19.d: Standard-stud partition (Everest and Pohlmann, 2015)

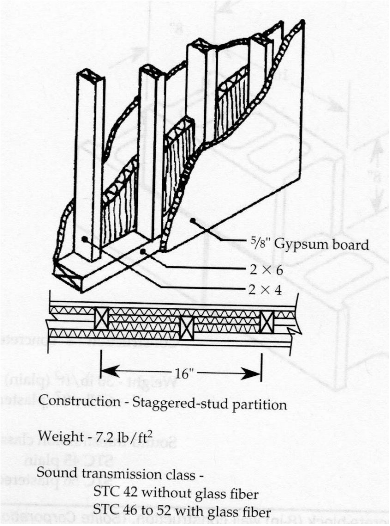


Fig. 19.e: Staggered-stud partition (Everest and Pohlmann, 2015)

Very often, a studio is built within an existing room which walls are not designed for high transmission loss. To fix this issue, an additional partition, that is characterized by high transmission loss properties, can be built on either side of the original wall. Layering isolating partitions and absorbent materials is an efficient way to higher the transmission loss capacity of a wall (White, 1993).

FLOOR AND CEILING

A very effective way to isolate the floor is to build a floating floor. Such flooring's surface is not in direct contact with the rest of the structure, isolating the room from any structure borne noise. The depth of the void underneath the surface depends on the space and the materials of the surface depends on the budget available. The more massive the floating floor is, the better the isolation (White, 1993).

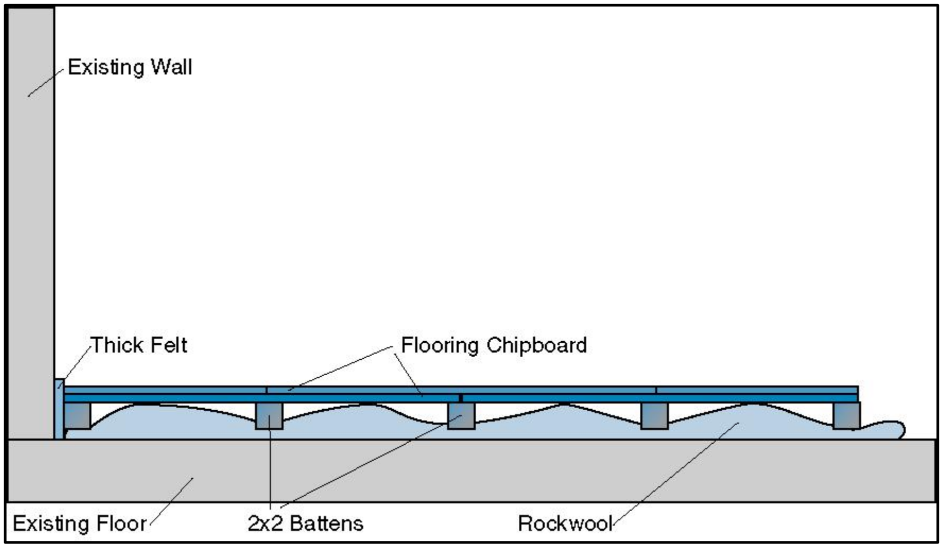


Fig. 20: Floating floor scheme (White, 1993)

It is very important to isolate the ceiling well; nobody wants to hear footsteps or speech residue in their studio. A suspended ceiling is an ideal option to isolate a room from noises coming from above it. However, it is more difficult to build than a floating floor. One can uncover the room's ceiling to access the floor's joists and add absorbent material between them and hang resilient gypsum-board layers. This way, the ceiling of the room is isolated from the structure. In the case there is access to the floor above the room's ceiling, and that the owner of that space agrees to cooperate, a floating floor or impact-reducing materials could be installed. Often, though, the upper room cannot be accessed (Everest and Pohlmann, 2015).

DOORS AND WINDOWS

Doors and windows need to be airtight. Sound finds its way through any small gaps that are left, degrading the sound isolation between rooms.

Regular doors are very poor sound isolators; they isolate less than a simple wall. Therefore, it is recommended to use a heavier, thicker door that is filled with layers of absorbent material or where possible, have a "vestibule-style" airlock by using a double-door system. The door frames should also not be in direct contact with the wall to reduce structure borne noise transmission (White, 1993).

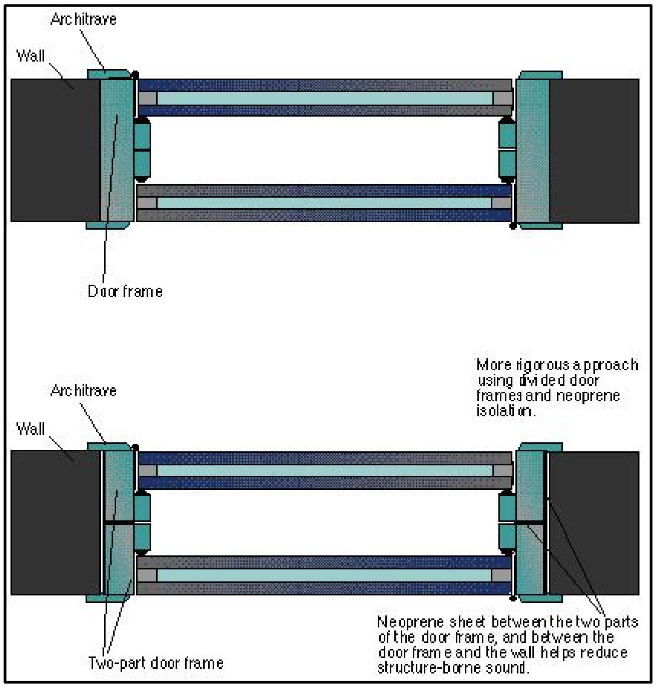


Fig. 21: Double-door fitting (White, 1993)

When it comes to windows, a double-glazed window is the minimum requirement to isolate two rooms from each other. Ideally, glass layers can be added to provide higher transmission loss, providing that there is still a big enough air gap in between the layers. The larger the air gap, the higher the transmission loss. The different panes should be of different thickness to ensure they do not resonate at the same frequency, and they should not be parallel to prevent the formation of standing waves. The glass should not directly be in contact with the wall to prevent the transmission of structure borne sound. Neoprene sheets are usually used to do so. Absorbent material can be placed by the junctions to absorb any noise that has gone through gaps (White, 1993).

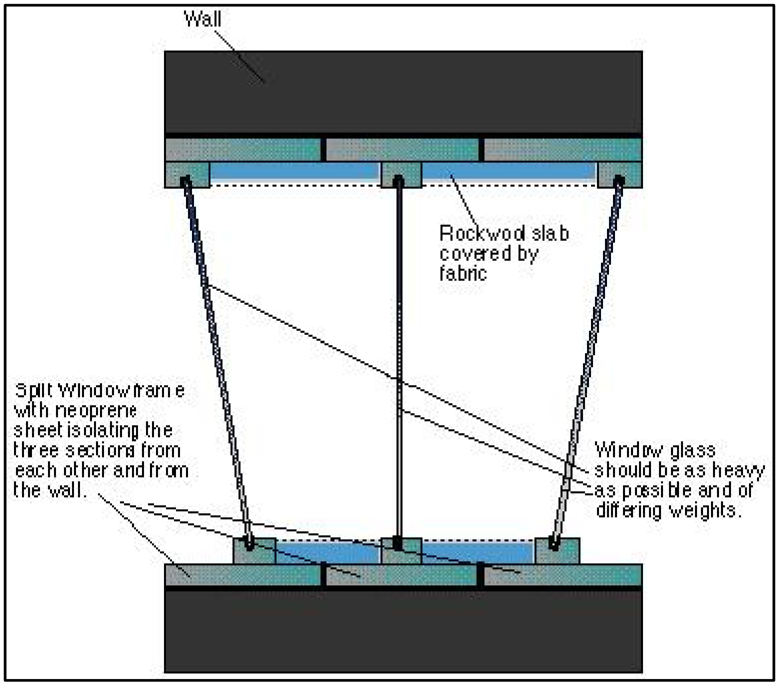


Fig. 22: Typical control room window construction (White, 1993)

iv. Acoustics of a Control Room & Video Room

When building a video recording studio that will mainly be used for talk-show-like recordings, three main audio aspects need to be taken into consideration upstream.

First, speech has very little energy below 100Hz and above 4kHz. Therefore, it is important to have the flattest frequency response possible in the live room in that frequency range. Second, the audible frequency spectrum is approximately from 20Hz to 20kHz, but it can vary slightly for each individual, depending on their age and physical condition. The control room hence has to be appropriately treated to provide the flattest frequency response across the audible frequency spectrum. Third, the reverberation time needs to be kept in a range of length to preserve the speech's intelligibility and its spatiality.

When treating the frequencies in a room made for speech recording, it is needed to look at the frequency spectrum in sections. First, there is the frequency range that can't be supported by the room. This range is below a frequency we will call f_1; we will name "Region A", for A : [20Hz;f_1]. There is no acoustic treatment needed as the frequencies cannot exist in that space. f_1 can be determined with the following formula:

$$f_1 = \frac{565}{3.28084 \times L}$$

565, constant

L, length of the room (in m)

3,28084, constant of conversion from feet to meters

The second frequency range is where the room modes are dominant and it is situated between f_1 and another frequency, f_2. Acoustic problems in this second region, "Region B", for B : [f_1;f_2], are usually treated with absorption. f_2 can be determined by the following calculation:

$$f_2 = 11250 \times \sqrt{\frac{RT60}{V}}$$

11250, constant

V, volume of the room (in ft^3*)*

A third section, for which a different type of absorption will be used, is found between f_2 and f_3 for: $f_3 = 4 \times f_2$. We can call this section "Region C", for C : [f_2;f_3].
Last, we will name the frequency range above f_3 "Region D", for D : [f_3;20kHz], for which diffusion will be used (Everest and Pohlmann, 2015).

Determining the needed RT60 for a video recording room is critical when filming a real time vocal performance. It is important to preserve the intelligibility of the voice and the sense of space around the speaker. Therefore, the RT60 should not be longer than 1.4s without being not too low. If the reverberation time value is higher than 1.4s, the voice will be subject to frequency masking, which will impair the intelligibility of the speaker. On the other hand, if the RT60 is too low, the voice will sound unnatural or odd because it is very rare in common environments to be exposed to very low reverberation times. When working with the RT60, it is important to always take into account the frequency range that is being dealt with. In order to find the most appropriate room specifications possible, the following formula can be used (Corelli, Felici and Martinelli, 2006):

$$RT_{60} = 0.161 \frac{V}{4Vm \times 10^{-6} + S\alpha}$$

V, volume of the room (in m^3)

m, absorption coefficient of the air (in Sabins)

S, sum of the areas inside the room (m^2)

α, average absorption coefficient of S (in Sabins)

The absorption coefficient of the air relative to the humidity can be found in table 4.

Relative Humidity	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz
10%	184	360	875	2786	9210	25098
20%	161	345	800	1428	4375	15427
30%	115	322	700	1174	2993	10131
50%	92	276	645	1151	2303	6447
70%	69	230	622	1243	2210	5296
90%	46	184	599	1289	2280	4835

Table 4: Absorption coefficients of the air (Corelli, Felici and Martinelli, 2006)

b. AUDIOVISUAL EQUIPMENT

In order to meet the standards in regards to the equipment a sound recording studio should have, and according to E-Home Recording Studio (n.d.) one should acquire:

A computer with a DAW which will be used for recording, editing and mixing the sound. The computer should be powerful enough to fulfill the DAW's and other necessary softwares' needs regarding processing resources such as CPU and GPU powers;

- A workstation, which is a desk that can accommodate audiovisual recording and monitoring equipment;
- An audio interface with microphone amplifiers to convert the sound from analog to digital, and inversely, by using professional audio recording and monitoring equipment;
- Microphones to record the sound. They can be dynamic microphones, relying on the electromagnetic principle to transduce sound, or condenser microphones, which use the electrostatic principle to that effect. Dynamic microphones, by the nature of their transduction method, have the advantage of providing a slight compression to the recorded sound, but may lack sensitivity to record low-level signals. Condenser microphones commonly have a higher sensitivity, and hence can record lower-level signals but they are more fragile and usually require 48V of power to function. Small condenser microphones, called Lavalier microphones, have been designed to be very portable and small. They are largely used to record sound on set in video production as they can easily be seamlessly fixed on and underneath clothes (Alten, 2011);

Fig. 23: Røde lavalier microphone (Røde, 2020)

- Headphones with amplifier for the recorded people to hear themselves and to communicate between rooms properly and without noise;
- Speakers with stands to be able to monitor the sound in the control room;
- Stands and cables to hold and plug the microphones into the recording system;
- And an UPS to prevent losses due to a sudden power shortage.

Additionally, some video recording and lighting equipment is necessary when building a studio that will also record visuals. According to Albright (2018), the following items are necessary for recording visuals:

- A camera with a shotgun microphone, which recorded sound allows the video to be synced with the sound recorded by other microphones, to record video. Multiple camera types are viable for professional video recording but a professional video camera is advised as it allows for more flexibility during filming and in post-production to tailor the image to one's desires. It is possible to use multiple cameras simultaneously in order to record multiple angles or the same event;
- Tripods to hold the cameras safely steady;
- Lighting to light up the space and the actors properly and create specific moods. There are multiple types of lighting, and hence different ways of using lights. The 3

main types are key lighting which is the primary light source used to light the subject, fill lighting which is a secondary light source brightening the darker areas created by the key light on the subject, and back lighting which adds division between the foreground and the background of a scene (Box, 2010).

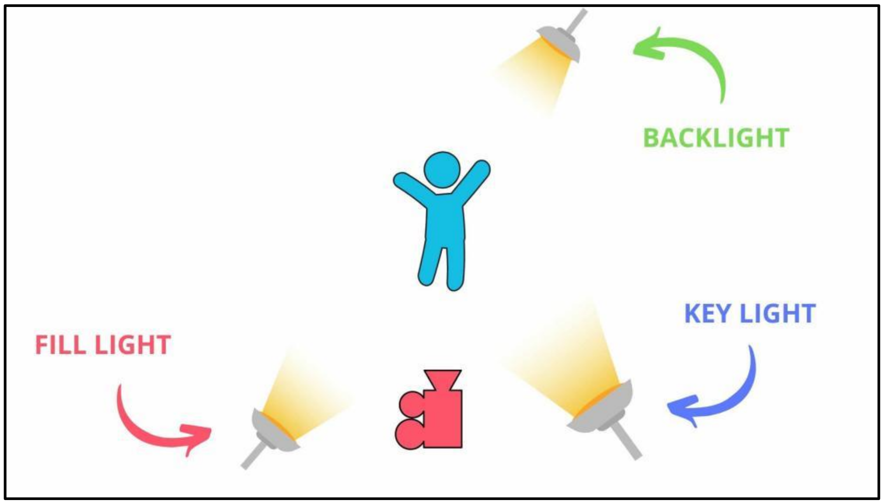


Fig. 24: 3-point lighting (StudioBinder.com, 2020)

It is important to keep in mind that lighting, video and sound are all equally important in the production process; if the quality of one decreases, the quality of the whole product does too, no matter how good the other two qualities are.

c. ENERGY

Lights, video equipment and sound equipment should be plugged into three different groundings. If all the equipment is connected to a single grounding, it is possible that an overload occurs. All the equipment of each of the three types of equipment should also be connected to the same grounding in order to avoid ground loops that are responsible for noise in video and audio systems (Beacham, 2018).

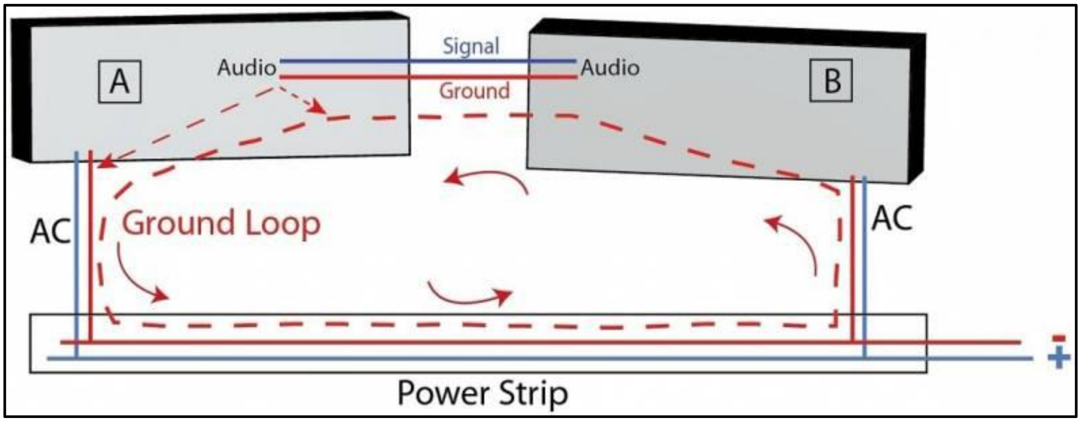


Fig. 25: Ground loop scheme (Beacham, 2018)

As mentioned earlier, an UPS is strongly recommended in professional recording studios to prevent losses and damage in case of a sudden power cut. Power cuts can damage the equipment, as it is then not properly turned off while being used.

UPS can vary from 200 Volt Amperes (VA) to 1500VA for domestic use, which can provide 5 to 10 minutes of power after a power cut, leaving enough time to safely back up and turn off all equipment (E-Home Recording Studio, n.d.).

There are 3 types of UPS one can choose from: Offline, online and line-interactive. An offline UPS feeds the equipment with power directly from the power socket. When the unit notices a power cut, it switches to provide power through its battery. An online UPS does not switch when the power cuts off by constantly providing power directly through its battery. It is the generally most pricey type of UPS. A line-interactive UPS does not only respond to power cuts but also to temporary power changes, which are more frequent than power cuts, providing constant power to the equipment at all times (Cooper, 2019).

METHODOLOGY

Now that we know the needs of a video recording studio and the possibilities to reach those needs, we can apply and adapt this knowledge to a real-case scenario. An existing room has been chosen for this application. Measurements have been conducted in order to determine the settings from which to work from. Since a spatial division had to occur to create a control room and a live room, theoretical simulations were considered in addition to the empirical measurements. The different equipment and acoustic treatment options were discussed and contrasted to find an appropriate solution for the control room and for the live room, while complying with the set budget of 80,000€ excluding VAT. The method process is detailed hereafter.

a. REFERENCE ROOM ANALYSIS

The choice of using an existing room as a reference was made to give a realer aspect to the conception of a video studio; such a studio is meant to be incorporated in a building rather than built as a stand-alone construction. The chosen room, or reference room, is located on the ground floor of a two-story office building in a residential area in northern Amsterdam. The traffic is poor and most of the environmental noise does not get inside the building. There is rarely audible noise coming from the first floor or the adjacent rooms. All measured noise was of less than 5dB above the noise floor.

