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Practice Room Acoustics: What Matters to Musicians About the Practice Space

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Abstract

Why do people always prefer the practice room in the corner on the second floor than the others? What's the reason why string players often go for the "dryer" room than the wind players? Wondering why brass players often occupy the resonant room? This paper is here to decipher all the mysteries behind all of the questions above by the acoustic analysis suggested by Bonnelo and the other supplying papers on sound absorbing materials. The question to be answered is how the rooms are different from each other in terms of their dimensions and damping surfaces. Eventually, construct a criteria for adjusting the acoustic characteristic by using sound absorbing materials. Through a survey filled out by conservatory students, it informs general preferences of choosing practice room and a frequency dependent reverberation time test is run accordingly. Having gathered all the information, it can be concluded that there is a direct relation between how preferable a room is and room dimension and the evenness of reverberation time throughout a frequency interval. Besides from the method of damping excessive resonance through locating high and low pressure area of the standing wave suggested by the Bonello paper, there are also possibilities of using different absorbing materials and Helmholtz resonator to change the reverberation time and modal density of the targeting frequency of a room. Therefore, with the results of this paper, musicians are a step closer to a simple yet career changing acoustic tool for constructing practice rooms.

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Introduction

Practicing is an essential part of a musician's life. How well a musician can harness their musical instrument is greatly related to how many hours they put into daily solitary practice and the fact is acknowledged by most of the greatest musicians. The hours one can put into practice everyday, however, is only so many due to biological constraints and the fact that there are only twenty four hours in a day. The other crucial factor that affect the result of practicing is the efficiency of a practice session. In other words, the more efficient one can be during practicing, the more goals can be achieved. Besides from all the technique of how to plan out a practice session or the equipment one can use to gain efficiency, the acoustic character of the practice room musicians practice in can be a game changer. How can the acoustic character of a room affect the efficiency of one's practice session? Leaving the technical acoustics terms on the side, a simple change such as covering one's ears up during their practice session would be enough to turn the practice session into aimless movements. This shows that what one hears is crucial to the quality of their practice. Even if a musician's ears are free from being covered, what one hears matters immensely to the quality of one's practice session and how the space one practices in takes a huge part in it. Therefore, surveys will be conducted among musicians in an attempt to find patterns in their preferences.

Although it is important to know what acoustic environment musicians like to practice in, building a practice room for them will be very difficult without the understanding of the relationships between musicians' preferences and what distinguishes rooms physically. This research attempts to collect some of the known acoustic tools and through the connection of the subjective aspects to the physical aspects to find out the ideal environment for practicing. Then through the survey taken by the Bard College Conservatory students to rank the practice rooms in both the Bito Conservatory building and Blum Music building in terms of the musicians' preferences. With the knowledge gain via research on various acoustic characters, experiments can be design to figure out trends that the more favored rooms share with each other. Thus, a complete knowledge of practice room acoustics can be established and benefits the musicians.

Subjectivity and Objectivity of Acoustics for Musicians and Acousticians

Very often musicians express their feelings of a sound with words, which are often times vague experiential terms. For example, a violinist might describe a concert hall as a "dry," which is seldom considered as an empirical term. Such adjectives, though not very physically quantifiable, can be quite effective in terms of describing the acoustics of a space to another musician. Although these terms are indeed informative for musicians, they can be absolutely confusing for acousticians since there is not an intuitive physical quantity that quantify how "dry" a room is. It was not until the late nineteenth century that people start to figure out some mathematical patterns in acoustics, which was starting to be considered as a scientific field. However, it is still a territory where few have stepped their feet in to explore.

Over the years, acousticians have devoted themselves to making acoustics less subjective by narrowing their definitions and have rotated qualitative terms to more measurable quantities of the room. For instance, when a musician says a room has a lot of liveness, they mean the sound they make takes a while to die out in the room until inaudible. Such an aspect of a room is primarily related to reverberation time, which is how long it takes sound to die out in the room. Reverberation time, in turn, is determined by the size of the room and the absorption of its surfaces. Then the quality of liveness can be quantified into some physical quantity. Studying rooms in terms of these physical parameters will hopefully organize the responses of musicians.

The next and one of the most important steps would be figuring out which physical parameter is relevant to a certain subjective quality. Some of them are more widely known and intuitive, such as clarity, which is directly related to reverberation time, while others like how a room colors or give sound a certain timbre are less known. First, the former should be straightforward and primarily addressed. The main factor that differentiate spaces into different function is clarity. As previously mentioned, a lecture hall would strive for great clarity while concert hall go for the opposite. The ratio between clarity and liveness on the reverberation spectrum is closely related to the functionality of a room. More clarity would be prefered in a lecture hall and longer reverberation time would be best for a musical performance space. The functionality of a practice room, though it is a space designed for playing musical instruments, requires more clarity since the clarity of sounds would be more valued in a practice session rather than the resonance of sound. In order to achieve that, a rather short reverberation time would characterize the room with clarity. However, because each room has its special resonating frequencies, overdamping the reverberation might cause amplification of certain frequency bands.

Another example is the Bonnelo Criterion, which determines the clustering of standing wave frequencies for a room as a benchmark of its performance as an acoustic space. The Bonnelo criteria is considered one of the leading research ideas on the acoustic character of small studios. Using psychoacoustic properties and node analysis, the criteria is successful in constructing small to medium size studios with consistent results. With the help (and potential modification) of the criteria we can determine how well a room is in terms of resonating throughout the frequency spectrum. With the current existing hardware in Bard conservatory building and also the music department building, the project aims to understand the properties of the rooms and modify them in the easiest way possible, which is through damping certain frequency bands with sound absorbing materials or with Helmholtz resonators. Such criterion and similar analysis will be considered and adapted in this project's analysis of practice spaces.

Standing waves

In order to understand how resonance of sound works, it would be easier to start from a simple one-dimensional model to get a sense of what it would be like in our three-dimensional world. In introduction of physics, often professors start with a string model when it comes to waves. Usually the string is tied to a wall while the other end is held by someone. Then the person shake the string in a way that it has the same period as the period of the wave shape to travel to the wall and back to where it started and a standing wave is created. As literal as its name means, the string only changes like a sine function changing its amplitude and it looks like there is no wave going back and forth. Built on the same foundation, the standing wave of a sound works just like the string. Since it is usually assumed that the speed of sound is uniform in a closed room, the only factor that could change the wavelength is the frequency. The higher the frequency is, the shorter the wavelength is. This leads us to the fact that, under the circumstance that the dimensions of a room is fixed, only certain frequencies can be resonated in a room. One difference from the string model is that both of the ends of the string are free to move in this case since it has to be an antinode at the walls. Then the wavelength of the fundamental resonance is 2L and for the next resonance is L...etc. For the nth overtone, the wavelength would therefore be $\frac{(2n-1)L}{2}$, where n is an integer. Therefore, for a one-dimensional room with length L, any frequency that has a wavelength that can excite a standing wave in the room would be amplified by the room.

On a two-dimensional surface, the situation is a bit more complicated. Not only that we have one more direction to discuss, there are also two-dimensional standing waves. Conventionally, a 2D standing wave can be characterized by its mode and can be notated as $(x,\ y)$. For example, a fundamental standing wave in the x direction will be notated as $(1,\ 0)$, since there is one node in the x direction and none in the y direction. The wavelength will therefore be $2L_x$ and it would look like a 1D standing wave stretched in the y direction and the same is true for $(0,\ 1)$. The equation that describe a two-dimensional standing wave looks like:

$$Acos(n_x \frac{\pi x}{L_x})cos(n_y \frac{\pi y}{L_y})$$

where A is a constant, $n_{x,}n_y$ describe the modes in x and y direction. After we have gone through the two fundamental frequencies, the next lowest frequency is $(1,\ 1)$. This means there is a node in each direction. The cross sections in each direction would still look like standing waves with a node but with different amplitude. As the number of nodes increases, the 2D standing wave gets more complicated. Same logic can be applied to the three dimensional case, which is the closest case to the reality. The equation for a three-dimensional wave is:

$$Acos(n_x \frac{\pi x}{L_x})cos(n_y \frac{\pi y}{L_y})cos(n_z \frac{\pi z}{L_z})$$

Where the third cosine describe the z component of the wave. Every extra dimension adds one cosine factor, so a N dimensional standing wave will have N cosine factors to its equation.

Reverberation Time (RT) and RT_{60}

An important way to characterize how long a sound stays in a room is by measuring its reverberation time. It is a quantity that can be understood without using mathematical equations. As mentioned in a previous chapter, a room that has a short reverberation time (RT) usually is described as a "dry" room, while a room with high liveness is characterized by a long RT. For example, someone talking in a room with carpets and cloth covered walls can hardly hear reflections of their sound. This type of room is classified as having a short RT since sounds do not reverberate and get absorbed very quickly. On the other hand, due to a long RT, it can be hard to hear people talking or speaking in a church because speech can mix with each other or even with its own reflections. A standardized measurement for RT is called RT_{60}, coined by Sabin and is defined as the time it takes for a sound to decay 60 dB.

In order to understand RT, one must first look at the energy lost of a room with an open window. The following derivation is derived with Professor Matthew Deady.

- Open Window Energy Loss

Suppose a room has volume V, completely reflective walls, and a single open window of cross sectional area A. As sound energy bounces around the room, the energy that escapes the room over time can be calculated. Standard wave physics tells us that the energy flux (*Energy*/*Area*/*Time*) can be easily related to the wave's energy density (*Energy*/*Volume*) and the wave speed (c), by

$$\Phi(W/m^2) = \frac{1}{4} \cdot c\ (m/s) \cdot u\ (J/m^3)$$

The $\frac{1}{4}$ accounts for the fraction of energy moving in any particular direction on average. If the total energy in the room at some time is E, then the energy density is u = E/V . For that open window, then, the energy lost per unit time is,

$$\frac{dE}{dt} = -\Phi \cdot A = -(\frac{1}{4} \cdot c \cdot u) \cdot A = -(\frac{1}{4} \cdot c \cdot \frac{A}{v}) \cdot E$$

That is, the energy remaining in the room dies out exponentially,

$$\frac{dE}{dt} = -\alpha \cdot E \ \ with \ \ \alpha = \frac{c}{4} \cdot \frac{A}{V} \ \ \Rightarrow \ \ E(t) = E_o e^{-\alpha t}$$

The characteristic time and the half-time are then,

$$\tau = \frac{1}{\alpha} = \frac{4V}{cA} \ \ \& \ \ \tau_{1/2} = \frac{ln(2)}{\alpha} = \frac{4ln(2)V}{cA}$$

This makes sense from a physics standpoint because:

* A larger room (V) will cause the room to lose its sound energy in more time

* A larger opening (A) will cause the room to lose its sound energy in less time

* A faster wave will cause the room to lose its sound energy in less time

- Sabine Reverberation Time

Walter Sabine (1868 - 1919) was a physicist at Harvard who was generally credited with founding the field of architectural acoustics. He was doing his early work before modern acoustical measuring instruments were invented, so he often relied on his finely atuned ears. We have incorporated modern techniques into the field, but still use some of his conventions.