The reference room is of a parallelepipedal shape. It is 8.60m long, 6.10m wide and 4.90m high. The floor is made out of linoleum, the ceiling out of concrete and the wall out of gypsum with solid backing. There is one window facing the door of the room, on the south side of the room.

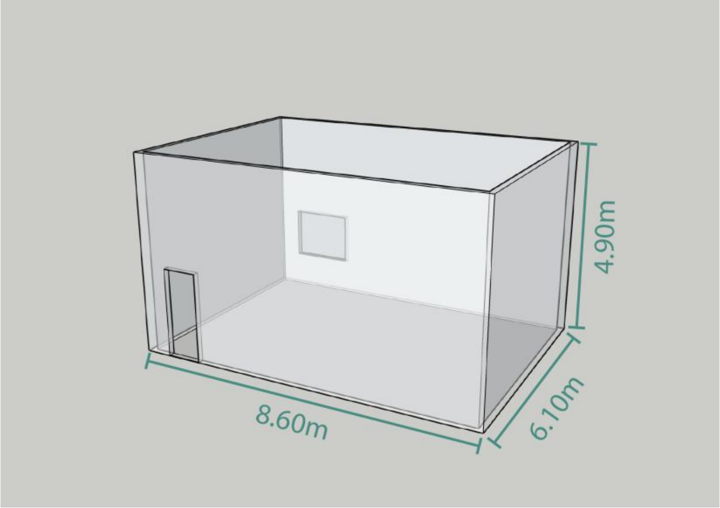


Fig. 26: Reference Room (Meissonnier, 2020)

The room was virtually divided in two in order to represent where the wall between the control room and the live room would be. The measurements were done in order to assess the acoustic treatment needed in the live room; the control room would be a room inside the reference room, hence the absence of practical measurements in the space for it. Since the live room would be exclusively used for video recording with sometimes speech, the use of a single loudspeaker was preferred, rather than a pair of loudspeakers, since the sound source in practice would be a single point source. At first, the speaker was placed in each corner of the live room space consecutively and measured in nine points of the virtual live room area, as shown in figure 27.a below. These measurements were meant to record a frequency response of the room as it would be picked up by a microphone held or fixed on a speaker, which is a moving sound source, and were called 'Measurements 1-4'.

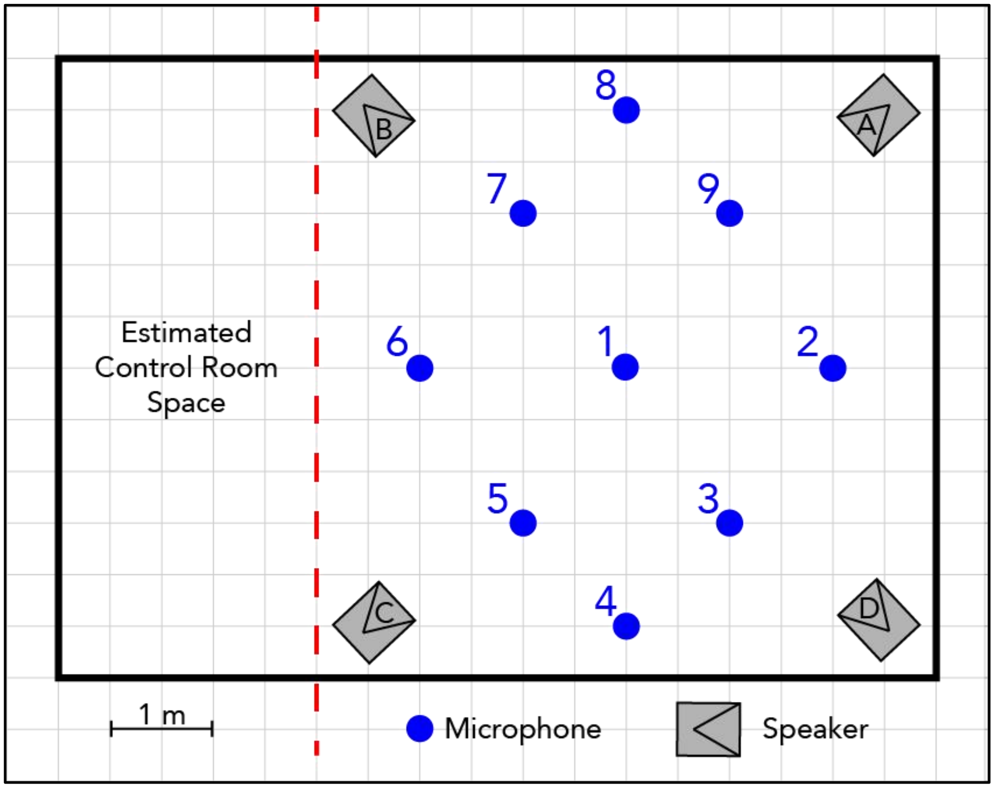


Fig. 27.a: Floor plan for general room frequency response, Measurements 1-4 (Meissonnier, 2020)

Second, three microphones were placed where the three cameras would be operating from, representing the shotgun microphones usually placed on top of the camera for an audio recording. The same loudspeaker was then placed in nine spots across the area where the speaker would be standing, representing the speech of that person.

These measurements, referred to as 'Measurements 5', were done to evaluate the frequency response of a sound a speaker, who is still the moving sound source, would be emitting at the shotgun microphone stand points.

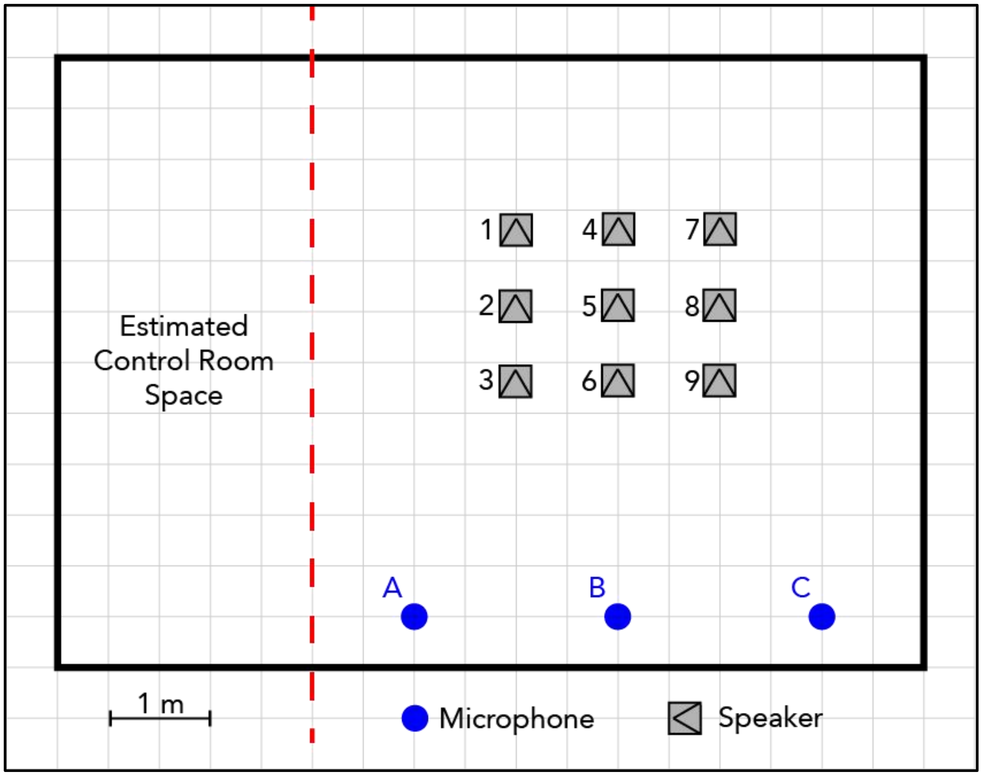


Fig. 27.b: Floor plan for video performance simulation room frequency response, Measurements 5 (Meissonnier, 2020)

To carry out the measurements, the software Room EQ Wizard was chosen. It is free, its interface is easy to use and the criteria analyzed are numerous and also generates a waterfall plot of the measurements, which is very practical when analysing all the results together. Moreover, REW has a calibrator feature that is very practical when setting up since an external calibrator is not needed to calibrate the microphone input. (Mulcahy, 2020)

After the installation of the loudspeaker and the microphone, and the calibration of the system, we proceeded to the measurements. The two most important criteria for this project were the frequency response and the RT60. The most significant results for the room's frequency response were kept and are shown below. The reference SPL is of 65dB SPL.

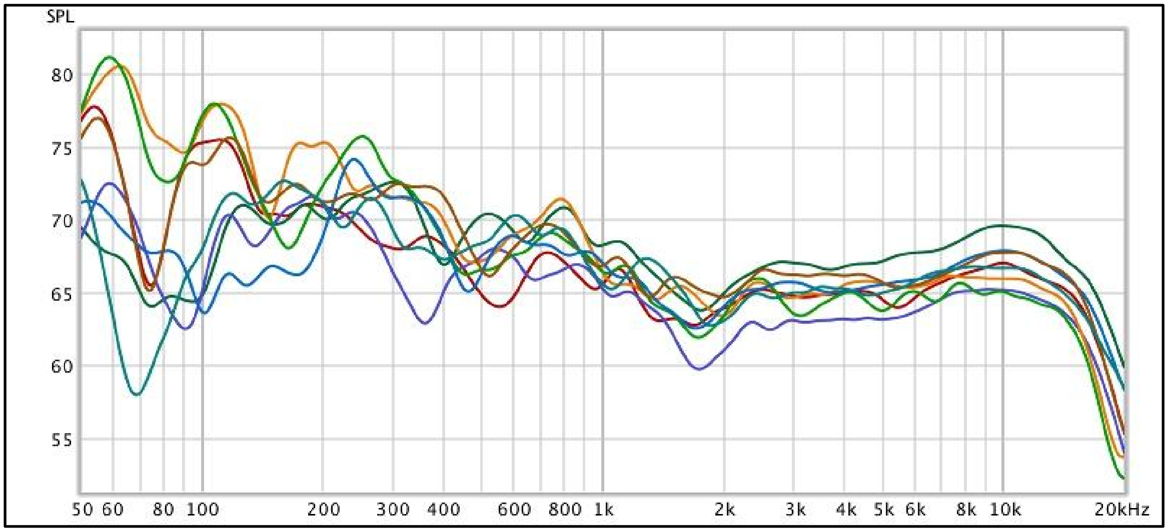


Fig. 28.a: Frequency response of the test room for Measurements 1-4 (Meissonnier, 2020)

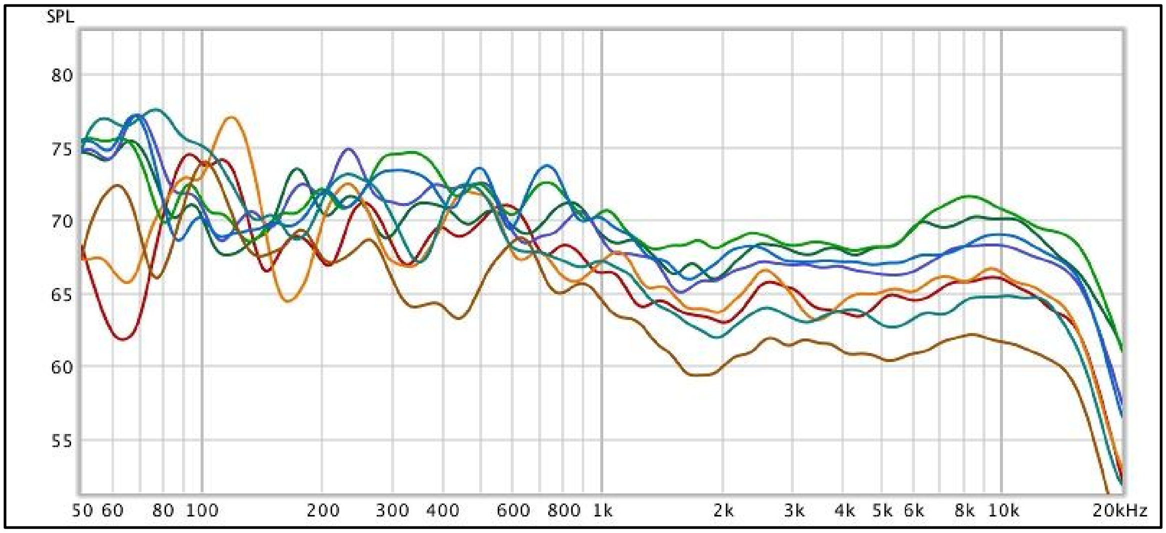


Fig. 28.b: Frequency response of the test room for Measurements 5 (Meissonnier, 2020)

It is needed to divide those results into frequency ranges in order to approach acoustic treatment per range since not all frequencies require the same acoustic solution. The table 5 below shows the graphics' results divided in 7 ranges and using 65dB SPL as a reference.

Measurements N°	Frequency Range	Minimum Boost	Maximum Boost
1-4	50-130Hz	+10dB	+16dB
5		+10dB	+13dB
1-4	130-400Hz	+6.5dB	+10dB
5			
1-4	400Hz-1.1kHz	+3dB	+6dB
5	400Hz-810Hz	+6dB	+8dB
1-4	1.1kHz-7.7kHz	+0dB	+3dB
5	810Hz-7.7kHz	+3dB	+6dB
1-4	7.7kHz-12.5kHz	+3dB	+5dB
5			
1-4	12.5kHz-18kHz	+0dB	+3dB
5			
1-4	18kHz-20kHz	Under reference SPL	Under reference SPL
5			

Table 5: Summary of the measured frequency response in measurements 1 to 5 (Meissonnier, 2020)

The amplification of the frequencies by the room is most significant below 400Hz which will require absorption to lower the energy in those ranges. Between 400Hz and approximately 1kHz, the boosts are more gentle and their energy can be dissipated with a combination of absorption and diffraction. Above 1kHz and below 18kHz, the sound is even less boosted which can be corrected mostly with diffusion and reflection. At 18kHz and above, the sound level drops below the reference SPL for which no acoustic treatment will be needed.

In addition to frequency responses, REW provided measurements of the RT60. Tables of those were made to gather the highest, hence most significant, results. The aim is to keep the TR60 at 500ms at most in both the control room and live room.

Frequency (Hz)	Average RT$_{60}$ (ms)	Frequency (Hz)	Average RT$_{60}$ (ms)
50	799	798	468
78	1115	1k	427
125	930	2.5k	356
200	672	4k	322
400	576	8k	283
630	469	10k	277

Table 6.a: Measured Reverberation Time of Test Room - Measurements 1-4 (Meissonnier, 2020)

Frequency (Hz)	Average RT$_{60}$ (ms)	Frequency (Hz)	Average RT$_{60}$ (ms)
50	707	798	468
62	1296	1k	404
125	1064	2k	375
200	691	5k	363
315	623	8k	274
500	573	10k	264

Table 6.b: Measured Reverberation Time of Test Room - Measurement 5 (Meissonnier, 2020)

The reverberation is most significant below 200Hz, at the lower limit of the voice's frequency range, and is above the desired length under approximately 800Hz. Low frequency sounds such as structure-borne noise create the most disturbing reverberation. It is therefore important to isolate the room from those sounds.

b. SPATIAL DIVISION

The first task to accomplish is to determine the size of the entrance, the control room and the live room, considering the following spatial layout:

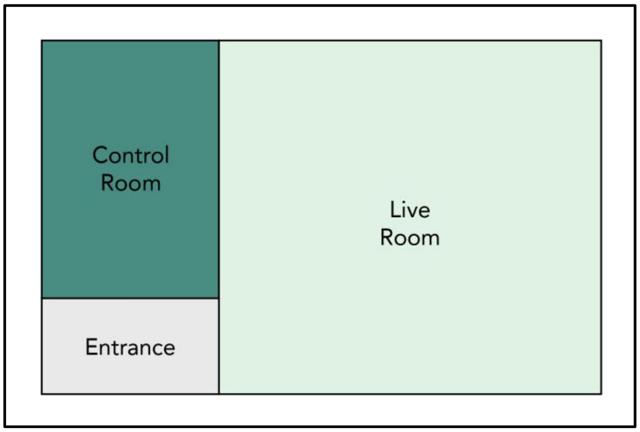


Fig. 29.a: Spatial layout of the studio space (Meissonnier, 2020)

The minimum width for each room is the only basic architectural constraint: 1.5m for the entrance, 2m for the control room and 5.9m for the live room, taking into account that the walls will be about 20 cm thick. Since the values of the volume and the surface vary proportionally to the length (L), width (W) and height (H) of the room, those values are the variables to be determined. The range for those dimensions can be calculated using the RT60 equation mentioned earlier and the room simulation feature of REW that displays the room modes up until 200Hz, which is enough to determine the fundamental frequency of each mode. We can note that the lower the volume's value the lower the RT60, and the smaller the room the higher the fundamental frequency of each mode.

It was decided to start with determining the dimensions of the control room as this room will have fixed acoustics, lowering the modulation possibilities. According to the constraints mentioned above, the control room can be up 4.10m long, 2.50m wide and 4.90m high. However, it cannot be shorter than 2m, narrower than 2m and lower than 2.5m. Using the room simulation in REW, it can be found that 2.4m of width, 4.1m of length and 3.2m of height are the best dimensions, spacing out the modes enough, preventing their amplification.