Sabine felt that he could accurately judge when the sound intensity level had reduced by a factor of 1,000,000, that is,

$$I(t) = I_o \cdot 10^{-6} \quad \Rightarrow \quad \frac{E(t)}{E_o} = 10^{-6} \quad \Rightarrow \quad \Delta SIL = -60\ dB$$

This time came to be called the *reverberation time*, RT_{60}.

Relating that to τ or α,

$$e^{-\alpha \cdot RT_{60}} = 10^{-6} \quad \Rightarrow \quad \alpha \cdot RT_{60} = ln(10^{-6}) \quad \Rightarrow \quad RT_{60} = \frac{4 \cdot ln(10^{-6})V}{cA}$$

Using $c = 344\ m/s$, with A in m^2 and V in m^3 gives,

$$RT_{60} = (0.161\ s/m) \cdot \frac{V\,(m^2)}{A(m^{3})}$$

Using $c = 2230\,ft/s$,, with A in ft^2 and V in ft^3 gives,

$$RT_{60} = (0.0490\ s/ft) \cdot \frac{V\,(ft^2)}{A(ft^{3})}$$

- Effective Absorbance Area

An open window removes all of the energy that strikes it from the room. Sabine's brilliant insight was that this is equivalent to saying that the energy was totally absorbed by the window area. He then extended this way of thinking to considering what happens to sound reflecting off of any partially absorbing surface. Consider a material that absorbs a fraction of the sound energy that strikes it and call that *absorbance factor* a. That is, for that surface,

$$I_{absorbed} = a \cdot I_{incident} \ \ \&\ \ I_{reflected} = (1 - a) \cdot I_{incident}$$

If sound strikes an area S of this material, then it has the same absorbing effect (energy removal) as would happen with an open window of area $A = S \cdot a$. That is, the effective absorbance area, A, is

$$A = S \cdot a$$

$$(Effective\ absorbance\ area) = (Geometric\ area) \cdot (Absorbance\ factor)$$

Then a room with volume V and a set of wall surfaces with areas S_i, each having its absorbance factor a_i would have reverberation time,

$$RT_{60} = (0.0490\ s/ft) \cdot \frac{V}{\Sigma\, S_i \cdot a_i}$$

In practical applications, most materials have different a factors for different frequencies of sound, so this RT_{60} calculation is frequency dependent.

The Bonello Criteria

The paper that inspired this research is written in 1981 by Oscar Juan Bonello, titled *A New Criterion for the Distribution of Normal Room Modes*. The idea is to examine the clustering of modes using mathematical formulas to locate the number of modes in one-third octave frequency bands. By doing so, it will be clear if the room dimensions examined has a desired distribution of resonance modes and thus fits the criteria. This introduces a consistent model instead of relying on acoustic designers' own subjective experiences.

The mathematics used by the paper is based mostly on classical wave theories. The frequency of a wave is decided by the modes in the three dimensions:

$$f_n = \frac{c}{2}\sqrt{(\frac{n_x}{l_x})^2 + (\frac{n_y}{l_y})^2 + (\frac{n_z}{l_z})^2} \quad \text{— (1)}$$

where

c is the speed of sound (344 m/s at $21^{\circ}C$)

$n_x,\ n_y,\ n_z$ are integer numbers 0, 1, 2, 3 …

$l_x,\ l_y,\ l_z$ are three dimensions of room

Because a certain frequency can have different combinations of n's, there can be multiple resonance modes at the same frequency and therefore some frequencies can be more resonant than others. Thus, the Bonello paper aimed to tackle the problem of uneven resonance throughout the frequency spectrum through the theoretical model of how normal modes are distributed.

In order to calculate the number of modes for a certain frequency, imagine a three dimensional space with each axes marked n_x, n_y, and n_z. Every point in the space is unique and represents a mode. If eq. 1 is mapped into the space, it would be shaped like a one-eighth sphere. One way of calculating the number of modes is to integrate the volume of the one-eighth sphere with a radius that is proportional to frequency. Then the total number of modes between 0 and frequency f will be (Bonello 598),

$$N_f = \frac{4\pi}{3} V\left(\frac{f}{c}\right)^3 + \frac{\pi}{4} S\left(\frac{f}{c}\right)^2 + \frac{L}{8}\frac{f}{c}$$

where

$V =$ volume of room, $= l_x l_y l_z$

$S =$ internal surface, $= 2(l_x l_y + l_x l_z + l_y l_z)$

$L = 4(l_x + l_y + l_z)$

Taking the partial derivative of this equation would get the number of modes per hertz of bandwidth,

$$\frac{\partial N_f}{\partial f} = \frac{4\pi V f^2}{c^3}$$

This implies that the density of modes is proportional to the frequency squared. However, as Bonello states in the paper, the equation of the density of modes is valid only for frequencies high enough that statistical analysis can be applied (Bonello 598). For low frequencies, the acquisition of number of modes can be done by calculation the difference of total number of modes. The density of modes equation also suggests that for small rooms there is a problem of coloring in lower frequencies. This is because the small rooms being addressed in this research are small in volume and the influence of frequency is too great due to the square dependence.

Now consider a normal mode sound source being played in a room and then the sound stops. The sound pressure decreases exponentially and can be described by the equation:

$$P_n = Ke^{-k_n t} cos\ \omega_n t$$

where

K = constant representing power, source location, and room volume

k_n = damping constant, representing room absorption

The steady-state sound pressure is given by,

$$P_{n\ max} = \frac{2K\omega}{\sqrt{4\omega_n^2 k_n^2 + (\omega^2 - \omega_n^2)^2}}$$

where

K = power

k_n = damping constant due to room absorption

The following derivation for resonance was derived in a project meeting by Professor Matthew Deady.

Suppose a damped oscillator with a undamped angular frequency $\omega_o = \sqrt{\frac{k_o}{m}}$. The system can be described by the equation:

$$mx'' + bx' + k_o x = 0$$

$$\Rightarrow \; x'' + \tfrac{b}{m}x' + \tfrac{k_o}{m}x = 0$$

$$\Rightarrow \; x'' + 2k_n x' + \omega_o^2 x = 0$$

where

m is the mass

b is the damping constant

k_o is the spring constant

$k_n = \frac{b}{2m}$

Solving the second order ordinary differential equation, assume $x = Ae^{\alpha t}$,

$$\Rightarrow \quad \alpha^2 + 2k_n\alpha + \omega_o^2 = 0$$

Then,

$$\alpha = -k_n \pm \sqrt{k_n^2 - \omega_o^2}$$

$$= -k_n \pm i\sqrt{\omega_o^2 - k_n^2}$$

$$= -k_n \pm i\omega_n$$

Thus,

$$x = Ae^{-k_n t}e^{i\omega_n t}$$

Take the real part,

$$Re\, x = Ae^{-k_n t}\cos \omega_n t$$

where

$A = x_o$ decided by initial condition

$e^{-k_n t}$ is the damping part

$cos\ \omega_n t$ represent the oscillation

For a driven damped oscillator driven at frequency ω, the equation for the system is:

$$mx'' + bx' + k_o x = F_D e^{i\omega t}$$

Assume

$$x(t) = A(\omega)e^{i(\omega t + \phi)}$$

Then substitute in for the equation of the system,

$$A\left[-m\omega^2 + ib\omega + k\right]e^{i\phi} = F_D$$

$$\Rightarrow\ A\left[(\omega_o^2 - \omega^2) + i(2k_n\omega)\right]e^{i\phi} = F_D$$

$$\Rightarrow\ A^2\left[(\omega_o^2 - \omega^2)^2 + (2k_n\omega)^2\right] = (\tfrac{F_D}{m})^2$$

Then,

$$A = \frac{2K\omega}{\sqrt{4\omega_o^2 k_n^2 + (\omega_o^2 - \omega^2)^2}}$$

Here substitute in the initial condition, then $A = P_{n\ max}$.

If $\omega = \omega_n$,

$$P_{n\ max} = \frac{2K\omega_n}{\sqrt{4\omega_n^2 k_n^2 + 0}} = \frac{K}{k_n}$$

which is the maximum sound pressure. The band width that gives pressure greater than the maximum pressure is:

$$\Delta f = \frac{k_n}{\pi}$$

To relate k_n with RT, it can be done by using the sound pressure equation. The time for a sound to drop 60 dB is $T_{60} = 6.91/k_n$ (Bonello 598). Then substitute in for k_n:

$$\Delta f = \frac{6.91}{\pi T_{60}}$$

This equation shows that the frequency band is independent of frequency and dependent only on RT_{60}. Bonello uses pink noise for the measurement of RT_{60} for this criteria for practical reasons. The band width for small rooms, given by the equation above, is between 3 and 10 Hz. Comparing different band widths, we have

$$\frac{\Delta f}{f} = 2^{1/2n} - 2^{-1/2n}$$

where 1/n is the bandwidth in octaves. As frequency increases, the bandwidth decreases; but as frequency increases, the number of modes also increases, and the opposite for low frequencies. Coloring in low frequencies can be avoided since wider bandwidth would include more modes in the low frequencies.

The criterion selected by Bonello's research is as the following (Bonello 599):

1. The curve $D = F(f)$, where D is the modal density function per one-third octave, should increase monotonically. Each one-third octave should have more modes than the preceding one (or, at least, an equal number if $D = 1$).
2. There should be no double modes. Or, at most, double modes will be tolerated only in one-third-octave bands with densities equal to or greater than 5.

Sound Absorption

While most people talk about how walls are shaped differently in concert halls affect their acoustic environment, the importance of sound absorption is often overlooked. The sophisticated calculated angles of the walls will be of no use if there is too little sound absorption and it would be very hard to tell different sounds apart. Besides, the unevenness of absorption in different frequency range will also result in undesirable acoustic environment. To understand how sound absorption works, it can be simplified by a classical mass on a spring system. When a sound wave passes through a medium, such as air, it vibrates the air molecules to pass on the wave. However, the air molecules collide and react with each other when they are vibrated just like a mass on a spring being driven by a force. Looking at the oscillating mass system, due to the resistance of the surrounding fluid or air, some of the energy is transferred into heat. Similarly, the sound energy is transferred into kinetic energy and heat when it passes through and vibrates the medium.