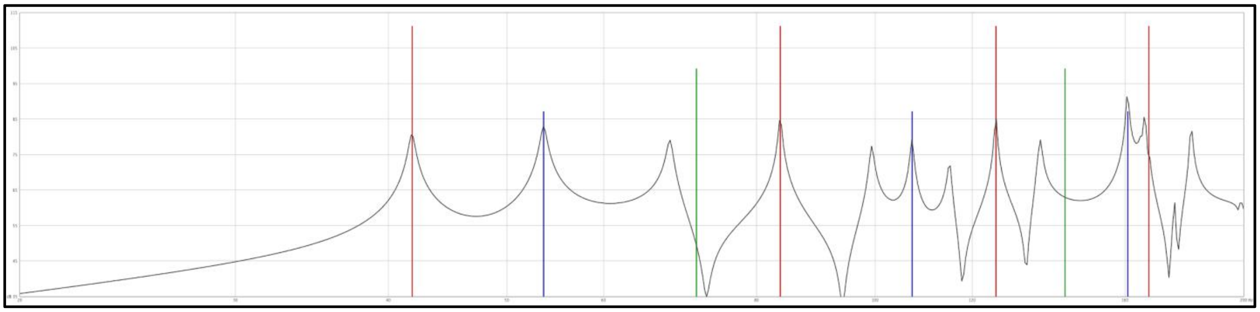


Fig. 30.a: Axial modes in the untreated control room (Meissonnier, 2020)

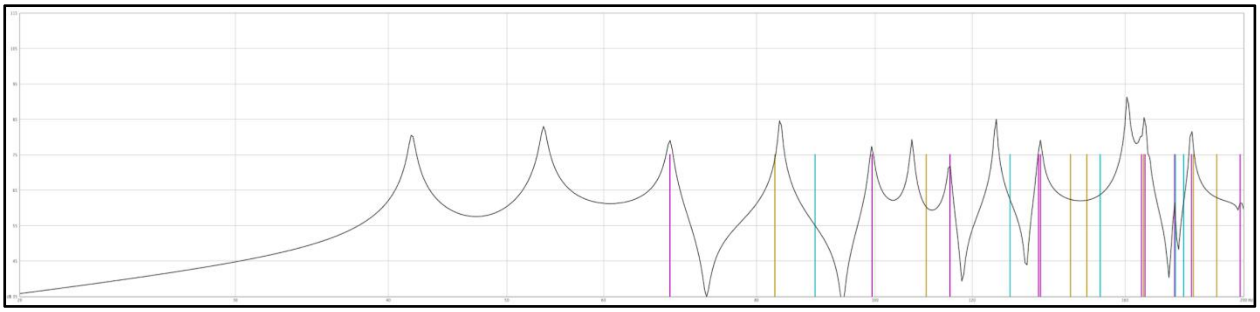


Fig. 30.b: Tangential modes in the untreated control room (Meissonnier, 2020)

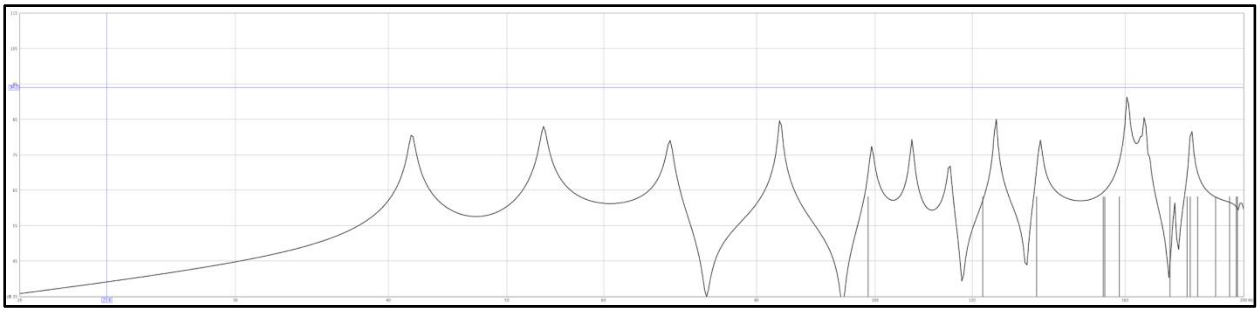


Fig. 30.c: Oblique modes in the untreated control room (Meissonnier, 2020)

Moreover, if the room's dimensions are 10cm longer, the RT60 will be above the desired 500ms in the lower frequency ranges. With the final dimensions, the RT60 was calculated using the formula $RT_{60} = 0.161\frac{V}{4Vm\times 10^{-6} + S\alpha}$ in a spreadsheet and is as follows:

Frequency	**RT60**	**Frequency**	**RT60**	**Frequency**	**RT60**
125Hz	0.496s	500Hz	0.411s	2kHz	0.305s
250Hz	0.495s	1kHz	0.351s	4kHz	0.161s

Table 7: RT60 in the untreated control room (Meissonnier, 2020)

Those results are theoretical and are expected to be slightly higher in reality, as the measured RT60 in the live room can be up to 300ms higher than the expected results from the simulation.

Since the live room's entrance needs to connect with the studio's entrance, instead of the control room which could cause disturbances for both rooms, the live room will conserve the original room's width of 6.10m as its length. Moreover, the height of 4.90m has to remain as it is space needed for the light rigging, and the width is going to be 6m since it needs to have a visual connection with the control room.

Using the RT60 equation, we can find the following reverberation characteristics of the bare, untreated live room. Those results are theoretical and are expected to be higher in reality by an average of 265ms between 250Hz and 2kHz.

Frequency	**RT60**	**Frequency**	**RT60**	**Frequency**	**RT60**
125Hz	0.901s	500Hz	0.744s	2kHz	0.547s
250Hz	0.898s	1kHz	0.634s	4kHz	0.287s

Table 8: RT60 in the untreated live room (Meissonnier, 2020)

The entrance will occupy the leftover space, which corresponds to 1.80m of width, 2.40m of length and 2.75m of height with the use of a suspended.

The spatial division is hence as follows, including 20cm of wall thickness between the spaces:

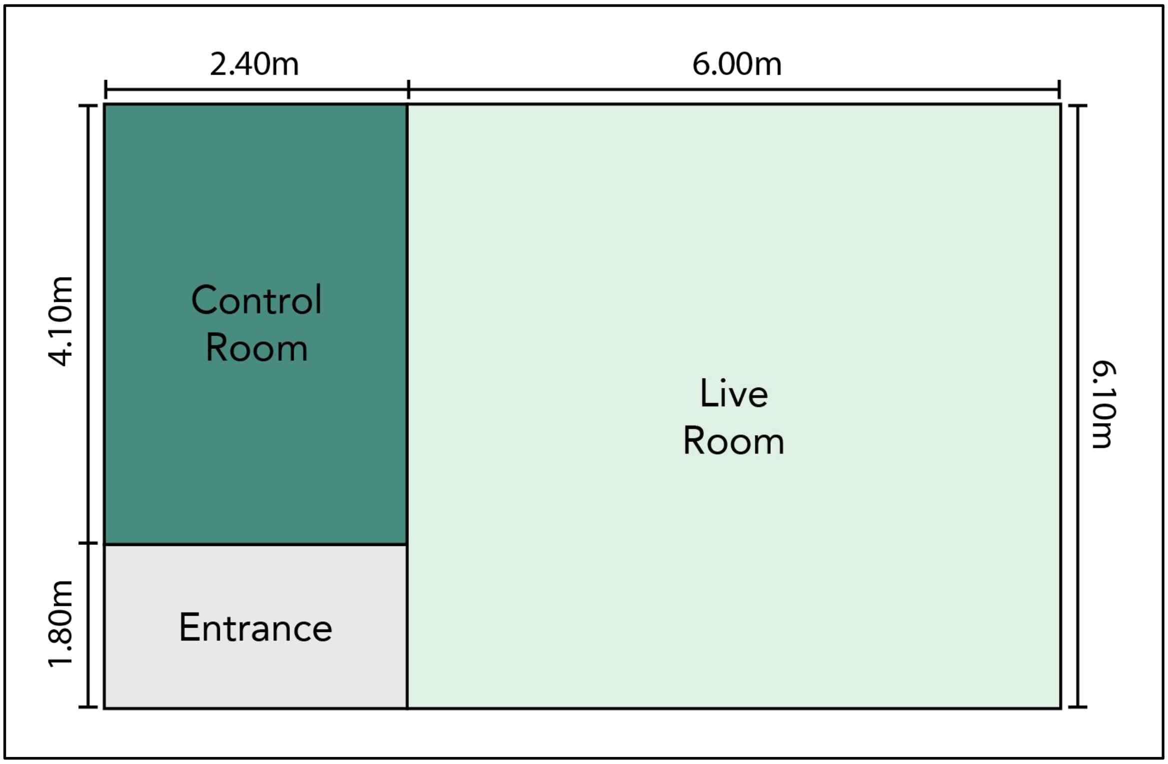


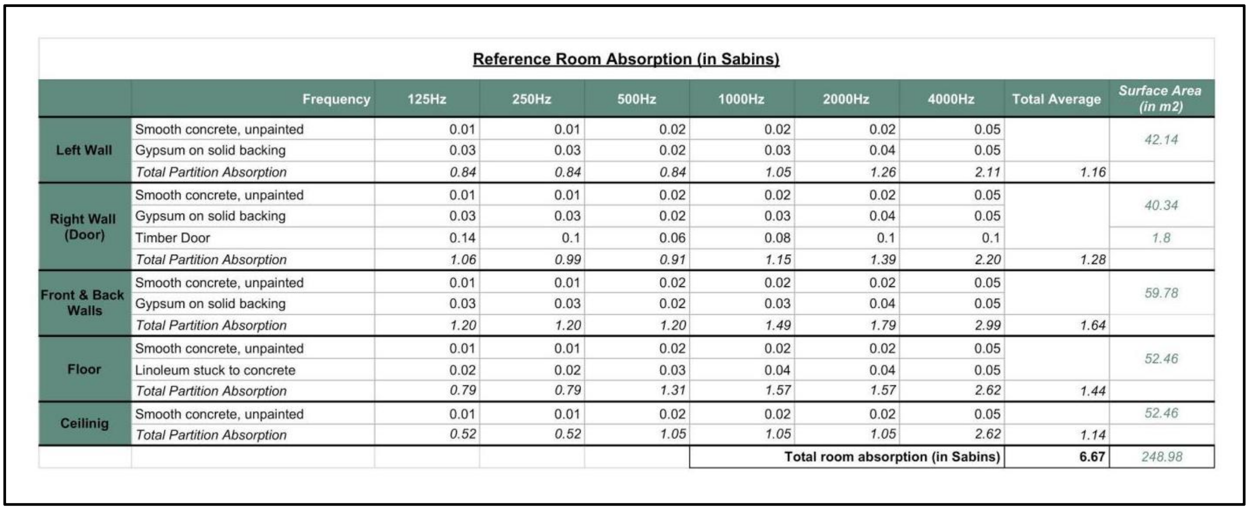
Fig. 29.b: Spatial layout of the studio space with dimensions (Meissonnier, 2020)

c. ACOUSTIC TREATMENT SOLUTION

It has been decided that the rooms will be kept at an average temperature of 20°C, the sound travelling hence at 343m/s.

In the construction of a studio, the STC should be between 55 and 70. When using materials with an STC in that range, only loud sounds can be heard in a room with low background noise. Said loud sounds should not be happening, both inside the studio, since only voice recordings or mixing at an average level of 80dB SPL will be happening, and outside the studio if the site selection has been done appropriately.

The reference room has the following absorption characteristics:



Reference Room Absorption (in Sabins)

	Frequency	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz	Total Average	*Surface Area (in m2)*
Left Wall	Smooth concrete, unpainted	0.01	0.01	0.02	0.02	0.02	0.05		*42.14*
	Gypsum on solid backing	0.03	0.03	0.02	0.03	0.04	0.05		
	Total Partition Absorption	*0.84*	*0.84*	*0.84*	*1.05*	*1.26*	*2.11*	*1.16*	
Right Wall (Door)	Smooth concrete, unpainted	0.01	0.01	0.02	0.02	0.02	0.05		*40.34*
	Gypsum on solid backing	0.03	0.03	0.02	0.03	0.04	0.05		
	Timber Door	0.14	0.1	0.06	0.08	0.1	0.1		*1.8*
	Total Partition Absorption	*1.06*	*0.99*	*0.91*	*1.15*	*1.39*	*2.20*	*1.28*	
Front & Back Walls	Smooth concrete, unpainted	0.01	0.01	0.02	0.02	0.02	0.05		*59.78*
	Gypsum on solid backing	0.03	0.03	0.02	0.03	0.04	0.05		
	Total Partition Absorption	*1.20*	*1.20*	*1.20*	*1.49*	*1.79*	*2.99*	*1.64*	
Floor	Smooth concrete, unpainted	0.01	0.01	0.02	0.02	0.02	0.05		*52.46*
	Linoleum stuck to concrete	0.02	0.02	0.03	0.04	0.04	0.05		
	Total Partition Absorption	*0.79*	*0.79*	*1.31*	*1.57*	*1.57*	*2.62*	*1.44*	
Ceilinig	Smooth concrete, unpainted	0.01	0.01	0.02	0.02	0.02	0.05		*52.46*
	Total Partition Absorption	*0.52*	*0.52*	*1.05*	*1.05*	*1.05*	*2.62*	*1.14*	
					Total room absorption (in Sabins)			**6.67**	*248.98*

Table 9: Reference room absorption characteristics (Meissonnier, 2020)

Acoustic solutions by Vivacoustic will mostly be used since they are easily available on online shops, their aesthetics fit the studio's visual identity and they comply with the budget.

i. *Live Room*

The measurements made in the reference room, in addition with room simulations, will be used to determine the most appropriate acoustic treatment needed for the live room.

When using the room simulation in REW, it can be found that 5.45m of width for the live room is the best dimension regarding modes because it parts some modes further, as can be seen below.

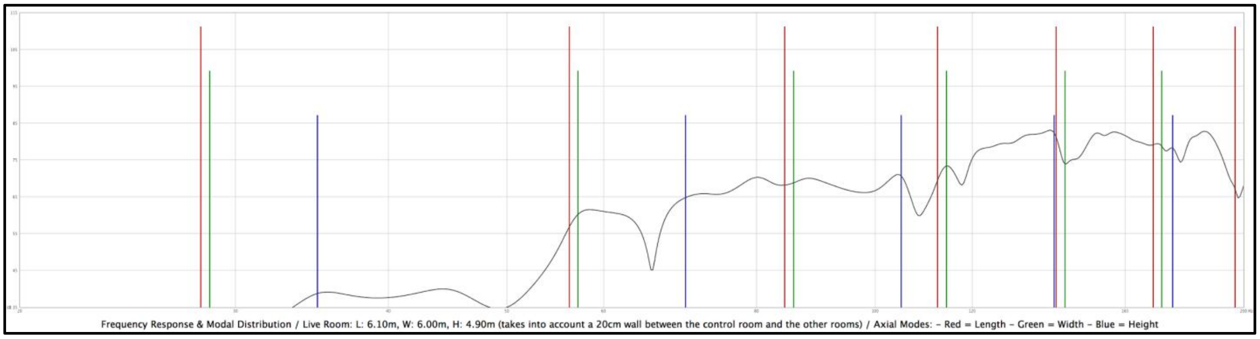


Fig. 31.a: Axial modes in the untreated live room (Meissonnier, 2020)

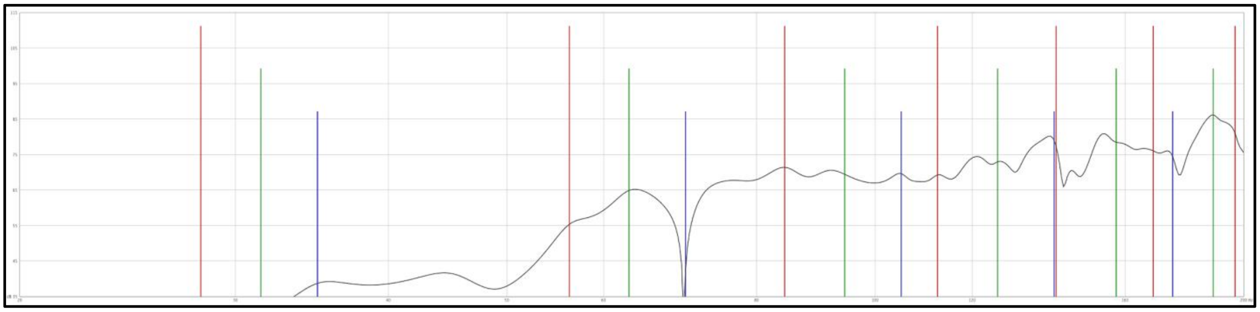


Fig. 31.b: Axial modes in the 5.45m-wide live room (Meissonnier, 2020)

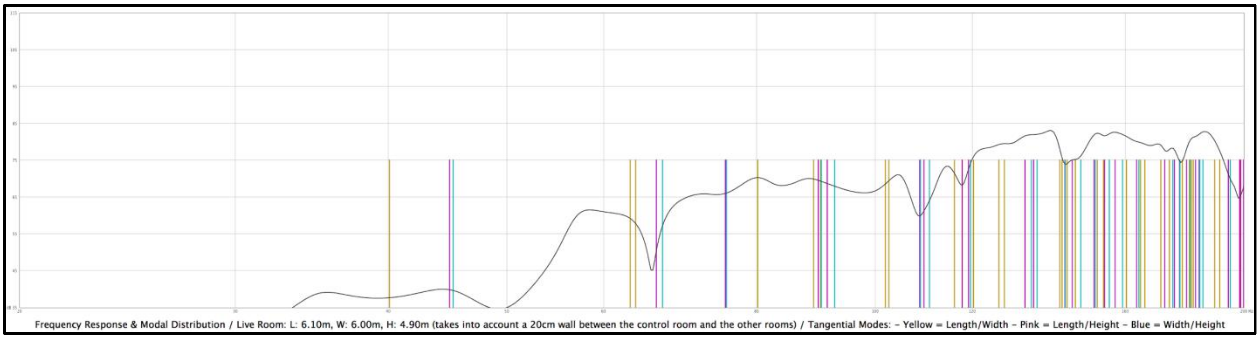


Fig. 31.c: Tangential modes in the untreated live room (Meissonnier, 2020)

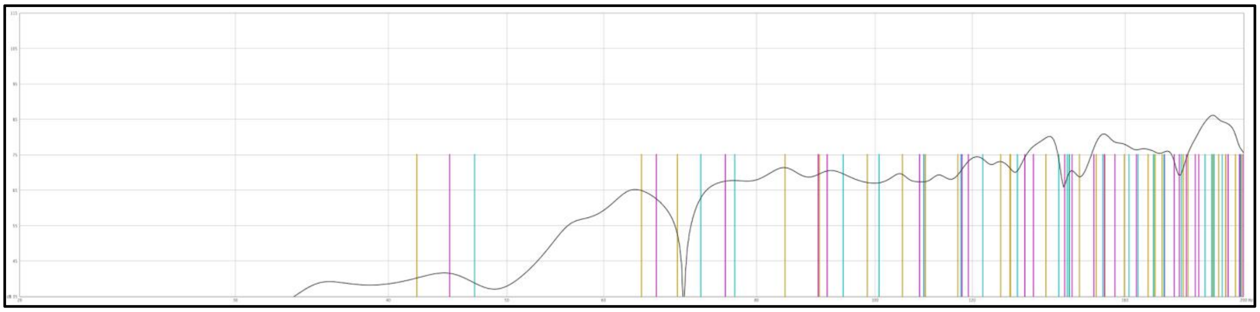


Fig. 31.d: Tangential modes in the 5.45m-wide live room (Meissonnier, 2020)

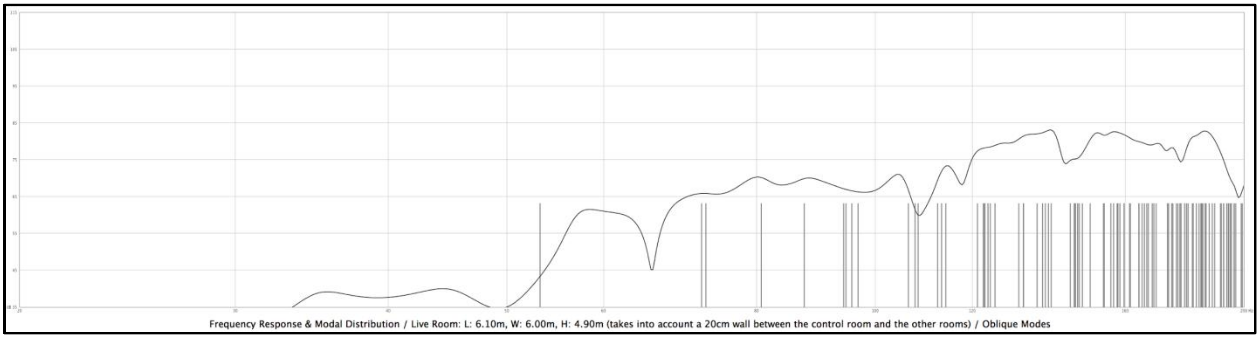


Fig. 31.e: Oblique modes in the untreated live room (Meissonnier, 2020)

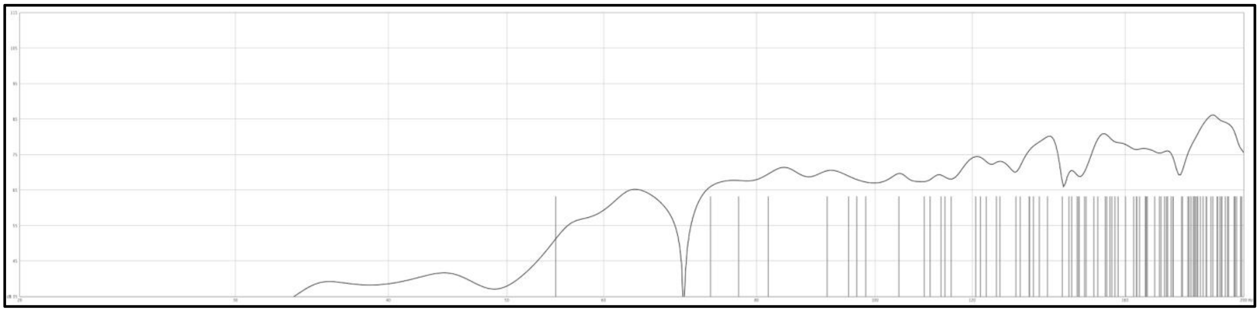


Fig. 31.f: Oblique modes in the 5.45m-wide live room (Meissonnier, 2020)

It would not have been possible to create a smaller room because it could have impaired a comfortable use of some lighting and video equipment by not providing enough space. However, the use of movable acoustics is then a good alternative. It can reduce the available space according to the needs of each situation, making the live room a space with flexible acoustics, which is also a strong selling point when promoting the studio to potential clients.

As mentioned earlier, the reverberation time is exceeding the desired maximum length of 500ms under 800Hz and more significantly under 200Hz. To determine how much absorption is needed, one can use the following calculations:

For 125Hz:

$$RT_{60} = 0.161\frac{V}{4Vm\times10^{-6}+S\alpha}$$
$$\Leftrightarrow \alpha = \frac{0.161V-(RT_{60}\times4mV\times10^{-6})}{S}$$
$$\Leftrightarrow \alpha = \frac{0.161\times162.9005-(0.5\times4\times92\times162.9005\times10^{-6})}{173.14}$$
$$\alpha \approx 0.151\ S$$

For 250Hz:

$$\alpha = \frac{0.161V-(RT_{60}\times4mV\times10^{-6})}{S}$$
$$\alpha = \frac{0.161\times162.9005-(0.5\times4\times276\times162.9005\times10^{-6})}{173.14}$$
$$\alpha \approx 0.151\ S$$

For 500Hz:

$$\alpha = \frac{0.161V-(RT_{60}\times4mV\times10^{-6})}{S}$$
$$\alpha = \frac{0.161\times162.9005-(0.5\times4\times645\times162.9005\times10^{-6})}{173.14}$$
$$\alpha \approx 0.150\ S$$

The same amount of absorption per frequency range under 800Hz will be needed in the live room to reach the RT60 goal. The average absorption coefficient should be of at least 0.15 Sabins, but not more than 0.45 to avoid too much absorption causing the room to lack natural reverberation. Considering that the original boundaries have an absorption coefficient ranging from 0.01 to 0.05, the absorption capacity of those boundaries should be increased significantly.

The minimum of acceptable total room absorption can be determined using the related formula by Everest and Pohlmann (2013): $A = \Sigma S\alpha$. We know the total average absorption coefficient should be between 0.15 Sabins and that the total surface area of the room is 191.78m2. Therefore:

$$A_{min} = S \times \alpha = 191.78 \times 0.15 = 28.767\ Sabins$$

Since there is a desire to keep the budget as low as possible, it is decided to use plasterboards on battens with 18mm airspace filled with glass wool on the live room walls since it is easy to build, cutting the fabrication costs, and has an absorption coefficient of about 0.3 under 800Hz, which is sufficiently above the minimum desired absorption.

Acoustic treatment on the ceiling has a double function: controlling the acoustics of the room, as well as preventing unwanted noise from above. There are multiple material options available, but it was decided that the ceiling should be covered with 22mm thick gypsum tiles perforated at 17%. Such gypsum tiles were chosen because of their cheap price and they are one of the few options with the highest efficiency at absorbing low frequency sounds, and hence structure borne noise. They act as perforated panel absorbers.

The floor will be covered with vinyl only, partly absorbing sound from people walking in the room. Even though its absorption coefficient is low (under 0.1), the room's average absorption coefficient will still be above 0.15 Sabins since the ceiling is more absorbent than the wall.

Besides absorbing for reverberation issues, axial modes need to be dampened
It is shown in Figures 31.b, 31.d and 31.f that the axial modes fundamental frequencies are 28.2Hz (length), 31.5Hz (width) and 35Hz (height), which are the most significant modes to be treated. Additionally, the tangential modes fundamental frequencies are

42.3Hz, 45Hz and 47.1Hz, but those do not cause noticeable issues when recording a voice.

It is needed to determine the different frequency regions to consider for the control room and for the live room in order to approach acoustic treatment for those spaces.

The volume of the live room is 179.3m^3, which equals 6331.920ft^3, and the average RT60 is 592ms. Considering those values, we can determine $f_{(LR)1}$, $f_{(LR)2}$ and $f_{(LR)3}$.

$$f_{(LR)1} = \frac{565}{3.28084 \times L_{LR}} = \frac{565}{3.28084 \times 6.1} \approx 28.7Hz$$

$$f_{(LR)2} = 11250 \times \sqrt{\frac{RT60_{LR}}{V_{LR}}} = 11250 \times \sqrt{\frac{592}{6331.920}} \approx 108.78Hz$$

$$f_{(LR)3} = 4 \times f_{(LR)2} = 4 \times 11250 \times \sqrt{\frac{592}{6331.920}} \approx 435.17Hz$$

The different regions are hence as below:

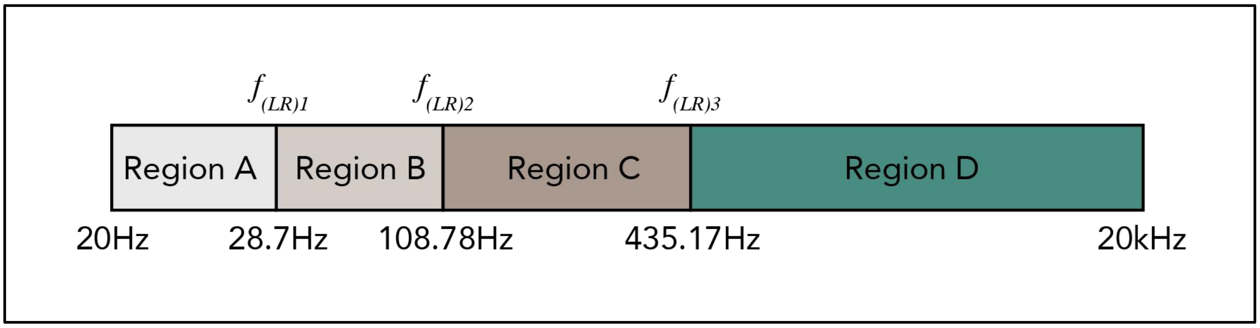


Fig. 32: Frequency regions for the live room (Meissonnier, 2020)

Frequencies below 28.7Hz do not need any treatment in the live room.

Between 28.7Hz and 108.78Hz, absorbing treatment will be needed. Since we aim at canceling specific frequencies without hindering too much liveliness in the room, using absorbers based on the Helmholtz resonator principle is a fair idea. Not only does it absorb the unwanted frequencies, but also diffuses the other frequencies. However, such absorbers are harder to build by alone. Consequently, it was decided to use *Wavewood Ultra Lite* resonant absorbers by Vivacoustic to be evenly spread across the wall to reduce standing waves. Those absorbers provide good absorption between 315Hz and 1000Hz, which is the frequency range experiencing problematic boosts as we saw in Figures 28.a and 28.b (Vicoustic, n.d.). Thus, this acoustic solution also provides solutions for the frequency Regions B, C and part of D.

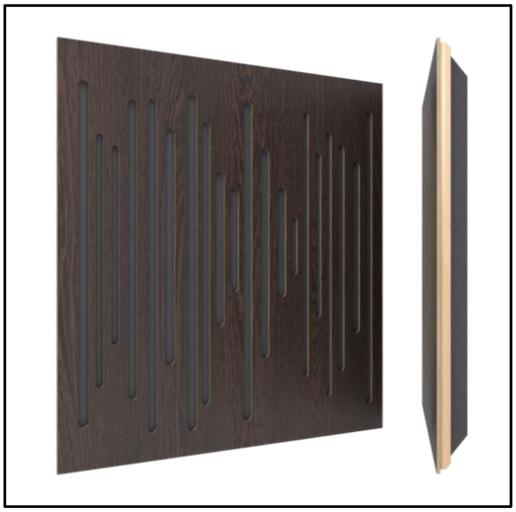


Fig. 33: Vicoustic Wavewood Ultra Lite absorber (Vicoustic, 2020)

In addition to those fixed acoustic treatments, movable panels are considered to be able to shape the frequency response of the room if necessary. The modulable Vicoustic *Flexi Wall* was chosen for that effect. It is highly effective to reduce unwanted boosts above 1kHz, especially in Region D, with its absorptive *Flexi Panels*. It can also be used as mobile reflectors with its partly absorbent, partly reflective *Flexi Wood Ultra Lite* panels (Vicoustic, n.d.)

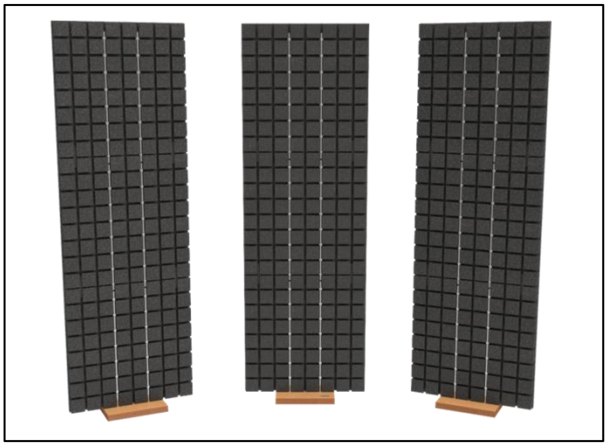


Fig. 34.a: Vicoustic Flexi Wall (Vicoustic, 2020)

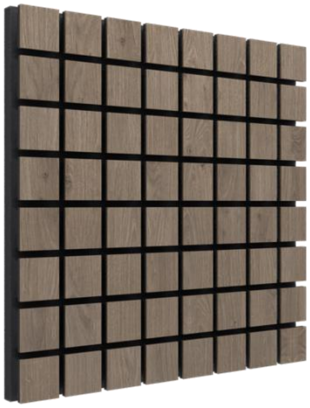
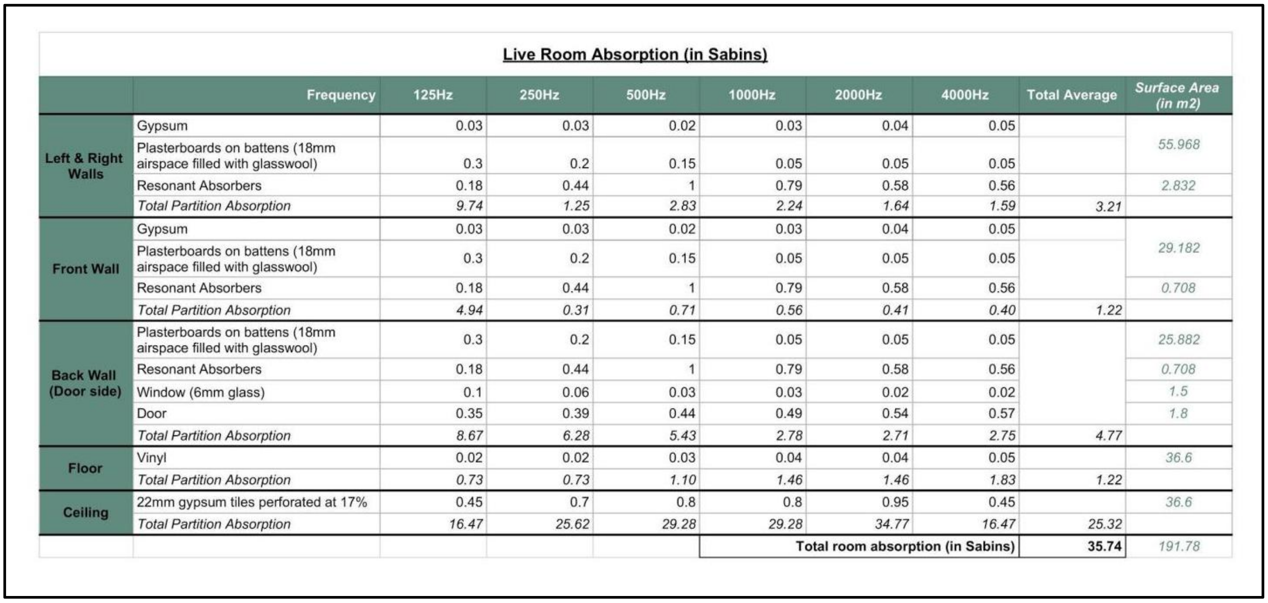


Fig. 34.b: Vicoustic Flexi Wood Ultra Lite (Vicoustic, 2020)

The live room's acoustic treatment hence consists of different types of fixed and movable absorbing panels in combination with fixed resonating absorbers. Reflective and diffusing elements were avoided as much as possible to keep the acoustical liveliness of the room to a tightly controllable level when recording audio. If liveliness is lacking in the recording, it can always be added in post-production.

With those acoustic treatments, the room's absorption is 37.74 Sabins, which is higher than the desired minimum. A summary of the live room's acoustic treatment is shown in table 10 and figures 35.a and 35.b below.