Following the analogy of the mechanical model, the most sound energy is transferred into kinetic energy of the medium molecules when the driving frequency is close to the natural frequency of the medium. For every matter, there is a natural frequency to it. For a spring with a mass attached the natural frequency is $\sqrt{\frac{k}{m}}$, where k is the spring constant, which is the indication of the hardness of the spring, and m is the mass of the attached object. When a driving force is applied at a frequency close to the natural frequency, the mass will oscillate at the largest amplitude. Coming back to the sound wave, the closer the frequency of a sound is to the natural frequency of the medium, the more the medium is going to oscillate and hence more sound energy is dissipated. Thus, how well a material absorbs a certain range of frequencies is largely decided by the property of the material.

Subjective Aspects that Matter

In order to get a sense of which rooms are generally favored by musicians for practicing purposes, the best way is to ask their opinions. The reason that this makes up a significant part of the research is because of the subjectivity of some of the quality of sound and a lot of them we do not have a clear understanding yet. For example, although we can find the greatest acoustic engineers and pay them a fortune to design a room, they would not necessarily come up with the best product possible unless they know what we are looking for. Different goals should be achieved in terms of acoustic characteristics depending on the functionality of the space they are asked to design. For a lecture hall, the priority is that the speech made by the lecturer is expected be heard loud and clear by everyone in the space; on the other hand, a nice balance between the clarity and integration of sounds is favored in a musical context.

Except for clarity, which is measured by reverberation time, some other characteristics that can be found and straightforwardly quantified are loudness and intimacy. Intimacy is characterized by the time space between the direct sound and the first reflection. Due to the functionality of most spaces, from concert halls to lecture rooms, we prefer a particular intimate character. Echo is one of the products due to the wide space between the direct sound and the first reflection, and also incorporates the sound level of the reflection (Kuttruf 199). In our case, the factor will be eliminated naturally since our focus is mainly on practice room that is relatively on a smaller scale (Kuttruf 194). Then we are left with the reverberation and resonance of each frequency band. The way we are approaching this is the same old scientific method: collecting relevant data and then analyzing it in terms of correlations between quantities and qualities. In this way, we get to combine the subjectivity and objectivity to understand better about how we perceive sound. If a recording studio were to ask a acoustic designer to construct a recording space which could capture every sound with great clarity and without too much of change in its color, then the engineer who took on the request should first understand which characteristics of a space make each individual sound clear. Therefore, designing a survey that can extract the subjective aspect of information that's the most relevant to us is crucial to this study.

Before starting to design the survey, one of the keys is to determine which information is relevant to us. Since our ultimate goals are recognizing the rooms that musicians prefer to practice in and also what makes them more advantageous, we want to make sure that our survey would be able to tell us information that is relevant to those goals. Information that is relevant to the study, such as the acoustic feedback a musician wishes to get from playing in the room, should be valued more than other preferences, such as the set-up of or the aesthetics of the room. Another challenge is the analysis of data, since most of the feedback would be subjective and people generally would use different terms, such as dry or clear feedback, that have the same meaning, it needs to be categorized instead of taking individual data points. Then we can narrow down the main questions to asking what are the rooms that are regarded as beneficial for practicing musical instruments and the reasons for their preferences.

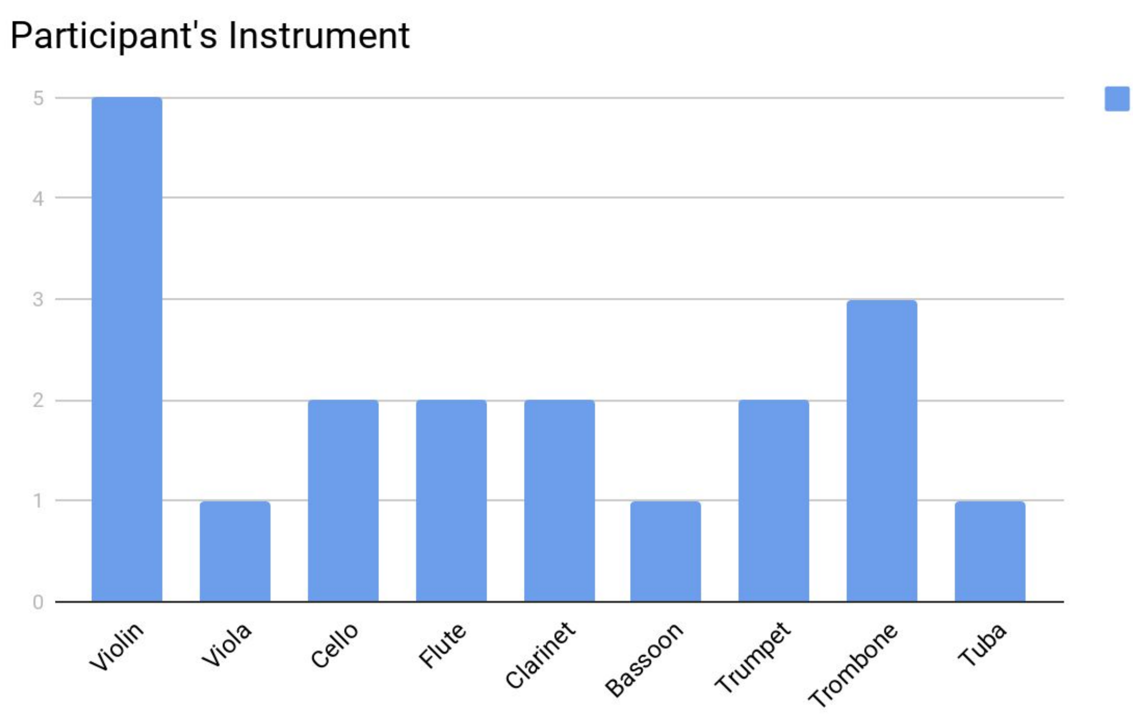
In the online survey that was made through the Google Form, we try to incorporate the structure that was discussed. The main goal is to get a sense on which practice rooms are generally more preferred and the reason why people choose them over the others. The beginning of the survey starts with a short explanation of terms so the participants can organize their thoughts in a way that align with our benefit. Proceeding into the next section, the main questions are asked, such as:

- Participant's instrument
- Ranking of practice rooms in the Bito and Blum buildings
- Acoustic reasons that they rank these rooms

In this way, correlation between musicians with different instruments and their preferences of acoustic characters of practice space can be easily extracted through the short answers they give in the short answer section. It will also be clear that which of the rooms are considered to be having some of the characteristics over the others so it will be more obvious which physical quantities are related to the subjective qualities. Thus, the extraction of data will be less confusing and less likely to compromise the reliability of the data itself.

Now a direction for the questions has been established, a sample group is needed. It is preferred that the samples to be collected from musicians since they are the focus group for the matter of the subject and the fact that Bard has a conservatory on campus is the most advantageous condition. The survey is going to be asked to be done by the conservatory students since they devote a great part of their time awake for practicing. During the stage of data collection, the misinterpretation of the terms, such as acoustics, can and have affected their feedback. It can be challenging in terms of extracting the information that is relevant to the study. Thus, another alternative of collecting feedback would be more preferred at the moment. Comparing with the first survey we made online, filling it out in person with assistance, such as having people who can answer questions present, would reflect the patterns with more credibility.

Of all the samples of the survey, the instruments of the respondent are: violin, viola, cello, clarinet, bassoon, trumpet, trombone, and tuba. Pianist are not considered due to the fact that the quality of the piano plays a great part in their preferences of practice rooms. Among all



Distribution of instruments participants play the practice rooms in Bito Conservatory Building and Blum Music Building, room 118 in Bito is preferred over all the other rooms by a margin. Since room 118 is relatively larger than the other rooms, it would be more beneficial to compare the rooms in different size categories rather than compare them all together. Among the rooms of same volume, Bito room 203, 205, 207, 117 are measured and compared, while Blum room N008 and N013 are compared separately. According to the survey, there are no particular trends for musicians who play different instruments when it comes to practice room preferences. However, brass players generally like bigger rooms that are more "echoy", which corresponds to longer RT, and larger rooms are not compared in this research. Therefore, it would be easier to conclude what musicians look for when they choose their practice space.

Potential Improvements

Although it would be great if schools have the budget of building new practicing facilities, most schools would prefer a more economic way of improving their practicing facilities. Building a acoustically satisfying space is not easy, but modification of existing structures can be as much difficult. Especially when resources are limited, an effective and efficient method is needed. However, the number of factors that can affect an environment acoustically is substantial. From the material of the interior to the number of windows, any deviation from the original setup could lead to a huge acoustic difference. Thanks to acousticians' hard work, some major factors have been more understood and their effects have become tools in our belt. First comes the identification of the problem, then the solution.

Firstly, the modal density of a room for a certain frequency band can be changed by minimizing the RT of desired frequency band despite the impracticality of changing room dimensions. In order to achieve this, it is important to first identify the resonance modes in that frequency band. Since it is desirable to decrease the RT of the frequencies within the band instead of damping it entirely, it is useful to locate which of the modes should be damped so that minimal damping is done on other frequencies outside of the targeting band. Damping targeting frequency can be done through understanding the standing wave that forms at the frequency. In other words, the high and low pressure areas have to be located and damped accordingly by placing sound absorbing material at the high or low pressure area to decrease the RT of that mode. For example, taking a room which would like to improve acoustically. The dimensions of the room are first used to calculate the modal density for different frequency bands. Then it is shown on the modal density chart that the density of modes increases monotonically except there is a drop in, say, the 70 Hz to 90 Hz frequency band. In order to make the number of modes increases monotonically, the number of modes that the previous frequency bands has to be decreased to at least as many as the 70 Hz to 90 Hz frequency band. Then decide the frequency bands that should be quieted more, find out where the high or low pressure areas are of those resonance frequencies and place sound absorbing materials accordingly.

Another issue that cannot be located by the Bonello criteria is the timbre change caused by the unevenness of absorption of frequencies by the surfaces of a room. Although the resonance of different frequency bands can be calculated and graphed by the application of the Bonello criteria, the reverberation of a sound is something that has to be addressed as well. The reason that it is worth paying attention to is because the ability of a surface to absorb different frequencies would cause some frequencies to be damped earlier than others. Since the ratio between different frequencies is crucial for us to recognize timbre differences, the very effect could result in the reverberation of a sound has a different timbre than the original. For example, if a surface has a reflection coefficient of $\frac{1}{4}$ for the low frequencies, $\frac{1}{2}$ for the middle frequencies, and ¾ for the high frequencies, then for the first reflection we would get $\frac{1}{4}$, $\frac{1}{2}$, and $\frac{3}{4}$ of the original for the low, middle, and high frequencies. However, if we look at the second reflection, the surface will again damp the frequencies differently. Since the lower the frequency is, the more it is damped, we would get much weaker second reflections in the lower frequencies. In the example we have, the second reflection would have the amplitude of $\frac{1}{16}$, $\frac{1}{2}$, and $\frac{9}{16}$ for the low, middle, and high frequencies. It is clear that in the second reflection, the lower frequencies already have $\frac{1}{9}$ of the amplitude of the higher frequencies. The lost of consistency of the ratio of reflection amplitude between different frequencies is one of the main cause of timbre change of reverberation. This step has to be carried out experimentally through measuring the RT of the whole frequency spectrum to identify how much the timbre of a sound changes as time progresses.