Live Room Absorption (in Sabins)

	Frequency	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz	Total Average	*Surface Area (in m2)*
Left & Right Walls	Gypsum	0.03	0.03	0.02	0.03	0.04	0.05		*55.968*
	Plasterboards on battens (18mm airspace filled with glasswool)	0.3	0.2	0.15	0.05	0.05	0.05		
	Resonant Absorbers	0.18	0.44	1	0.79	0.58	0.56		*2.832*
	Total Partition Absorption	*9.74*	*1.25*	*2.83*	*2.24*	*1.64*	*1.59*	*3.21*	
Front Wall	Gypsum	0.03	0.03	0.02	0.03	0.04	0.05		*29.182*
	Plasterboards on battens (18mm airspace filled with glasswool)	0.3	0.2	0.15	0.05	0.05	0.05		
	Resonant Absorbers	0.18	0.44	1	0.79	0.58	0.56		*0.708*
	Total Partition Absorption	*4.94*	*0.31*	*0.71*	*0.56*	*0.41*	*0.40*	*1.22*	
Back Wall (Door side)	Plasterboards on battens (18mm airspace filled with glasswool)	0.3	0.2	0.15	0.05	0.05	0.05		*25.882*
	Resonant Absorbers	0.18	0.44	1	0.79	0.58	0.56		*0.708*
	Window (6mm glass)	0.1	0.06	0.03	0.03	0.02	0.02		*1.5*
	Door	0.35	0.39	0.44	0.49	0.54	0.57		*1.8*
	Total Partition Absorption	*8.67*	*6.28*	*5.43*	*2.78*	*2.71*	*2.75*	*4.77*	
Floor	Vinyl	0.02	0.02	0.03	0.04	0.04	0.05		*36.6*
	Total Partition Absorption	*0.73*	*0.73*	*1.10*	*1.46*	*1.46*	*1.83*	*1.22*	
Ceiling	22mm gypsum tiles perforated at 17%	0.45	0.7	0.8	0.8	0.95	0.45		*36.6*
	Total Partition Absorption	*16.47*	*25.62*	*29.28*	*29.28*	*34.77*	*16.47*	*25.32*	
					Total room absorption (in Sabins)			**35.74**	*191.78*

Table 10: Live room absorption characteristics (Meissonnier, 2020)

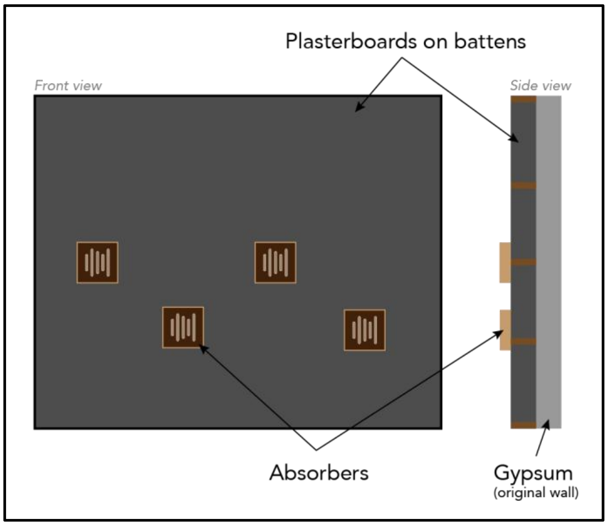


Fig. 35.a: Simplified live room acoustic treatment scheme - Left & right walls (Meissonnier, 2020)

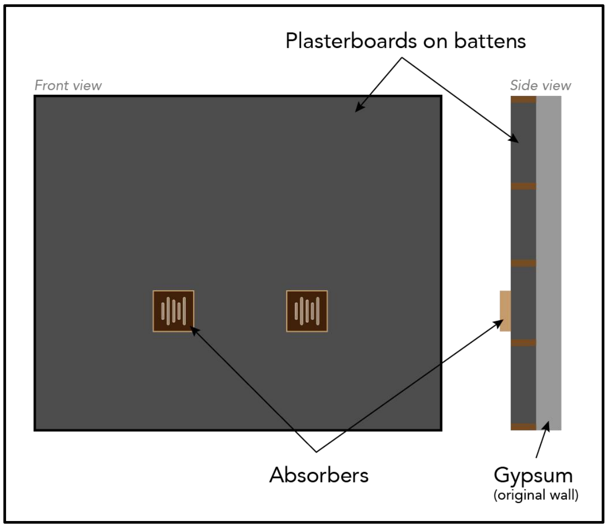


Fig. 35.b: Simplified live room acoustic treatment scheme - Front wall (Meissonnier, 2020)

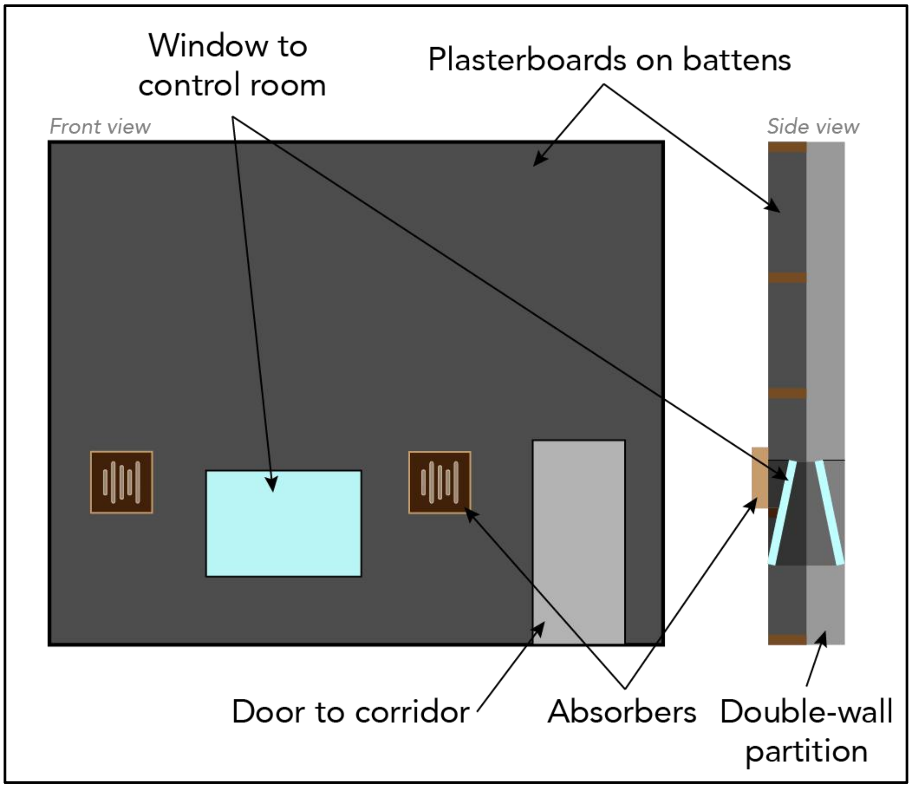


Fig. 35.c: Simplified live room acoustic treatment scheme - Back wall (Meissonnier, 2020)

ii. *Control Room*

The control room acoustic solutions will be based on the room simulation only since it is a "room in a room". Indeed, for the control room to be well isolated from its surroundings, it should not be in direct contact with the surrounding structure (Everest and Pohlmann, 2013). External sound should not pass through the room's boundaries. White (1993) recommended layering isolating partitions and absorbent materials in that effect.

As mentioned earlier, a 20-cm space is reserved for a partition between the control room and the surrounding spaces. The partitions should have an STC rating of at least 55 to keep the majority of noise out of the room and space should be left to implement absorbent material onto the boundaries to flatten the room's frequency response. Indeed, when simulating the control room's acoustics, the higher the average absorption coefficient, the flatter the frequency response. However, one must keep in mind that the room should not be too absorptive which could cause high frequencies to be reduced too much.

Among the different wall structure possibilities presented earlier in figures 19a to 19.e, a double-wall partition with 3.5 inches glass fiber seems to be the most appropriate solution because it provides an STC of 55 and roughly 10cm of extra room for absorptive coverage.

A floating floor solution was adopted in order to be able to isolate the room from below as well. Absorbent material can be placed underneath the floor in order to isolate and absorb more efficiently than the single use of carpet on a hard surface floor would (Web Absorption Data Eng., n.d.). Floating floors are usually mounted with battens on top of rockwool. Since the reference room is located on the ground floor, 50mm of 33kg/m3 rockwool will be sufficiently isolating and absorbing.

Regarding the ceiling, since the optimal height, according to the simulation, is 1.7m lower than the original ceiling, the same suspended solution as in the live room will be used for identical reasons. However, the lowered ceiling creates a cavity that can be problematically resonant if left empty. Therefore, additional rockwool will be placed on the cavity's boundaries to reduce any resonance to an acceptable level and to increase the transmission loss to the live room and to the control room. Rockwool also has thermic isolation properties which will decrease the heat loss in the room, and hence reduce the energetical needs for the heating.

The walls as well as the floating floor should be connected to the pre-existing structure with thick felt to reduce structure borne noise from entering the room.

According to the room simulation, the three fundamental frequencies for the axial modes are 41.9Hz (length), 53.7Hz (height) and 71.5Hz (width), which are the most significant modes to be treated. Additionally, the tangential modes fundamental frequencies are 68.2Hz (length/height), 82.8Hz (length/width) and 89.6Hz (width/height). One could notice that boosts in the frequency response of the simulated room corresponded with the axial mode and with the tangential length/height mode, as shown in figure 36.

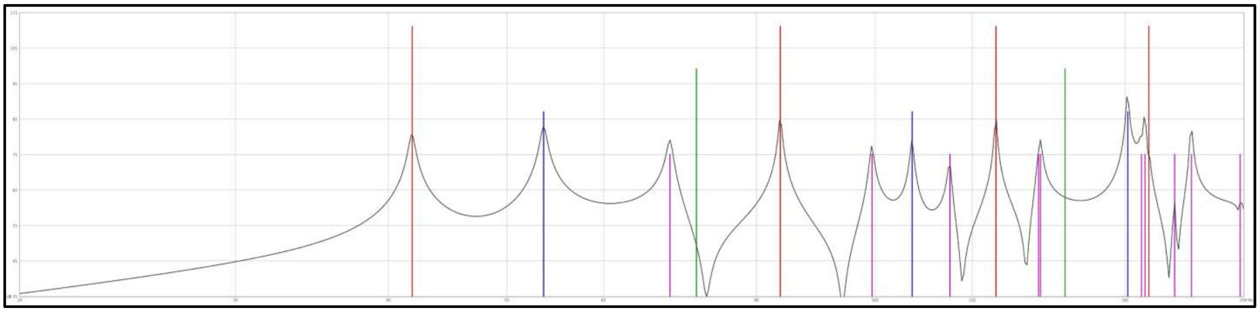


Fig. 36: Frequency response related to room modes in the control room (Meissonnier, 2020)

Using the RT60 equation, we can determine the minimum average absorption coefficient necessary to have a maximum RT60 of 500ms.

At 125Hz:

$$\alpha = \frac{0.161V - (RT_{60} \times 4mV \times 10^{-6})}{S}$$

$$\alpha = \frac{0.161 \times 31.488 - (0.5 \times 4 \times 92 \times 31.488 \times 10^{-6})}{40.36}$$

$$\alpha \approx 0.13\ Sabins$$

At 250Hz:

$$\alpha = \frac{0.161V - (RT_{60} \times 4mV \times 10^{-6})}{S}$$

$$\alpha = \frac{0.161 \times 31.488 - (0.5 \times 4 \times 276 \times 31.488 \times 10^{-6})}{40.36}$$

$$\alpha \approx 0.12\ Sabins$$

At 500Hz:

$$\alpha = \frac{0.161V - (RT_{60} \times 4mV \times 10^{-6})}{S}$$

$$\alpha = \frac{0.161 \times 31.488 - (0.5 \times 4 \times 645 \times 31.488 \times 10^{-6})}{40.36}$$

$$\alpha \approx 0.12\ Sabins$$

At 1kHz:

$$\alpha = \frac{0.161V - (RT_{60} \times 4mV \times 10^{-6})}{S}$$

$$\alpha = \frac{0.161 \times 31.488 - (0.5 \times 4 \times 1151 \times 31.488 \times 10^{-6})}{40.36}$$

$$\alpha \approx 0.12\ Sabins$$

At 2kHz:

$$\alpha = \frac{0.161V - (RT_{60} \times 4mV \times 10^{-6})}{S}$$

$$\alpha = \frac{0.161 \times 31.488 - (0.5 \times 4 \times 2303 \times 31.488 \times 10^{-6})}{40.36}$$

$$\alpha \approx 0.12\ Sabins$$

At 4kHz:

$$\alpha = \frac{0.161V - (RT_{60} \times 4mV \times 10^{-6})}{S}$$

$$\alpha = \frac{0.161 \times 31.488 - (0.5 \times 4 \times 6447 \times 31.488 \times 10^{-6})}{40.36}$$

$$\alpha \approx 0.12\ Sabins$$

The total average room absorption coefficient should be of at least 0.13 Sabins. However, the simulations reveal that a flatter, more easily correctable frequency response occurs when that coefficient's value is between 0.35 and 0.4 Sabins, as shown in figures 37.a and 37.b. If α goes above 0.4 Sabins, a significant dip at 160Hz is observable, which is undesirable.

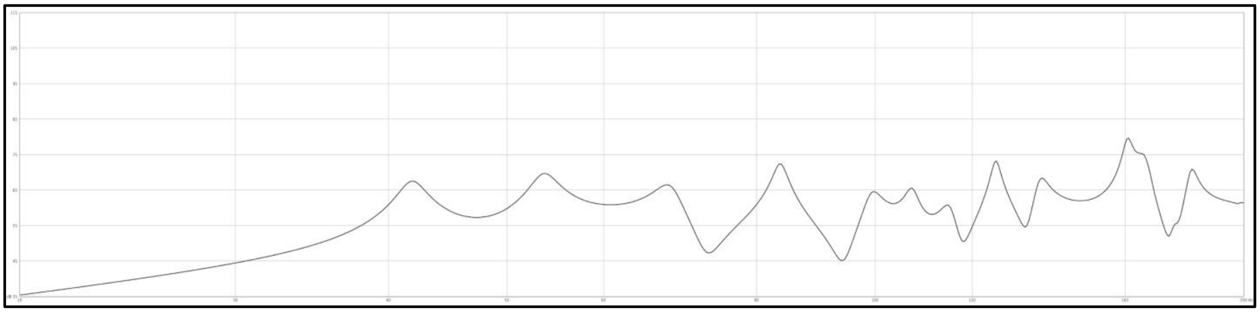


Fig. 37.a: Control room's frequency response for α= 0.13

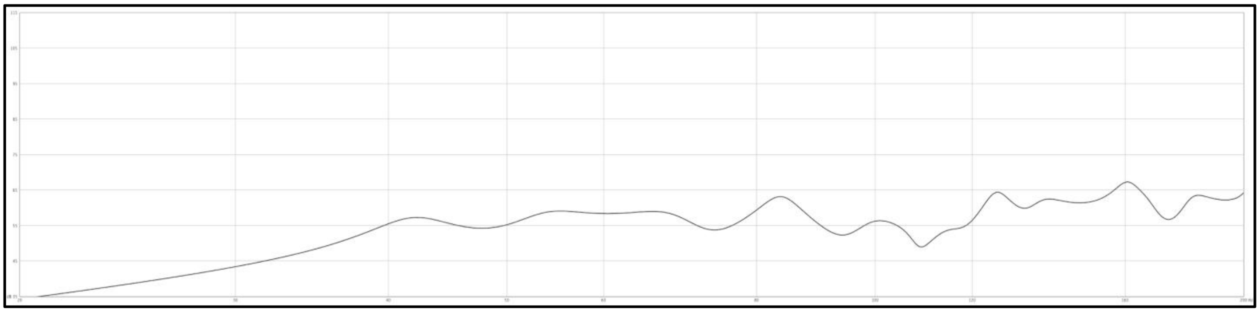


Fig. 38.b: Control room's frequency response for α= 0.35

The current control room's boundaries have a total average absorption coefficient of 0.39 Sabins, which is reaching the upper desired limit for that characteristic. It is important to note that the ceiling and walls surface materials of the control room are very reflective for frequencies above 1kHz. It is hence important to add absorbent and diffusing material for those frequencies.

The range of acceptable total room absorption can be determined using the related formula given by Everest and Pohlmann (2013): $A = \Sigma S\alpha$. We know the total average absorption coefficient should be between 0.35 and 0.4 Sabins and that the total surface area of the room is 61.28m2. Therefore:

$$A_{min} = S \times \alpha = 61.28 \times 0.35 = 21.448\ Sabins$$

$$A_{max} = S \times \alpha = 61.28 \times 0.4 = 24.512\ Sabins$$

To resolve modes and frequency response, one should determine the room's frequency regions. The volume of the control room is 31.5m^3, which equals 1112.412ft^3, and the desired RT60 is 500ms.

$$f_{(CR)1} = \frac{565}{3.28084\times L_{CR}} = \frac{565}{3.28084\times 4.1} \approx 43.1Hz$$

$$f_{(CR)2} = 11250 \times \sqrt{\frac{RT60_{CR}}{V_{CR}}} = 11250 \times \sqrt{\frac{500}{1112.412}} \approx 238.25Hz$$

$$f_{(CR)3} = 4 \times f_{(CR)2} = 4 \times 11250 \times \sqrt{\frac{500}{1112.412}} \approx 954.04Hz$$

The different regions are hence as below:

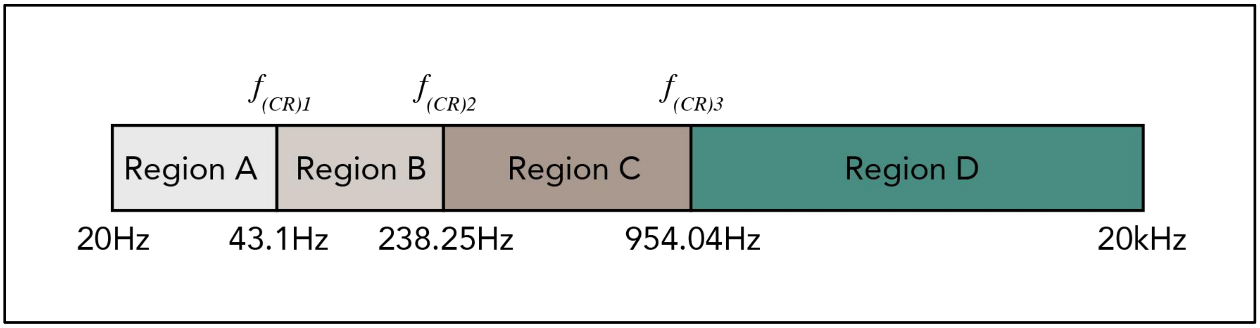


Fig. 39: Frequency regions for the control room (Meissonnier, 2020)

As mentioned above, the walls and the ceiling are very reflective for high frequencies, especially the wall with the window to the live room. 15mm-thick melamine-based foam, covered with a thin layer of colored fabric for aesthetics, can be added onto the walls and the door, as around the window to avoid flutter echoes. It is recommended to add a ceiling panel absorber to absorb sound waves that would potentially reflect on the ceiling, especially from the inclined window (as we will discuss later on). Vicoustic's *Flat Panel VMT* provides a good solution because it is light (≈

2.6kg/m2) and absorbs frequencies above 1kHz very efficiently (α> 0.6). It should slightly be inclined towards the rear of the room in order not to potentially reflect frequencies towards the mixing position.

Fig. 40: Vicoustic Flat Panel VMT (Vicoustic, 2020)

In smaller control rooms, bass frequencies can easily create constructive interferences. It is hence important to place bass traps in the room. The Vicoustic *Super Bass Extreme Ultra* bass traps provide an appropriate solution for this control room. They are characterised by an absorption coefficient of approximately 0.36 for Region B (Vicoustic, n.d.). Indeed, the room has little bass frequencies issues, heavier bass treatment is therefore not needed. One of those bass traps can be placed at each vertical corner of the room, and one extra in the corners behind the speakers in combination with 50mm-thick melamine-based foam. This way, speaker-boundary interference, which is the result from sound spreading behind the speaker and being reflected by a boundary interferes with the direct sound coming out of the front of the speaker, is reduced (Everest and Pohlmann, 2015).

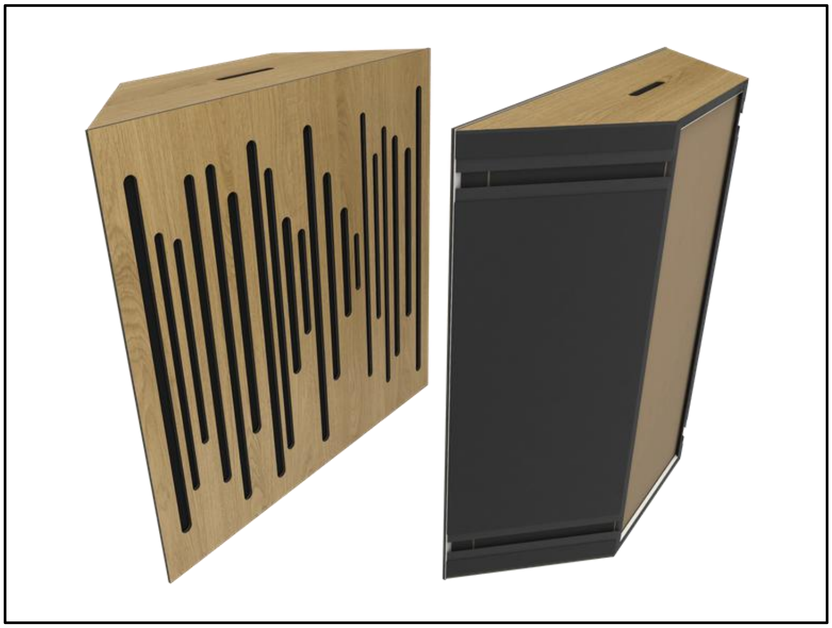


Fig. 41: Vicoustic Super Bass Extreme Ultra (Vicoustic, 2020)

In order to treat the frequencies that would not be absorbed and to keep some liveliness in the room, a "live-end" should be created. This means that the back wall should hold a diffusing element. As discussed during the literature review, grated diffusers provided the most effective sound diffusion. The *Multifuser DC2* by Vicoustic has a diffusion coefficient ranging between 0.62 and 0.75 Sabins (Vicoustic, n.d.). This diffuser will be placed partly on the back wall and partly on the door.

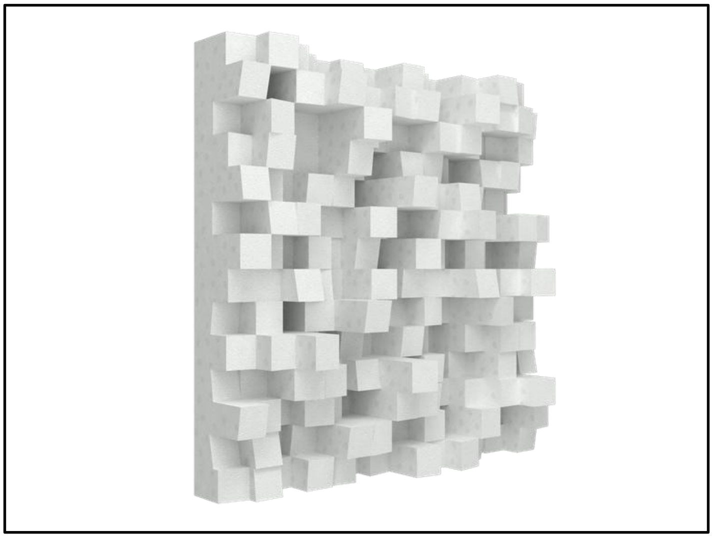
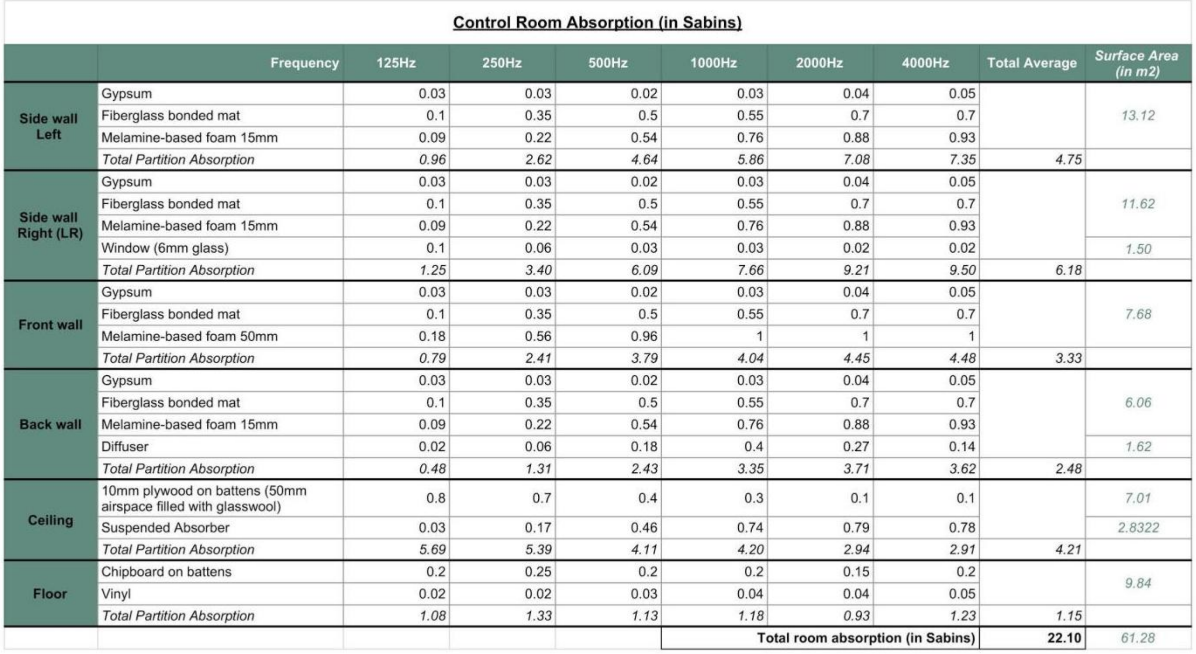


Fig. 42: Vicoustic Multifuser DC2 (Vicoustic, 2020)

With those acoustic treatments, the room's absorption is 22.10 Sabins, which fits within the determined range. A summary of the control room's acoustic treatment is shown in table 11 and figures 43.a to 43.d below.



Control Room Absorption (in Sabins)

	Frequency	**125Hz**	**250Hz**	**500Hz**	**1000Hz**	**2000Hz**	**4000Hz**	**Total Average**	***Surface Area (in m2)***
Side wall Left	Gypsum	0.03	0.03	0.02	0.03	0.04	0.05		*13.12*
	Fiberglass bonded mat	0.1	0.35	0.5	0.55	0.7	0.7		
	Melamine-based foam 15mm	0.09	0.22	0.54	0.76	0.88	0.93		
	Total Partition Absorption	*0.96*	*2.62*	*4.64*	*5.86*	*7.08*	*7.35*	*4.75*	
Side wall Right (LR)	Gypsum	0.03	0.03	0.02	0.03	0.04	0.05		*11.62*
	Fiberglass bonded mat	0.1	0.35	0.5	0.55	0.7	0.7		
	Melamine-based foam 15mm	0.09	0.22	0.54	0.76	0.88	0.93		
	Window (6mm glass)	0.1	0.06	0.03	0.03	0.02	0.02		*1.50*
	Total Partition Absorption	*1.25*	*3.40*	*6.09*	*7.66*	*9.21*	*9.50*	*6.18*	
Front wall	Gypsum	0.03	0.03	0.02	0.03	0.04	0.05		*7.68*
	Fiberglass bonded mat	0.1	0.35	0.5	0.55	0.7	0.7		
	Melamine-based foam 50mm	0.18	0.56	0.96	1	1	1		
	Total Partition Absorption	*0.79*	*2.41*	*3.79*	*4.04*	*4.45*	*4.48*	*3.33*	
Back wall	Gypsum	0.03	0.03	0.02	0.03	0.04	0.05		*6.06*
	Fiberglass bonded mat	0.1	0.35	0.5	0.55	0.7	0.7		
	Melamine-based foam 15mm	0.09	0.22	0.54	0.76	0.88	0.93		
	Diffuser	0.02	0.06	0.18	0.4	0.27	0.14		*1.62*
	Total Partition Absorption	*0.48*	*1.31*	*2.43*	*3.35*	*3.71*	*3.62*	*2.48*	
Ceiling	10mm plywood on battens (50mm airspace filled with glasswool)	0.8	0.7	0.4	0.3	0.1	0.1		*7.01*
	Suspended Absorber	0.03	0.17	0.46	0.74	0.79	0.78		*2.8322*
	Total Partition Absorption	*5.69*	*5.39*	*4.11*	*4.20*	*2.94*	*2.91*	*4.21*	
Floor	Chipboard on battens	0.2	0.25	0.2	0.2	0.15	0.2		*9.84*
	Vinyl	0.02	0.02	0.03	0.04	0.04	0.05		
	Total Partition Absorption	*1.08*	*1.33*	*1.13*	*1.18*	*0.93*	*1.23*	*1.15*	
							Total room absorption (in Sabins)	**22.10**	*61.28*

Table 11: Control room absorption characteristics (Meissonnier, 2020)

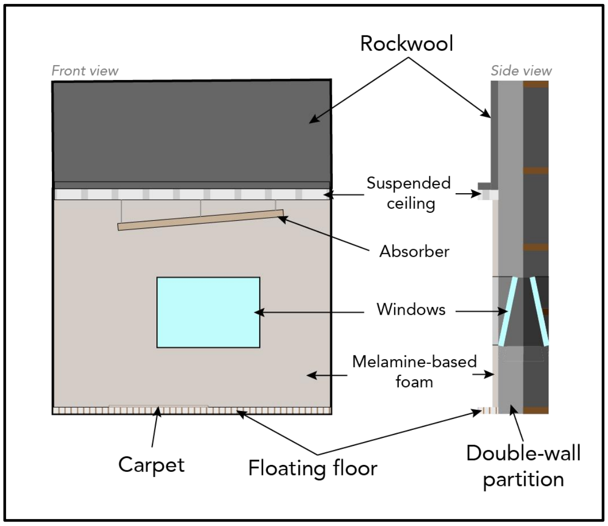


Fig. 43.b: Simplified control room acoustic treatment scheme - Right wall (Meissonnier, 2020)

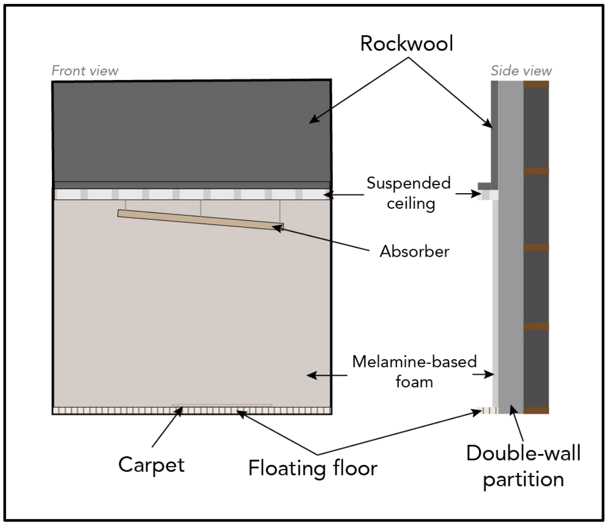


Fig. 43.a: Simplified control room acoustic treatment scheme - Left wall (Meissonnier, 2020)

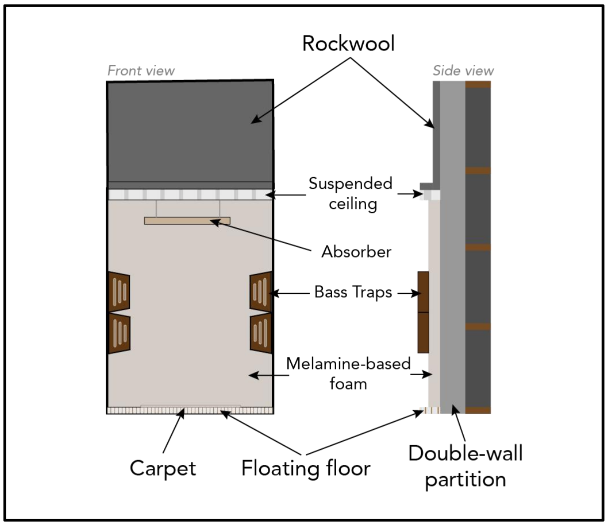


Fig. 43.c: Simplified control room acoustic treatment scheme - Front wall (Meissonnier, 2020)

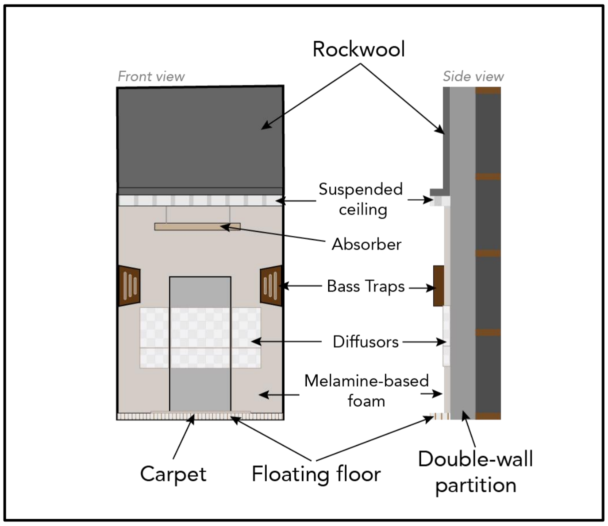


Fig. 43.d: Simplified control room acoustic treatment scheme - Back wall (Meissonnier, 2020)

iii. Doors and Windows

Door and windows can be the weakest acoustic isolation element in the structure of a studio. In order to maintain the isolation between rooms, heavy materials should be used for doors, and multiple panes should be used for windows. Moreover, they should be sealed to prevent sound leaks through small holes between the door or window and the surrounding structure (Everest and Pohlmann, 2013). White (1993) advises that "the most effective way to seal a door is to use a half - round neoprene gasket fitted to the door frame (including the bottom), in conjunction with a pressure latch".

Since the wall between the entrance room and the live room is the continuity of the partition between the control room and the live room, which has a STC of 55, and since we want to prevent noises from circulation in the entrance travelling into the live room, it makes sense to use a door with a STC close to that rating between the entrance and the live room. A good price-quality ratio was found with the *Extreme Studio Door* by Vicoustic, which has a STC of 52 (Vicoustic, n.d.). Raised voices in the corridor should not be heard inside the entrance, requiring a STC of at least 40. Hence, for the main studio entrance, a door with a lower STC rating can be used, like the *Premium Studio Door* by Vicoustic which has a STC of 46 (Vicoustic, n.d.). The same door will be used for the control room because only sound from the entrance needs to be kept out, which will not require a higher sound isolation parameter.

Fig. 44: Vicoustic Extreme studio door (Vicoustic, 2020)

Fig. 45: Vicoustic Premium studio door (Vicoustic, 2020)

As White (1993) advised, non-parallel double-paned windows are recommended for good sound isolation. Those panes should be inclined so that the reflected sound waves do not directly come back at the source, but instead bounce off other boundaries. The control room has a suspended absorptive panel and the live room's ceiling is the most absorptive boundary. Therefore, both panes should be inclined upwards with an angle at which sound waves would respectively bounce to the absorptive panel and to the ceiling. Kozijnshop (2020) provides single-pane 6mm windows made to the desired dimensions of the customer that can easily be incorporated into the studio's structure.

d. AUDIOVISUAL EQUIPMENT INCORPORATION

Regarding the audiovisual equipment, the choice of portability, and therefore modulability, was preferred. There is no imposing piece of equipment.

The set equipment is composed of audio, lighting and camera equipment. First, a combination of dynamic handheld and wireless Lavalier microphones was adopted to ensure respectively robustness and mobility (Alten, 2011). Second, there is a blend of lights, which could serve as key lights, fill lights, top lights and back lights, that can be rigged to a ceiling rail system. This way, the crew wouldn't have to dismount the lights every time to place them elsewhere but only have to slide the fixture to the desired place. Moreover, using a ceiling rail system avoids the use of tripods that could occupy undesired floor space and be in the camera view. Another advantage of the chosen lights is that the parameters of most of them are remotely controlled through a mobile application. Therefore, the crew does not have to access the lights to adjust their settings (Box, 2010). Last, three camera angles were needed for the instances of streaming or talk show type of recordings, hence the choice of obtaining three identical compact cinema cameras.

The control space had to be able to process multiple visual and audio signals simultaneously. The visual signals would be centralized through a switcher that would then send the signals to the computer and back to the live room to a monitor if necessary. The audio signals would be processed through an external audio interface and a DAW. Similarly to the video, the audio could be sent back to the live room through the same path (Best, 2017). The challenge was to design the routing so that it would have the least amount of cables and connections possible to keep the routing simple and clear. This would also make it easier to find a connection issue if there was to be one since there are less intermediate cables.

e. ENERGY OPTIMISATION

Regarding the energy consumption optimization, only a few equipment elements could be subject to variation. The first variable option is for the monitor screens used in the control room and in the live room. Their screens can use different methods to emit light. The most common are LED (light-emitting diode), LCD (liquid crystal display), CRT (cathode ray tube) and plasma. As the diagram below shows, CRT and plasma displays consume over twice as much power as LED and LCD screens. The key differences between those two types is that LED technology reproduces colors more realistically than LCD, and consumes less power. Hence, the choice of LED screens was made for the studio (HowStuffWorks, 2018).

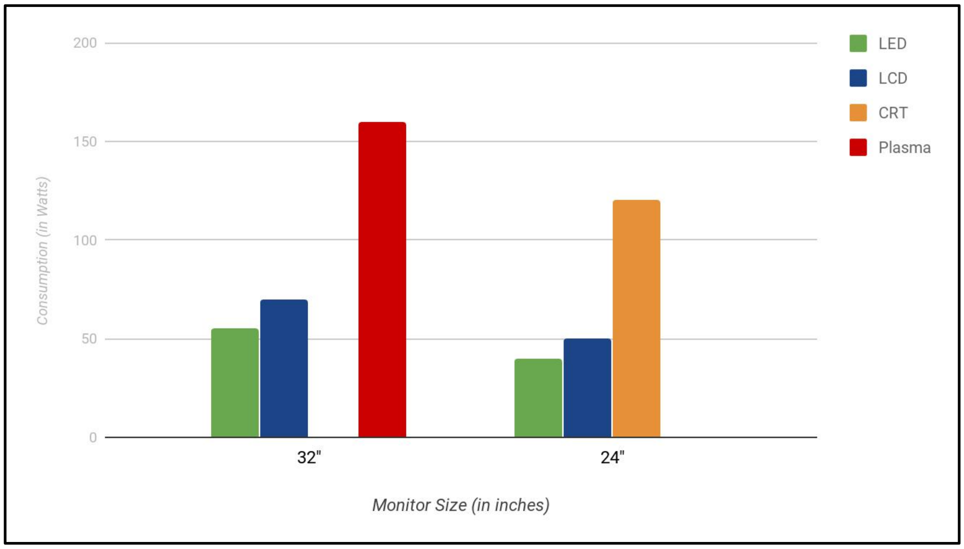


Fig. 46: Monitor screens power consumption comparison (Meissonnier, 2020)

The second, and most significant, variable option are lights. There is a wide range of lighting types. Their efficacy can be judged by the amount of lumen they can produce per watt. In other words, one can compare them by the amount of light they can produce per watt of energy consumed to do so. The diagram below shows the energy consumption of common types of lighting.