Having done research on how sound works at the fundamental level, studying different aspects of room acoustics and various acoustic characters, and methods of approaching the subjectivity of acoustics from an experimental angle, this project is currently at the stage of integrating all the information that has been collected and hopefully translating it into a system we can depend on. After organizing the known information, coming up with a systematic model of as a way to replicate the desire acoustic characters in a practice space is the next step. The reason why this can be challenging is because this research is trying to convert the expressing quality of acoustic characteristics into something that is quantifiable. This confrontation is also a great way to integrate my knowledge as both a musician and physics student into a skill that is seldom possessed by one or the other.

Set up/Method

There are two parts to the experimental section of the research: acquire dimensions of rooms and compare them, and measuring the RT_{60} of rooms. The first part is more straightforward, including measuring the actual dimensions of rooms and fit them to the Bonello criteria. In this way, it would be clear which frequency bands would be resonated more than the others in a room. The calculation can be done easily through a small set of functions and Excel would be sufficient to complete the task. There are also resources on the internet that can perform the Bonello criteria calculation, such as The Room Mode Calculator from amcoustics.com, which is used in this research.

Measuring the RT_{60} is the other part of the experiment. It is defined as the time for a sound in a room to decay by 60dB. RT_{60} takes an essential role in determining the acoustic characteristic of a room. It is also needed for the room mode calculation since it decides the width of frequency bands used by the criteria. Often the measurement can be done by using an impulse sound source, such as popping a balloon, and recording the explosion. Using audio softwares such as Audacity can easily analyze the data and read the RT_{60} off of a graph. However, in a musical scenario, measuring RT_{60} by impulsion does not give us the most informative knowledge of the acoustic environment. Since a sound can be composed of different frequencies, the impulse measurement only tells us about how fast the loudest frequency decays. Therefore, we need some other ways to measure the RT_{60} of different frequencies.

The method adopted for this project is called sine wave sweep. It is a longer process comparing to the impulse method since the sound source plays a sine wave starting at some frequency and it gradually raises the pitch until it has arrived at the highest frequency desired. The process is usually repeated a few times so the averaged data can be acquired with higher precision. In this way, a continuous RT_{60} can be measured and graphed with respect to the frequency. The sound source generator used is a studio monitor, which can generate a frequency range from 100 Hz to 12000 Hz, borrowed from the Bard Audio Visual department. Although a lowest frequency around 50 Hz is desired, the studio monitor from the AV department is the best speaker available for this purpose. The receiving microphone is a Nady CM-100 Reference Measurement Microphone recommended by the Bard AV department as well. Both the speaker and the microphone is connected to a Forsite Saffire 40 audio interface, which is connected to a MacBook computer. Besides from the hardware setup, the software used to run the measurement is the Room EQ Wizard V5.1, which has a built in measuring procedure that can provide RT_{60} data.

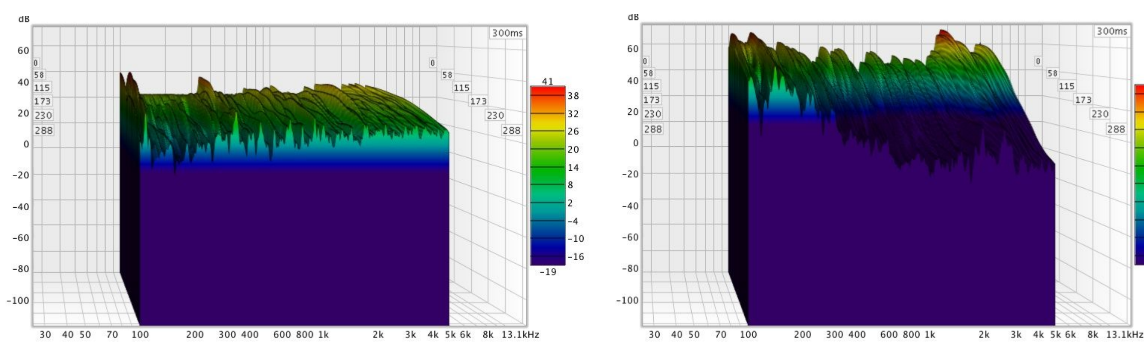
The physical setup has a studio monitor as the output source, a measuring microphone as the input source, and an audio interface connected to a MacBook for data organization and analyzation. The speaker is placed around the middle where the musicians play and the microphone is placed at ear height. The pre-measuring procedure, according to the help section from the Room EQ Wizard website, has four steps to it. Firstly, choose the audio input and output, which we have a reference measuring mic and a studio monitor connected to the Forsite audio interface. The next step would be calibrating the soundcard using the built-in calibration function. Calibrating the soundcard allows the software to remove the response of the soundcard and give us a better measurement in the extreme low and high frequencies[1]. After the calibration of the soundcard comes the level checking of the output. This process helps the software to line up the speaker output level with the system output. Finally, the calibration of the SPL meter. Repeating the pre-measuring procedure everytime when the setup is moved to a different room would result in more accurate measurements since the instruments may act a little differently to new measurements in different rooms and the calibrations would normalize the environmental variances, such as background noise.

One advantage of this program is that once everything is in place and calibrated, the measuring program automatically runs the test according to the preferences set by the user. Once the test is finished, the program will automatically generate graphs of some data and other more complicated graphs, such as waterfall graph, can be generated upon user's request. In the tests run for the purpose of this research, the testing method is the sine sweep method and the frequencies are swept eight times from 100 Hz to 5k Hz. Each run lasts about 47 seconds and they each has its own calibration file to make sure the credibility of the data. The measurements are made for some of the more popular practice rooms and the less popular ones.

[1] "Getting Set up for Measuring." *Room EQ Wizard Help*, www.roomeqwizard.com/help/help_en-GB/html/calsoundcard.html#calmeasure.

Analysis of Measurement

The measurement is taken in room 117, 118, 203, 205, 207 in the Bito Conservatory Building, and room N008, N013 in the Blum Music Building. In the most preferred room 118, its waterfall graph (Fig. 1) shows a consistent decay throughout the 100 Hz to 5k Hz range during a 300ms time interval. On the other hand, the measurement carried out in room N008 shows a great difference in terms of RT in different frequencies (Fig. 6). In the 700 Hz to 5k Hz range, the sound pressure dropped almost 65 dB within the 300ms time interval, while in the 100 Hz to 300 Hz range the sound pressure decreased at a minimum of 23 dB. The acoustic character of the later room can result in a very dramatic change in the timbre of the sound produced in the room. Waterfall graphs of other rooms can be found in the graphs and diagram section.



Waterfall graph of Bito room 118 and Blum N008

In terms of the Bonello room mode calculation, all the rooms fits the criteria except for room N013 in the Blum Music building. All the modes can be seen on the resonance modes in one-third octave bands diagrams taken from the Room Mode Calculator on the amcoustics.com[2].

[2] https://amcoustics.com/tools/amroc?l=495&w=410&h=290&r60=0.44

The number of modes increases monotonically for all the analysis. While all other rooms fits the criteria, in room N013 in the Blum Music building, there is a drop in the number of resonance modes, which is unsatisfactory according the criteria. In terms of the Bonello mode analysis, only room N013 requires work to adjust the resonance response. However, room N013 is preferred over room N008 despite the fact that considering the result from the criteria it is less satisfactory. Therefore, the result implies that fitting the Bonello criteria does not give a room acoustic advantages.

Conclusion

Although most of the rooms fit the Bonello criterion, there is still a gap between the more preferable rooms and the others. It implies that there are some factors that influence the acoustic characters of the rooms other than the resonance modes distribution. The most substantial difference between the better rooms and the less preferred rooms is the evenness of reverberation time throughout the frequency spectrum. The ideal acoustics environment, such as room 118 in the Bito Conservatory building, would present a generally even RT in different ranges and thus the sound made in the environment remains consistent in terms of timbre. On contrast, the room that presents an uneven spread out of reverberation time throughout the frequency spectrum, such as room N008 in the Blum Music building, are less favored. Therefore, it can be concluded that the evenness of sound decay affect how much a practice room is preferred.

Besides the acoustic factors, the psychological aspect is also a crucial element in musicians' practice quality. Concluded from the section of survey that asks the participant for their non-acoustic reason for choosing a practice room, having a window or a plant or two in a room would generally enhance the chances that a musician would have an enjoyable practice session. Since practicing a musical instrument is a mentally-exhausting task and requires intense focus, it makes sense that they seek an environment that is emotionally comforting to practice.

The suggestion results from this research for the rooms in the Blum building is adding sound absorbing material which has a better performance in terms of absorbing lower frequencies. As for room N013, there is a possibility of improving by fitting the resonance modes distribution to the Bonello criteria, but addressing the inefficiency of absorbing low frequencies should be prioritized. To sum up the findings of the research, there is clearly a trend between the evenness of RT and how preferable a practice room is for musicians. Practice rooms to musicians are similar to the relationship between mirrors and dancers. If a dancer cannot see a clear and realistic reflection of their posture, it would be very difficult for them to pay attention to the finest detail. Correspondingly, musicians would not be able to achieve their best if they cannot hear the product they produce. Although individuals and institutions tend to look for the most economical way to build practice spaces, it should be noted that budget for well-performing sound absorbers should not be cut!

Graphs & Diagrams

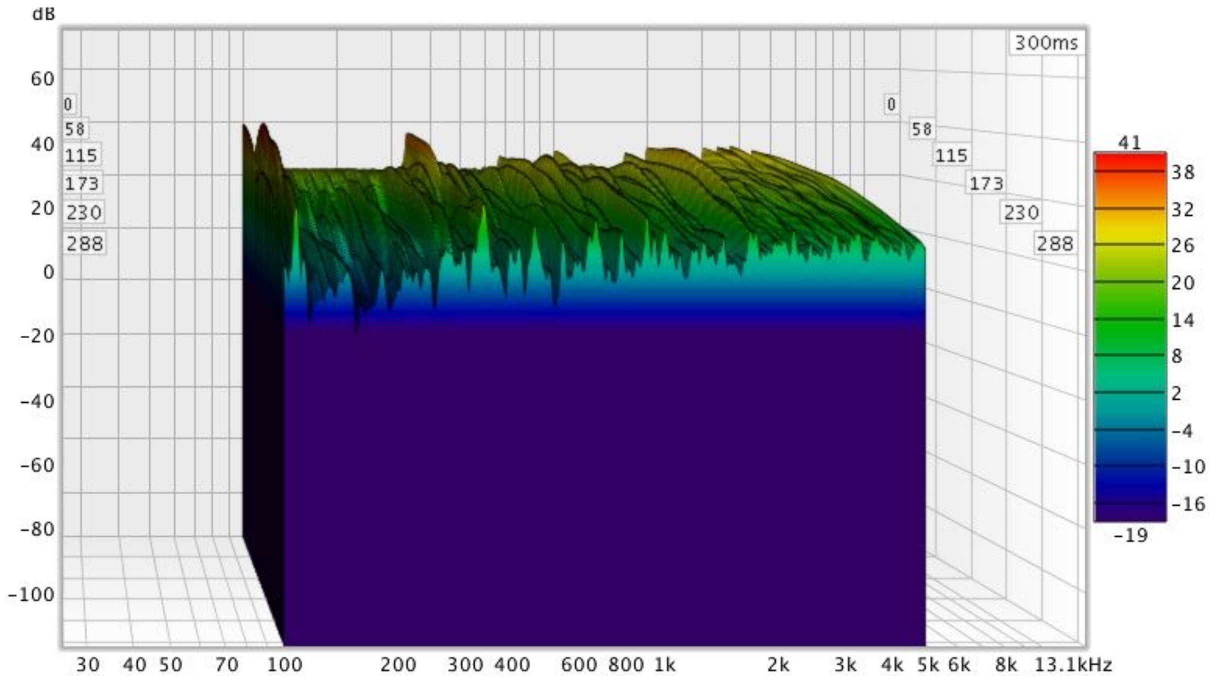


Figure 1. Waterfall graph of Bito room 118

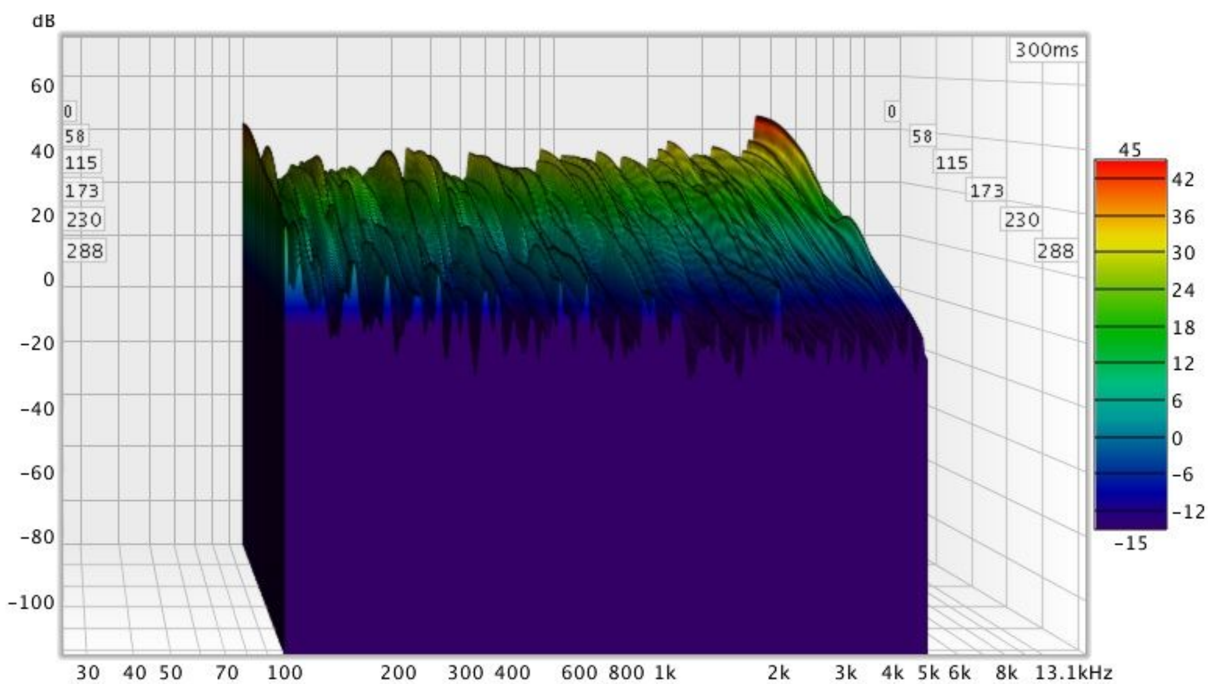


Figure 2. Waterfall graph of Bito room 117

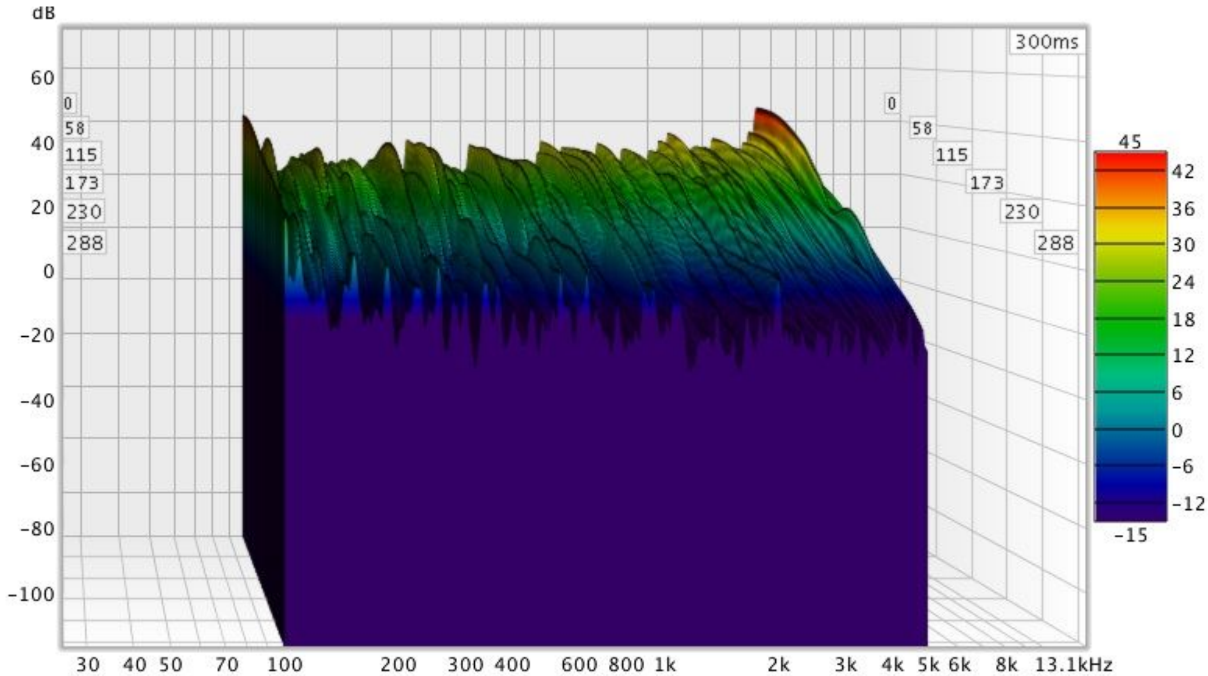


Figure 3. Waterfall graph of Bito room 203

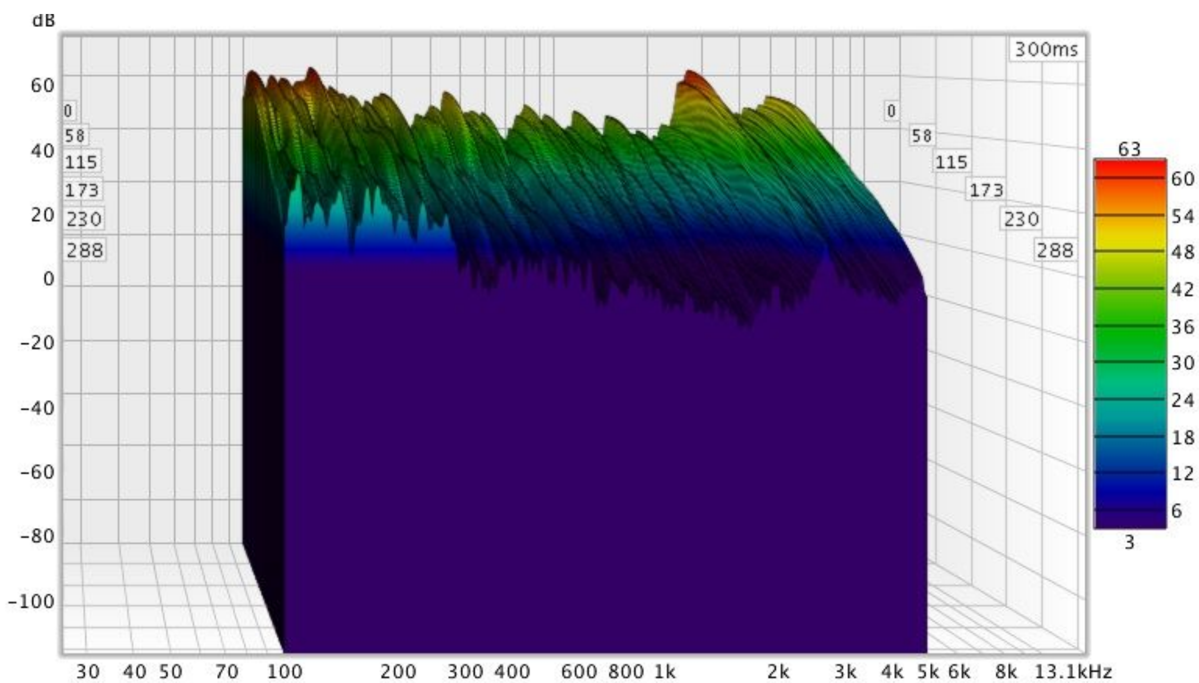


Figure 4. Waterfall graph of Bito room 207

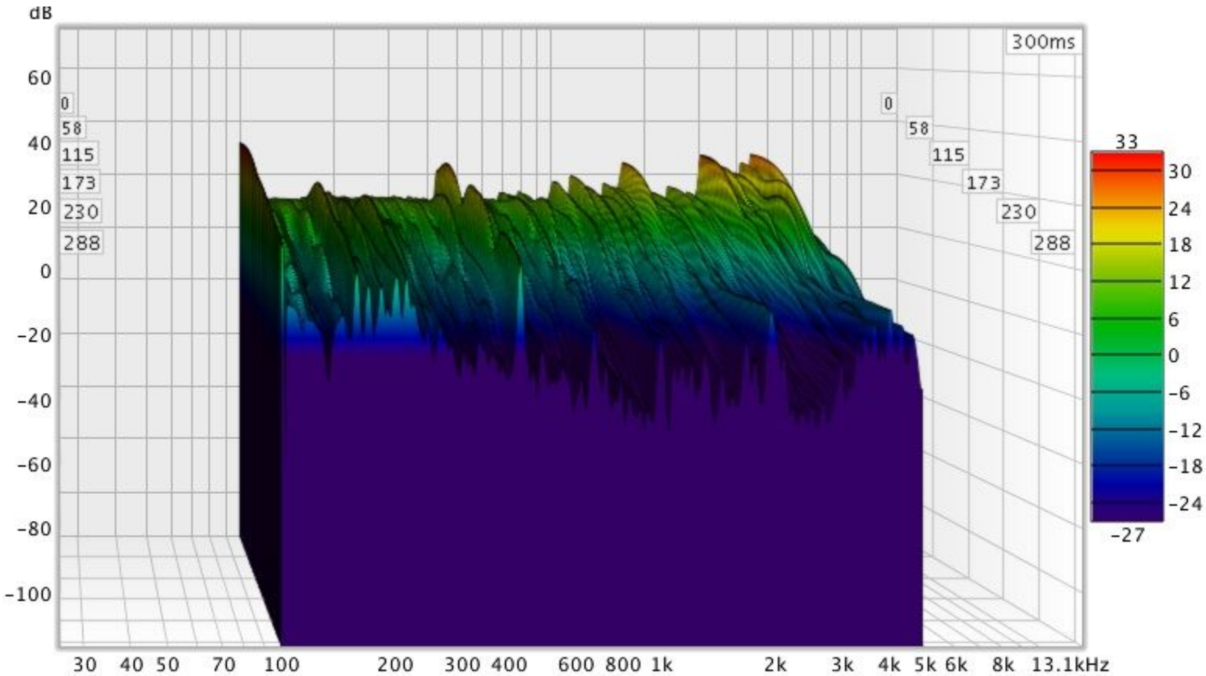


Figure 5. Waterfall graph of Blum room N013

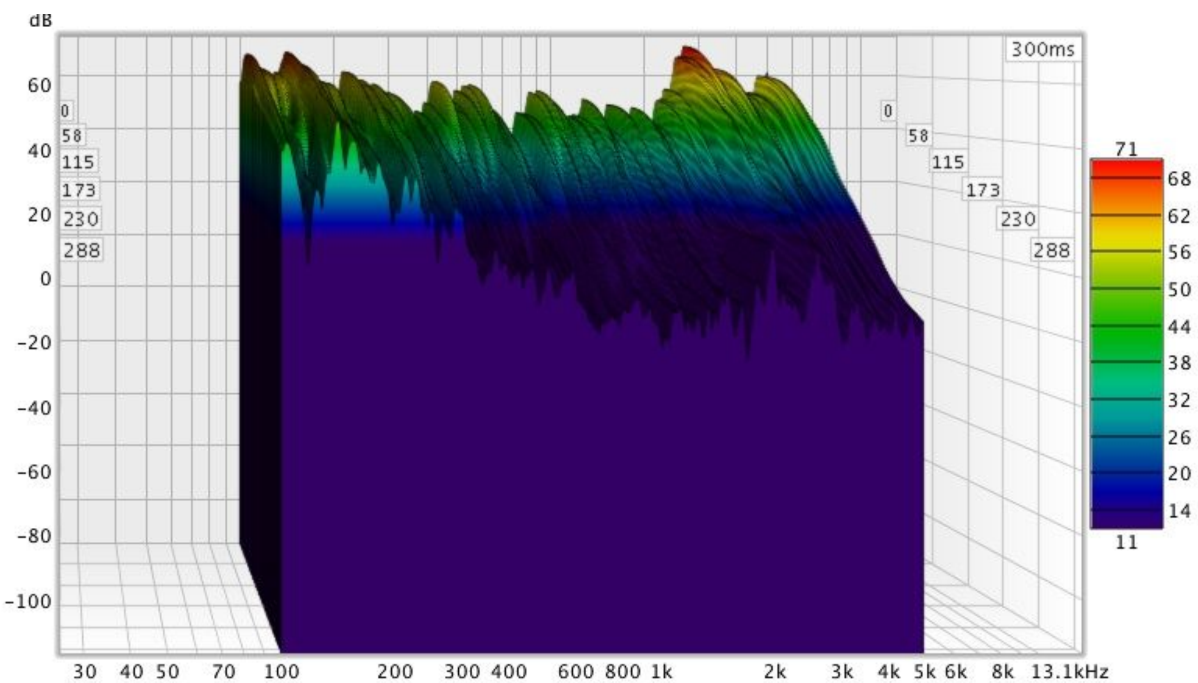


Figure 6. Waterfall graph of Blum room N008