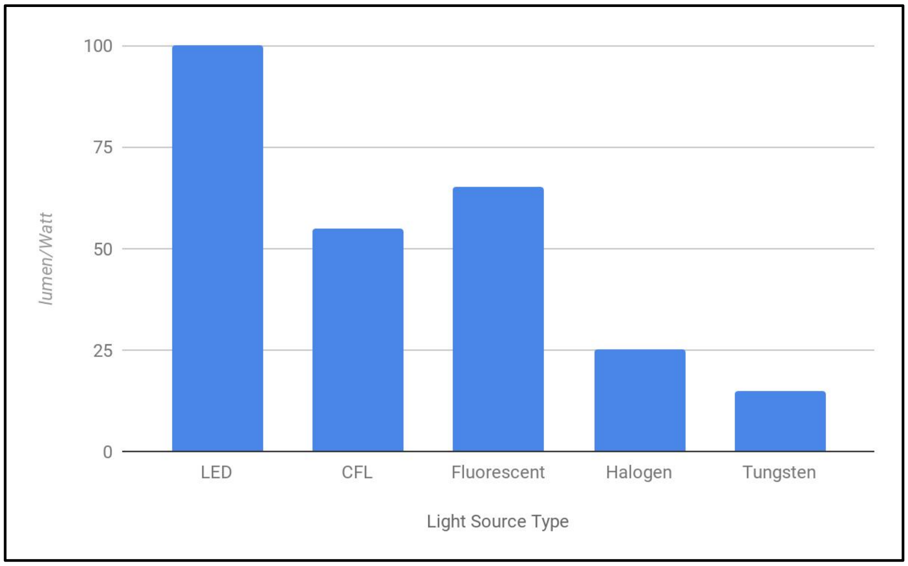


Fig. 47: Light source power consumption comparison (Meissonnier, 2020)

Similarly to LED monitor screens, LED lights provide a significantly higher efficiency than other lighting types. Additionally, LED lamps are lighter, smaller, have a longer use life and do not emit physical warmth. One disadvantage LEDs can have is that, even though they are the most efficient, they can be less powerful than other lighting types. However, modern technology constantly increases the power of LED lights, removing that issue from the decision-making process (Box, 2010). All those characteristics made LED light the most favorable option, even though they are more pricey than alternative options.

A detailed list of equipment and their power specifications can be found in Appendix B. This list has been used to calculate the total energy consumption of the studio per 8-hour working day.

$$\Sigma P_{office\ equipment} = P_{MacBook} + P_{MacMini} + P_{Router} + P_{Air\ Conditioning} + P_{UPS}$$

$$\Sigma P_{office\ equipment} = 100 + 150 + 10 + 6 + 700 = 966W$$

$$\Sigma P_{audio\ equipment} = P_{Audio\ Interface} + P_{Zoom\ H5} + P_{Speakers} + P_{Headphone\ Amplifiers}$$

$$\Sigma P_{audio\ equipment} = 15 + 5 + 2 \times 90 + 2 \times 11.5 = 403W$$

$$\Sigma P_{video\ equipment} = P_{Cameras} + P_{Wall\ Monitor} + P_{Desk\ Monitor} + P_{Live\ Room\ Monitor} + P_{Switcher}$$

$$\Sigma P_{video\ equipment} = 3 \times 14 + 47 + 31 + 20 + 18 = 158W$$

$$\Sigma P_{lighting\ equipment} = P_{LS\ C120D\ II} + P_{LS\ C300D\ II} + P_{LS\ Mini\ 20C} + P_{LED\ Panels} + P_{Mirror\ Lamps}$$

$$\Sigma P_{lighting\ equipment} = 3 \times 135 + 350 + 25 + 7 \times 29 + 34 + 4 \times 12.5 + 10 \times 4.5 = 1112W$$

$$t_{day} = 8h$$

$$P_{day} = \frac{(\Sigma P_{office\ equipment} + \Sigma P_{audio\ equipment} + \Sigma P_{video\ equipment} + \Sigma P_{lighting\ \ equipment})}{1000} \times t_{day}$$

$$P_{day} = \frac{966+403+158+1112}{1000} \times 8 = 21.112\ kWh$$

The total energy consumption for the studio will be 21.11kWh per full working day.

f. INTERIOR DESIGN

The goal was to design an interior that would make the clients feel relaxed yet energetic, especially in the control room. The first option that could come to one's mind is to use saturated warm hues. However, it's been proven that using vibrant warm colors had a tendency to promote appetite. (Tokyo Grand Renovation, 2019) Therefore, the chosen color scheme included white and beige. White evokes the feeling of clarity and simplicity, and beige, which is a shade of brown, gives the impression of earthiness and reliability. An accent of green and blue was added for harmony (Psychological Properties Of Colours - Colour Affects, n.d.). Moreover, using brighter colors in the room will make the room seem more luminous and spacious, and will reflect the light better; less powerful lights will be needed to light up the space.

Fig. 48.a: Mood board for the control room design (Meissonnier, 2020)

The design for the live room had to remain more basic since it had to be neutral for lighting and set modulation purposes, hence the greyscale colors.

Fig. 48.b: Mood board for the live room design (Meissonnier, 2020)

The entrance being a small room serving as storage space and where people only pass by only needs basic features in the same manner as the live room. Only a touch of turquoise is added in order to give a sense of trust to the people walking in (Psychological Properties Of Colours - Colour Affects, n.d.).

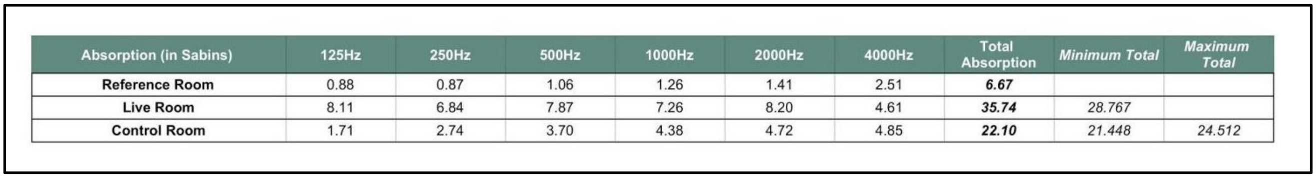
Fig.48.c: Mood board for the entrance design (Meissonnier, 2020)

RESULTS

a. ACOUSTICS

After making the acoustic measurements of the reference room, and considering the boundaries' original materials, and additional acoustic simulations, different acoustic treatment solutions were compared to find the most appropriate combination to reach the desired total room absorption and RT60, as well as reducing room modes.

The reference room's total average absorption was 6.67 Sabins. A spatial division was made in order to create a control room and a live room. Based on acoustic simulations, the most favorable dimensions for each were chosen. Taking into account the aim of having a RT60 under 500ms in both rooms and by using the RT60 formula by Corelli, Felici and Martinelli (2006), it could be determined that the total absorption of the live room should be of at least 28.767 Sabins while it should be between 21.448 and 24.512 Sabins for the control room. The association of absorbent and diffusing elements improved both rooms' total absorption to 35.74 Sabins for the live room, and 22.10 Sabins for the control room, meeting the set criteria, as shown in table 12.



Absorption (in Sabins)	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz	Total Absorption	*Minimum Total*	*Maximum Total*
Reference Room	0.88	0.87	1.06	1.26	1.41	2.51	***6.67***		
Live Room	8.11	6.84	7.87	7.26	8.20	4.61	***35.74***	*28.767*	
Control Room	1.71	2.74	3.70	4.38	4.72	4.85	***22.10***	*21.448*	*24.512*

Table 12: Absorption improvements (Meissonnier, 2020)

The following graphical representation of the absorption helps us visualize the improvements done in both rooms, in red and yellow, compared to the reference room, in blue. The total room absorption is not equal for all frequencies. It is gradually augmenting as the frequency increases in the control room, showing the necessity for more acoustic treatment in higher frequencies for this room. The live room's total absorption oscillates slightly around a center value up to 2kHz and experiences a decrease above that frequency. Moreover, the absorption is considerably higher than in the control room, revealing that the live room had to undergo a heavier acoustic treatment, especially for sound isolation from surrounding office spaces, because unlike the control room, most of its boundaries and acoustic treatment was put on the original partition wall. Resonant absorbers were also used to reduce or remove standing waves that had not been absorbed by the absorption installed on and in the walls of the rooms.

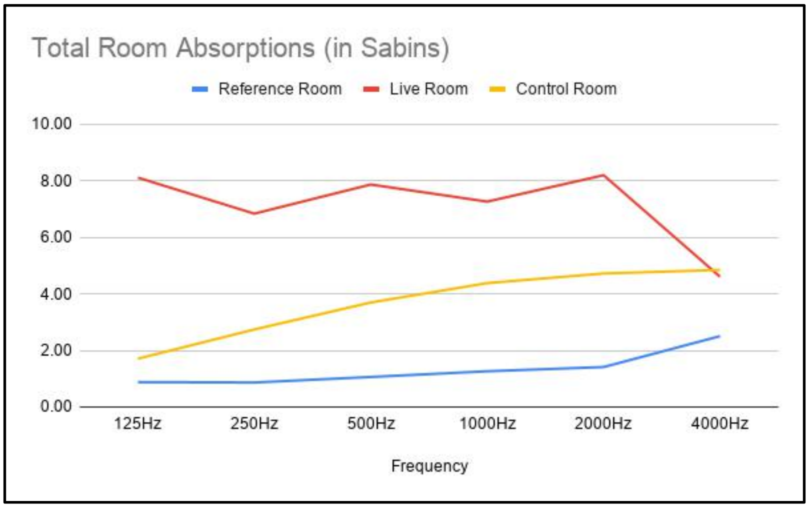
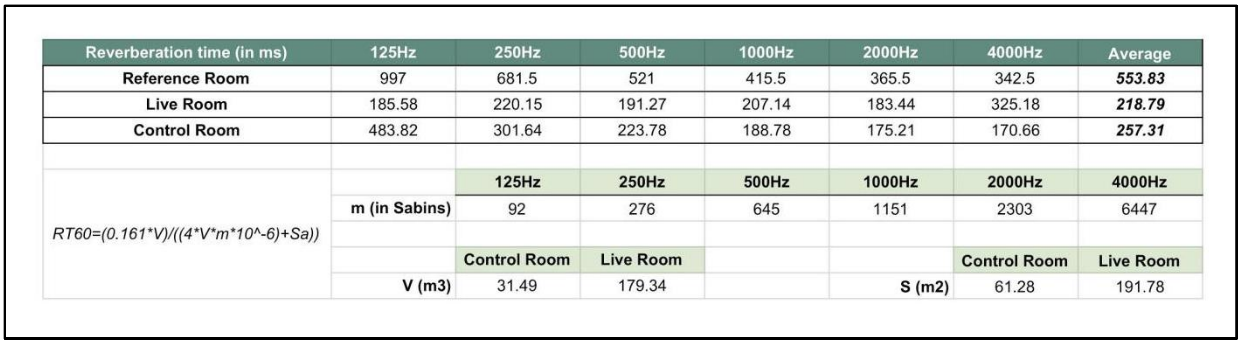


Fig. 49: Graphical representation of the rooms' total absorptions (Meissonnier, 2020)

Movable absorbers and reflectors were additionally chosen in order to shape the total room absorption of the live room if necessary.

The reference room's RT60 was obtained through measurements while the live room and control room's RT60 was calculated using the formula by Corelli, Felici and Martinelli (2006) and the absorption coefficients mentioned in table 12. The aim was to keep the RT60 under 500ms, which has successfully been achieved. Indeed, the theoretical RT60 for the studio averages 219ms in the live room and 257ms in the control room, as detailed in the table below.



Reverberation time (in ms)	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz	Average
Reference Room	997	681.5	521	415.5	365.5	342.5	***553.83***
Live Room	185.58	220.15	191.27	207.14	183.44	325.18	***218.79***
Control Room	483.82	301.64	223.78	188.78	175.21	170.66	***257.31***
*RT60=(0.161*V)/((4*V*m*10^-6)+Sa))*		**125Hz**	**250Hz**	**500Hz**	**1000Hz**	**2000Hz**	**4000Hz**
	m (in Sabins)	92	276	645	1151	2303	6447
		Control Room	**Live Room**			**Control Room**	**Live Room**
	V (m3)	31.49	179.34		**S (m2)**	61.28	191.78

Table 13: RT60 improvements (Meissonnier, 2020)

The following graphical representation of those results shows that the majority of the improvement was done in the lower frequencies, which were originally most problematic, through both acoustic treatment and specific spatial division of the reference room. We can observe that the RT60 of the live room, in red, and of the control room, in yellow, are well below the reference room's, in blue. The RT60 in both rooms was lowered and made more constant throughout the frequency spectrum. This helps prevent influencing the behavior of remaining room modes. Inversely to the absorption, the control room and the live room's RT60s are decreasing as the frequency increases. A note can hence be taken that absorption proportionally affected the RT60 duration, which is confirmed by the RT60 formula by Corelli, Felici and Martinelli (2006). Indeed, the absorption is one of the dividing variables used in said formula.

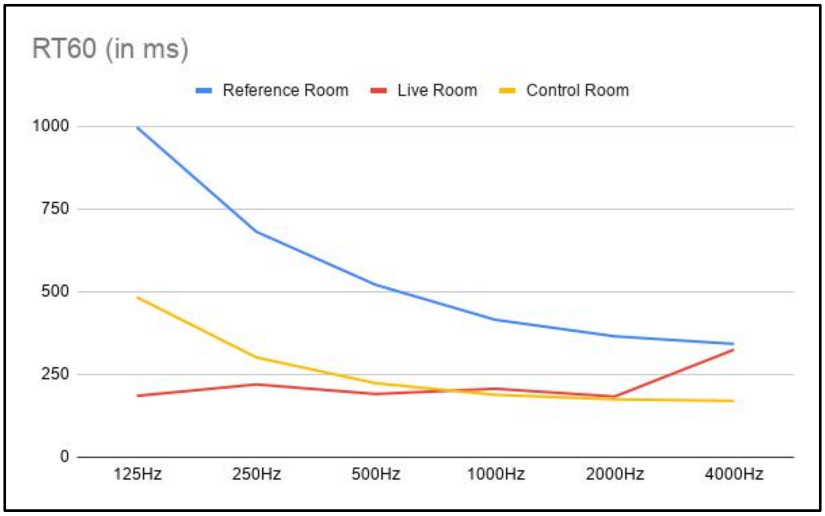


Fig. 50: Graphical representation of the RT60 (Meissonnier, 2020)

As a result of the acoustic treatment, the control room and the live room's frequency response is more balanced across the spectrum and will remain more constant when the rooms are in use.

b. EQUIPMENT

Accordingly to literature research, a list of equipment was made to fulfill the needs of this potential studio. In order to accommodate up to 4 subjects on-camera, 3 camera angles and 2 sets of 4 microphones, one of Lavaliers and one of dynamic SM7B microphones were chosen in compliance with visual aesthetics preferences for video recording. Moreover, a combination of Aputure LED lights with a ceiling rail system was necessary for a more practical workflow and workspace. Therefore, the studio's equipment consists of a selection of professional video, lighting and audio gear, as summed up in table 14.

A detailed list can be found in Appendix B.

Audio	Video	Lighting
8 microphones	3 cameras	5 lights
5 microphone stands	3 tripods	6 diffusers
4 headphones	3 monitors	2 multifunctional flags
2 headphone amplifiers	A video switcher	Gals packs
A pair of speakers	3 backdrops	General room lighting
A talk-back system	A backdrop frame	Lighting accessories
A crew communication system	Gaffer tape	
Audio accessories	Multicolor spike tapes	
	Video accessories	

Table 14: Audiovisual equipment summary (Meissonnier, 2020)

The equipment's routing was designed in such a way as to use the least amount of cables possible in the simplest and most orderly routing possible, and by processing the audio and video separately through two separate hubs before being recorded or streamed on the studio's computer. This allows two people to work simultaneously, one on the audio and the other on the video. Such a setup becomes especially useful in a streaming or live recording situation.

A diagram of the final routing, with all the cabling and connector types captioned, is shown below.

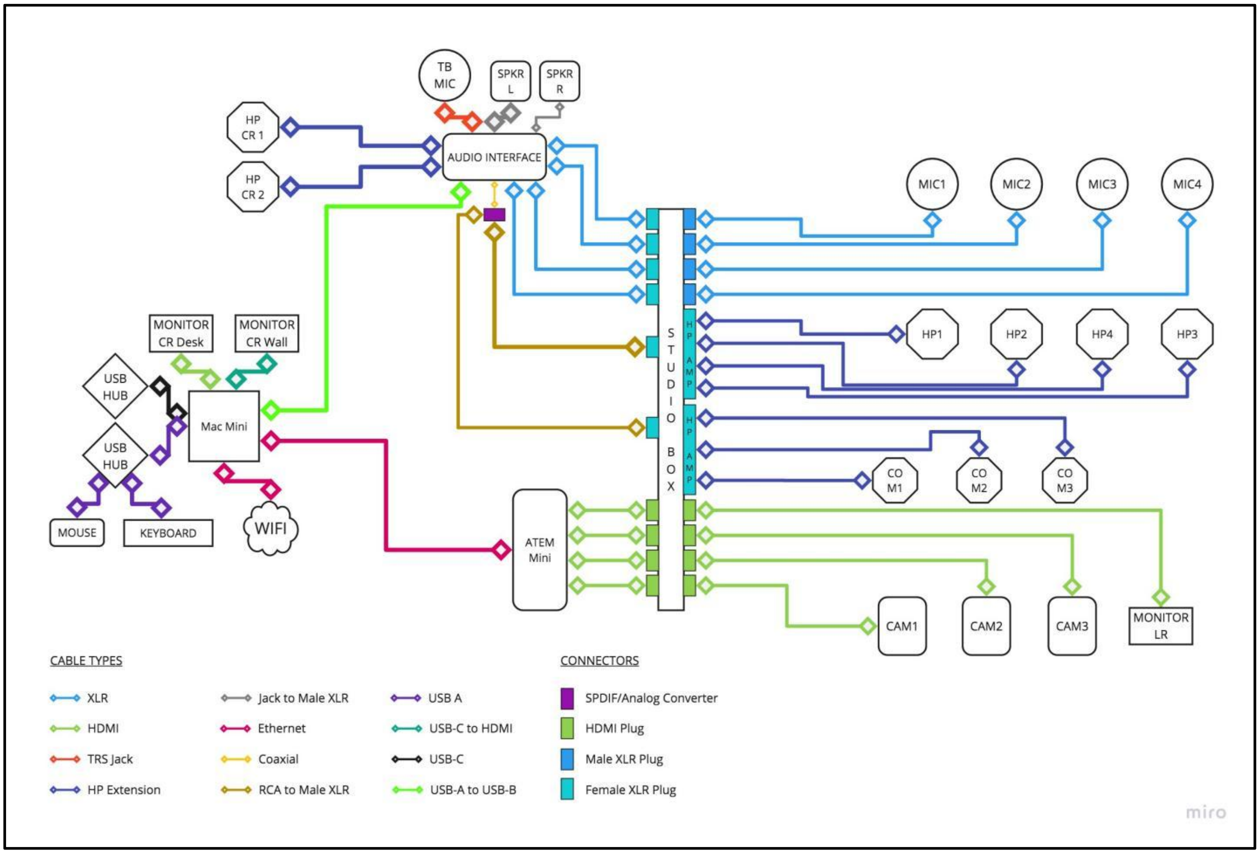


Fig. 51: Studio connections diagram (Meissonnier, 2020)

c. ENERGY

Nowadays, it is a concern to reduce energy consumption, especially in the professional work field to look more ethical to clients. In our case, only a few equipment items could be chosen among several options that could significantly reduce the energy consumption. The choice of LED screens and LED lights was therefore made to lower the studio's energy consumption. The rest of the equipment would not significantly change the energy consumption, either because their alternatives consumed roughly the same amount of energy or because they consumed little energy compared to the lights and screens.

There are on average 21 working days in a month, and in the Netherlands, a working day totals 8 hours of labor. Based on those facts, the maximum total power consumption of the equipment equals 21.11kWh for an eight-hour work day, assuming that all the equipment is on at all times. In reality, we can expect this consumption to be lower as rarely all of the electrical equipment will be used at the same time continuously throughout the day without being switched off. As a comparison, the average American household consumes approximately 30.4kWh of electricity daily (U.S. EIA, 2018). The studio hence consumes less energy than an average household. We can deduce that the studio is energy efficient.

Below are summaries of the studio's power consumption and divided among the different consuming elements.

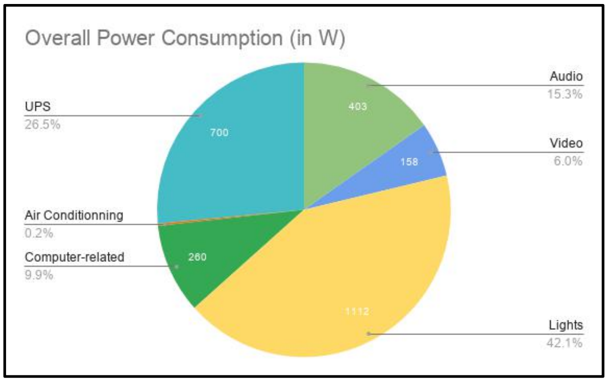


Fig. 52.a: Shares of the overall energy consumption (Meissonnier, 2020)

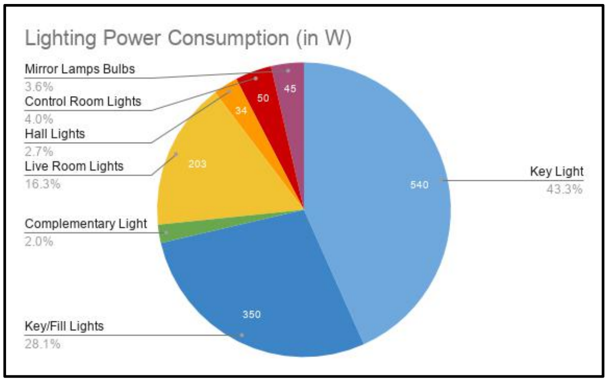


Fig. 52.b: Shares of the lights' energy consumption (Meissonnier, 2020)

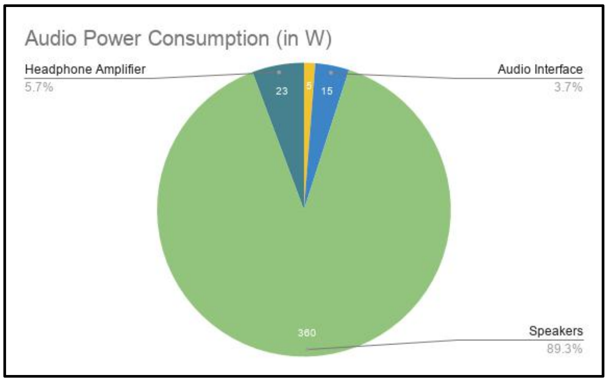


Fig. 52.c: Shares of the audio equipment's energy consumption (Meissonnier, 2020)

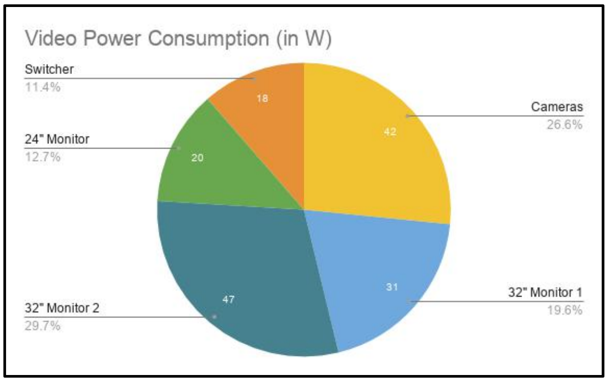


Fig. 52.d: Shares of the video equipment's energy consumption (Meissonnier, 2020)

d. BUDGET

The starting budget was 80,000€, excluding VAT. This budget excluded the author's already-owned equipment, which equaled approximately 15,000€. The final planned expenses reached 43,530.64€ including VAT, and 34,389.30€ excluding VAT. Assuming all the equipment had to be bought, the total budget will approximate 58,500€. This confirms that it is possible to build a video studio with appropriate acoustics and professional equipment for less than 80,000€, excluding VAT.

Figure 53 indicates the budget's share each category of equipment holds.

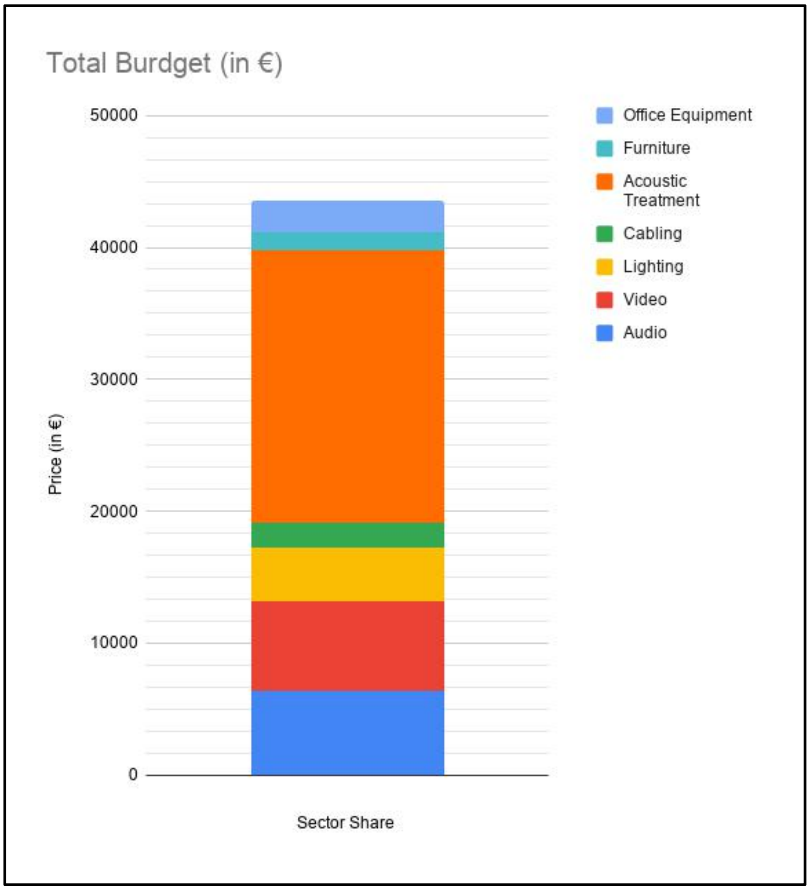


Fig. 53: Total budget and repartition (Meissonnier, 2020)

e. STUDIO 3D MODEL

A simplified 3D model of the final studio was made using Google Sketchup. It can help the reader understand and visualize the acoustic treatment and audiovisual incorporation discussed in this paper. The lighting rigging system was not included to not block the overview and because it is not the acoustic treatment, which is the main subject of this paper.

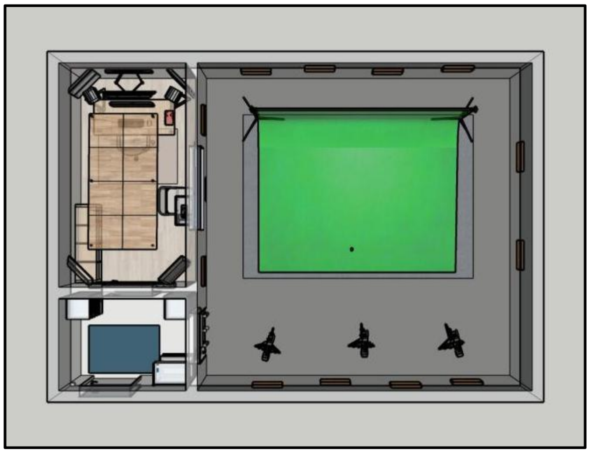


Fig. 54.a: 3D model - Top view (Meissonnier, 2020)

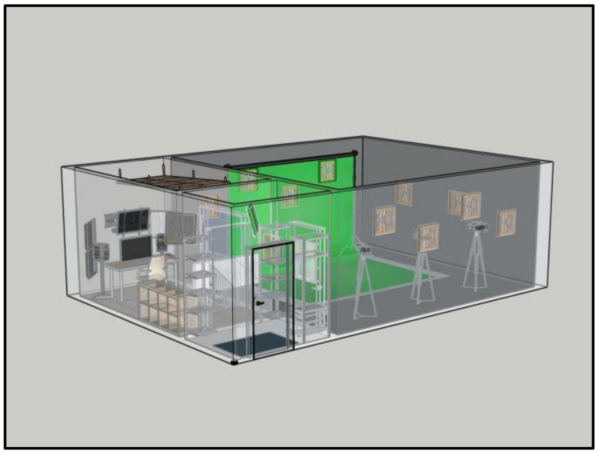


Fig. 54.b: 3D model - Oblique view (Meissonnier, 2020)

Fig. 54.c: 3D model - Control room close up (Meissonnier, 2020)

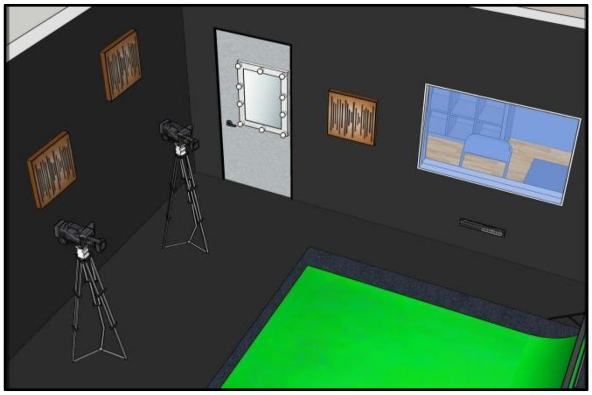


Fig. 54.d: 3D model - Live room close up (Meissonnier, 2020)

LIMITATIONS

The project's goals have been achieved. However, some limitations were encountered in its conduct.

First, because of the SARS-CoV-2 pandemic, access to school computers was suspended for 3 months. The usage of one of their computers was hence impossible to run acoustic simulations using the software Wayverb in that time period. An alternative had to be found, delaying the project's conduct. The usage of REW as an alternative proved to give enough information to continue the acoustic treatment, but a general overview of the rooms' responses would have been more efficient and complete.

Second, it was impossible to do a complete environmental noise survey in and around the reference room because it was not accessible at all times, and it was hence complicated to check on the continuous measurements over multiple days.

Third, the calculated power usage is a maximum value. An actual value would have been difficult to determine without assessing the actual pattern of studio usage first. Said usage depends on the quantity and nature of the projects being worked on, which cannot be provided at the moment.

Last, a case study was supposed to take place. However, because of the SARS-CoV-2 pandemic, such a study had to be canceled for sanitary purposes. Only a couple of weeks before the deadline of this project, I visited the studio of Mixed by Joost, which should have been my audio recording studio case study. I still observed and gathered some information to adjust the acoustic treatment implementation.

CONCLUSION

The conduct of this project was overall proficient, even though some setbacks and difficulties were encountered.

The literature review was challenging at first because a lot of information had to be found, gathered, selected and presented. It was often difficult to discern valuable and necessary information from less important and necessary ones. By the end of the research though, I could feel more confident about selecting and prioritizing information. This improvement in ease came together with the determination of the methodology.

Determining the methodology was the most challenging task: depending on the strategy taken, certain information was needed more than others. Since undertaking a project to design a studio was a new experience for me, I had to find out the hierarchy and relationship of the tasks that needed to be accomplished in order to achieve the project's goals. It would have been helpful to do further upstream background research to determine which clearer or more specific approach to take, and to first get a better understanding of wave physics and of the different technical departments.

Applying this methodology was fairly straightforward, as I found it well constructed in the end and easy to follow. Measuring the acoustic response of the reference room in two different ways, instead of one, proved to be helpful in determining the general behavior of sound in the room in different settings. Though, I would have liked to be able to assess the environmental noise in a deeper and more specific way. I am indeed doubtful the isolation of the rooms might not be enough when a lot of movement happens in the building, such as cars parking in front and grouped movements in the morning, evening or during lunch breaks. I also regret not having found an equivalent alternative to the acoustic simulation software Wayverb, which would have provided a 3D overview of sound behavior in the different rooms; REW's predictions were more restricted. Moreover, I should have had an alternative ready for the acoustic simulation software, which could be run on a less powerful computer than the ones available at school, so that when the facilities closed down, I could have continued working on the project without interruption and troubleshooting.

Besides, applying the methodology gave me a deeper and more concrete understanding of the topics discussed in the literature review. I acquired a practical understanding of acoustic treatments' construction and understood how I could make them myself if I have the adequate materials and their physical functioning. I also realized that acoustic solutions could be made in less expensive ways than the pre-made solutions are.

Looking at the results in acoustics, I could visualize the relationship between the different variables determining a room's frequency response, and especially between the RT60 and the absorption. Budget-wise, I was surprised to see that, even though I used pre-made acoustic absorbers and diffusers, and that the budget included the acoustic design of two rooms, less than half of the maximum budget was necessary to accomplish the desired goal. I could have lowered the necessary budget even more by building the acoustic panels myself. I was hoping to be able to be more knowledgeable about energy efficiency in professional studios, especially in the construction design. Although some acoustic treatment materials, such as rockwool, provide good thermic isolation, the studio design would have been closer to the project's goals by shaping the use of this material further to guarantee a better thermal performance.

This project was an opportunity for me to develop the basic knowledge I had acquired in acoustics earlier in the course. It also reinforced my knowledge about audio in video production, and I obtained basic knowledge about lighting and streaming systems in a studio environment. I am now confident to have more insight of what is needed in terms of sound, video and lighting to create a professional looking and sounding production. Finally, the completion of this project makes me consider doing a deeper and more complete research in the future to answer more broadly my main research question: “How can a professional video studio be designed?”.

RECOMMENDATIONS

If you would like to adapt this project to their own studio, I strongly recommend reading the Master Handbook of Acoustics by Everest and Pohlmann (2015) as it encompasses all the aspects of acoustics with different levels of detail, fitting for people with different degrees of knowledge about the subject.

Gaining additional waves physics and architecture knowledge prior to starting designing a studio will be found to be extremely helpful in order to accomplish this task mostly by yourself.

Visiting studios with similar specifications as the one you are aiming to build is also helpful. It can give you treatment, routing, equipment and design ideas you would not have thought of otherwise. Moreover, seeing an acoustically treated space and observing its construction can provide inspiration in material, solutions and implementation of those for your own space.

For larger-scale video production studios, it is necessary to conduct further research as the findings of this thesis apply more realistically to smaller spaces than to sound stages used for large scale scenes with decor or large green screen.

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APPENDICES

APPENDIX A

Presentation:

https://drive.google.com/drive/folders/1pK0ql2WIq9YUt5NQ1EFcB9_pGj8POE3g?usp=sharing

APPENDIX B

Gear List:

https://docs.google.com/spreadsheets/d/1714f2uWybz0vgEHFqrUsP6e0Khzc_bEPSY5CE78xRps/edit?usp=sharing

APPENDIX C

Google Sketchup Model:

https://drive.google.com/drive/folders/10sRVbSSGfyHTq10lFOViJWJAHRnA90On?usp=sharing

APPENDIX D

Logbook:

https://docs.google.com/spreadsheets/d/1FQZABV5MOhPRsep2OpczPRmBeozaCeEAGRMyVV3FPNE/edit?usp=sharing

APPENDIX E

Acoustic results Google sheet: https://docs.google.com/spreadsheets/d/1iG-WOKRmHSIpVthJ2iHBHJsrAzLLQnEZHSq4wTY3Du4/edit?usp=sharing