For figure 1 through 6, vertical axis is sound pressure (dB), horizontal is frequency (Hz), and the axis going out of the page is time (ms). The spectrum on the right corresponds to the color of the chart, represent the sound pressure (dB).

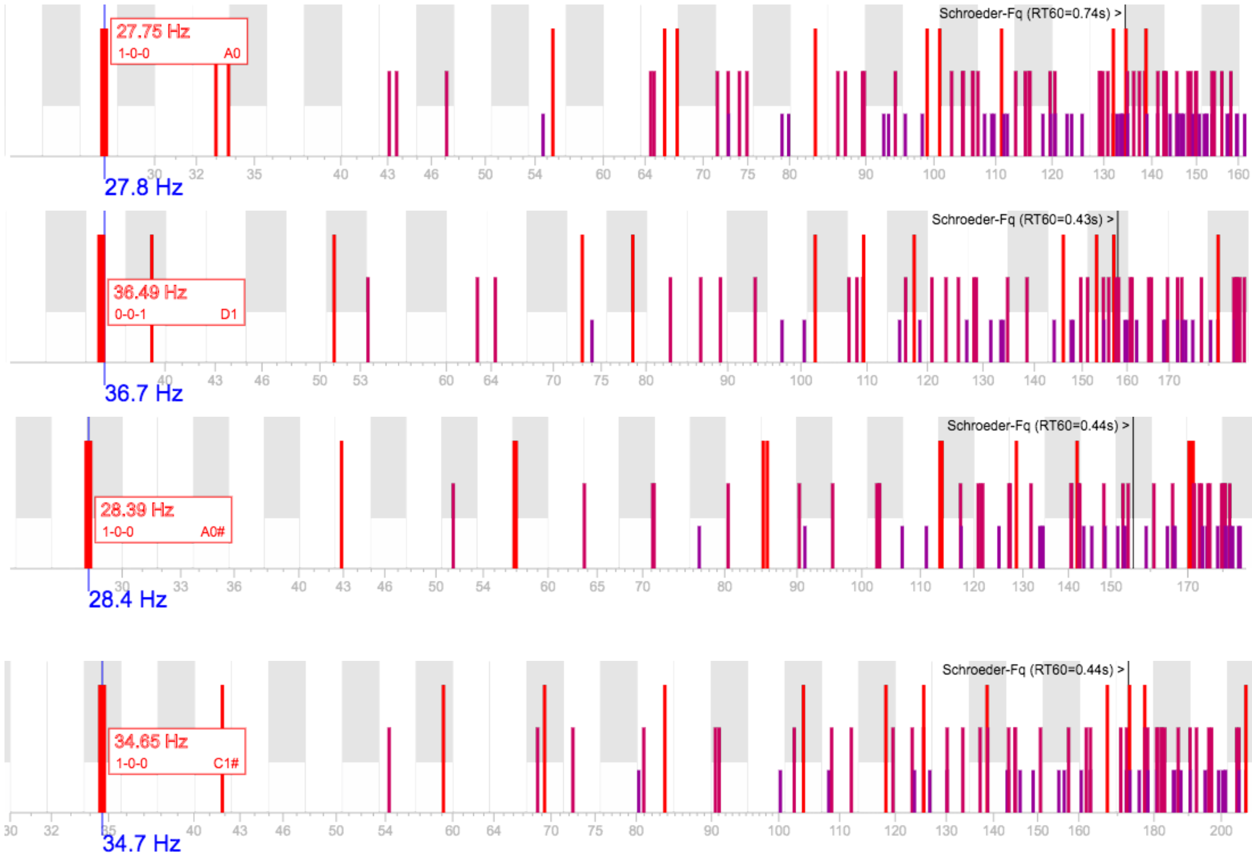


Figure 7. Resonance modes of Bito room (from top to bottom) 118, 117, 203, 207

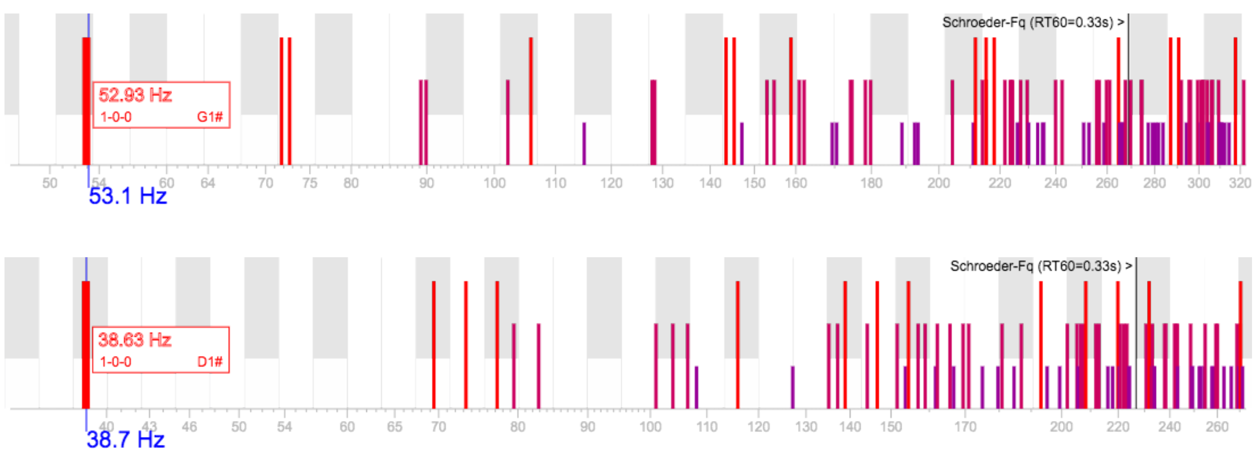


Figure 8. Resonance modes of Blum room (from top to bottom) N013, N008

For figure 7 and 8, each of the colored line represents a resonance mode.

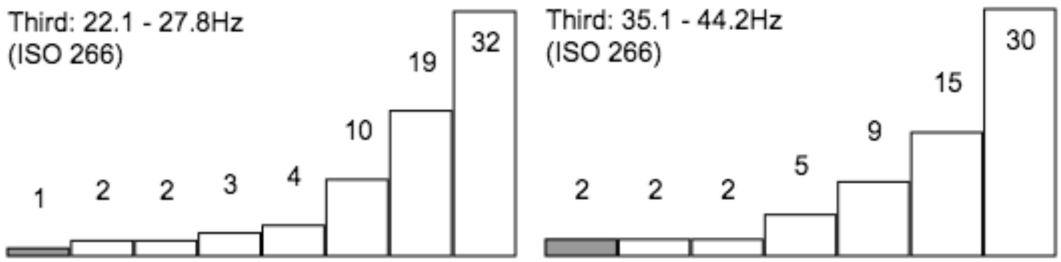


Figure 9. Modes distribution in one-third octave (Bito 118, 117)

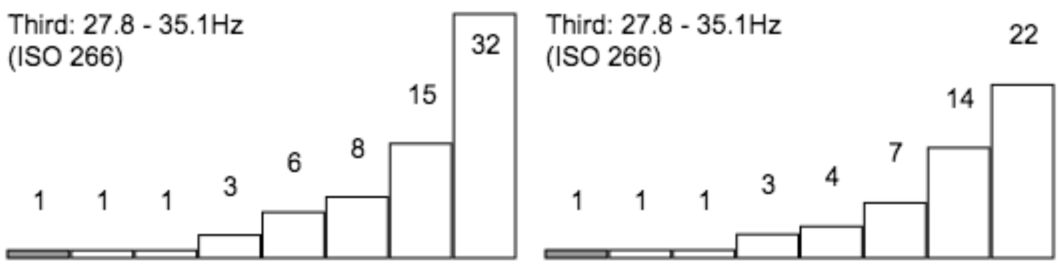


Figure 10. Modes distribution in one-third octave (Bito 203, 207)

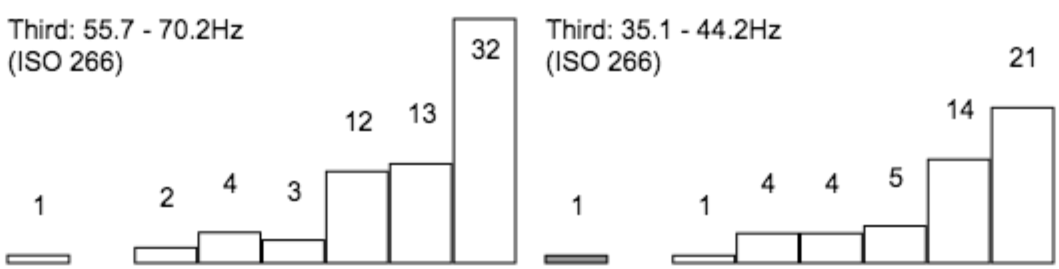


Figure 11. Modes distribution in one-third octave (Blum N013, N008)

For figure 9 through 11, each of the column represents the number of modes in each one-third octave band.

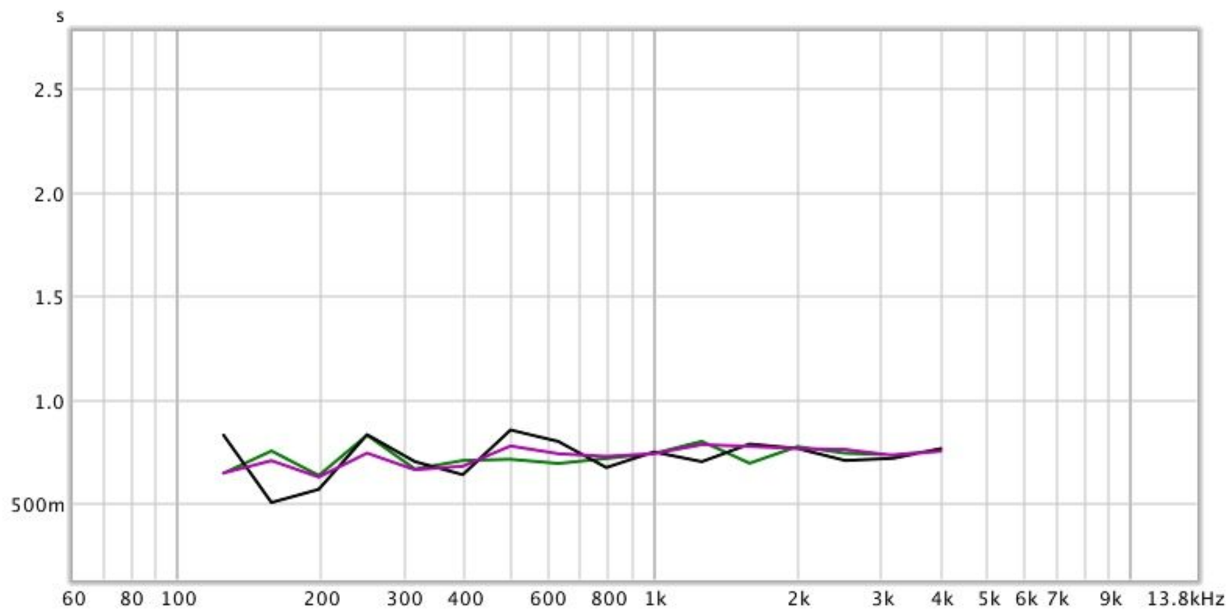


Figure 12. RT_{60} diagram of room Bito 118

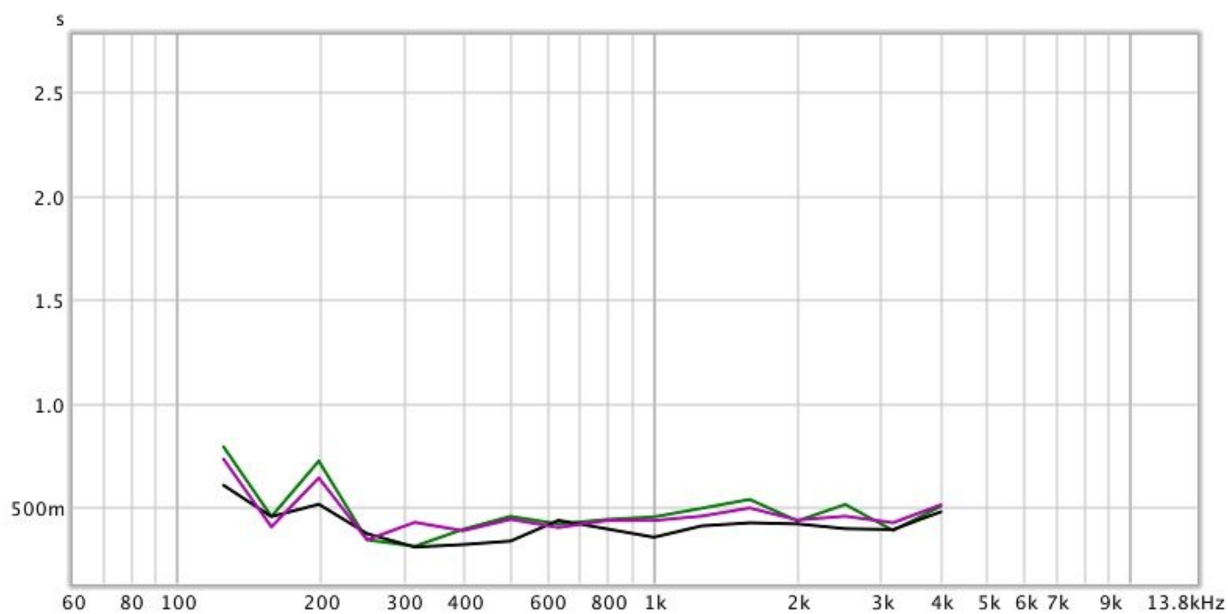


Figure 13. RT_{60} diagram of room Bito 117

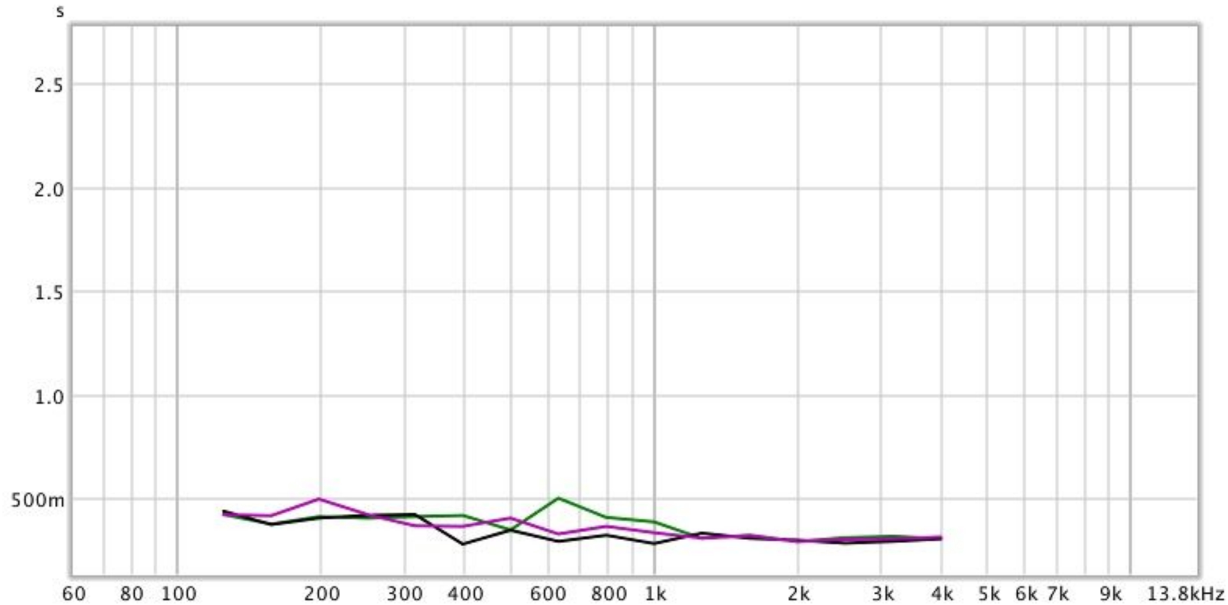


Figure 14. RT_{60} diagram of room Bito 203

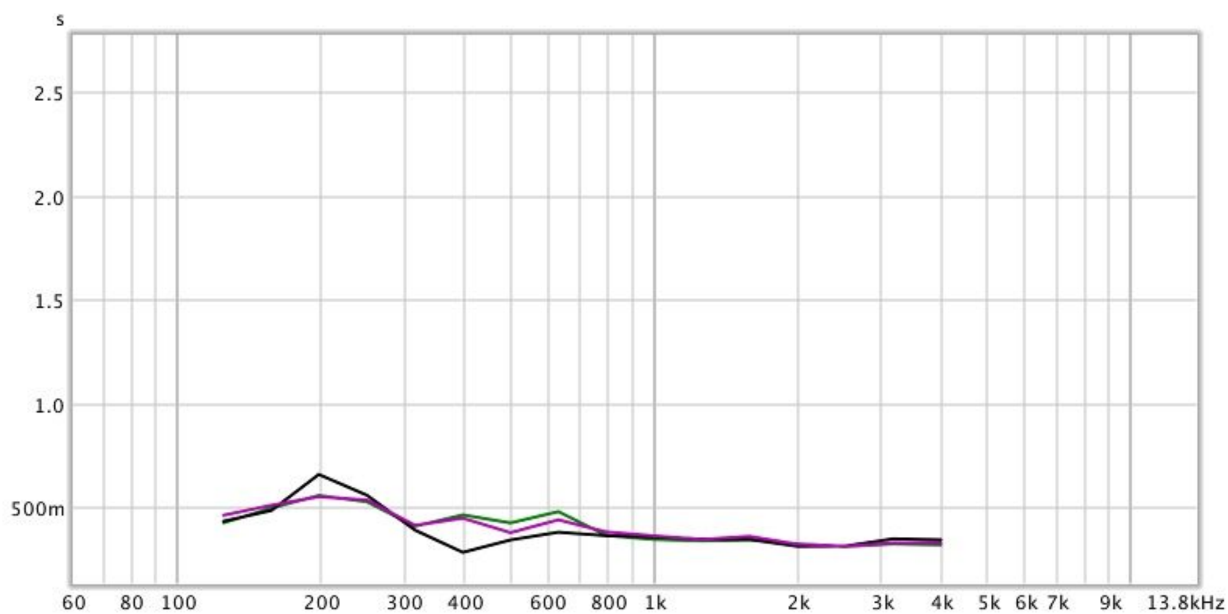


Figure 15. RT_{60} diagram of room Bito 207

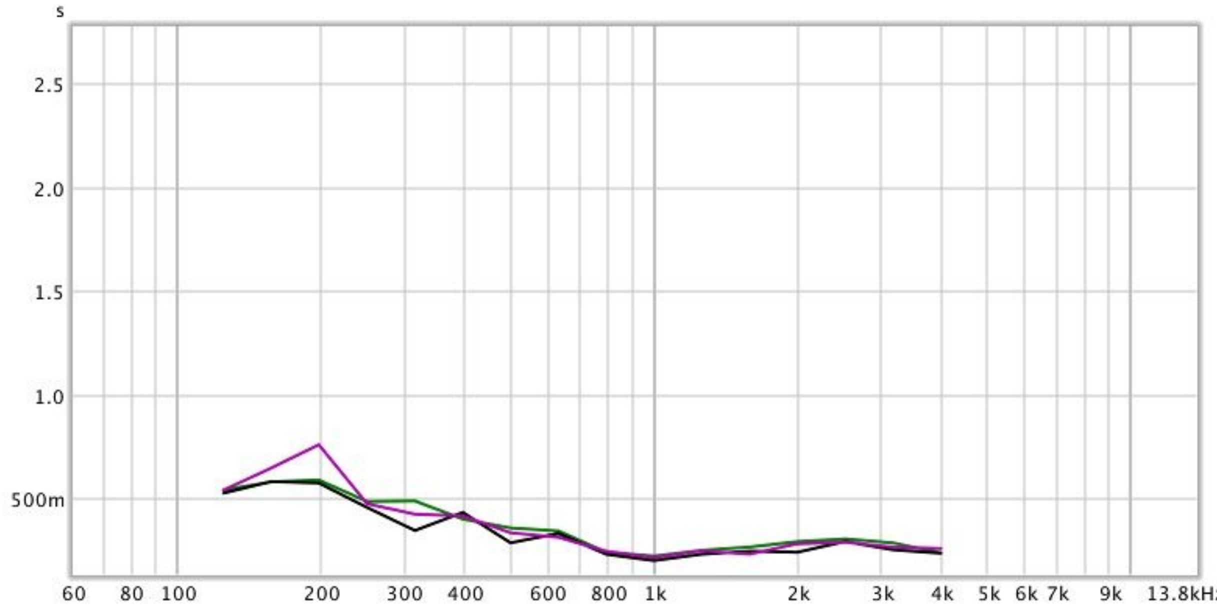


Figure 16. RT_{60} diagram of room Blum N013

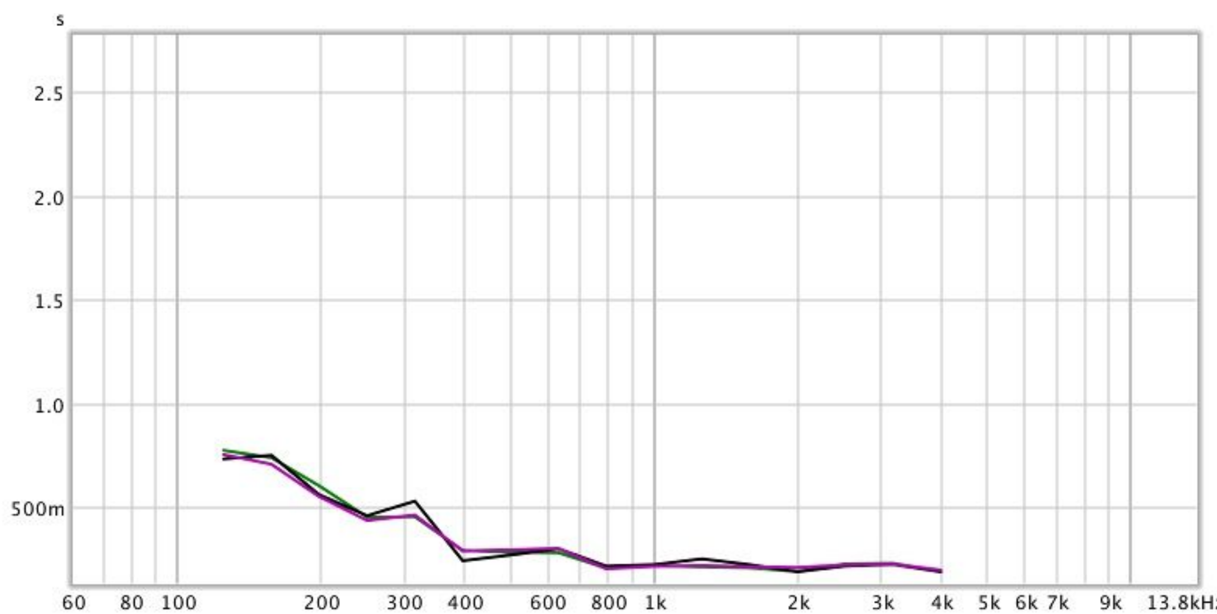


Figure 17. RT_{60} diagram of room Blum N008

Note: for figure 12 through 17, the different lines represents different reverberation time measurements, which include T_{20}, T_{30}, Topt, and TS. All of them show coherent results and the desire information is the trend.

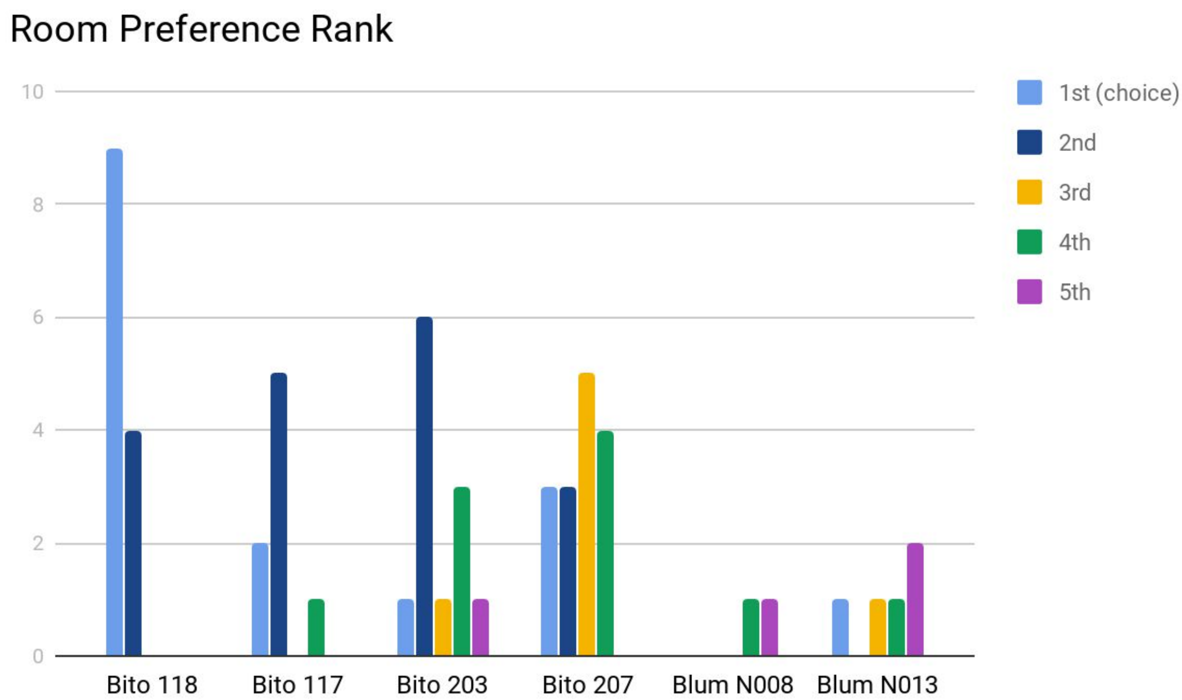


Figure 18. Room preference rank chart

Tables

Room \ Dimensions	Width	Length	Height
Bito 118	618	520	510
Bito 117	437	336	470
Bito 203	604	400	302
Bito 207	495	410	290
Blum N008	444	233/260	234
Blum N013	324	236	239

Table 1. Room dimensions

Bibliography

Kuttruff, Heinrich. *Room Acoustics*. 4th ed., CRC Press/Taylor & Francis Group, 2017.

Bonello, O. (1979). Acoustical evaluation and control of normal room modes. *The Journal of the Acoustical Society of America*, 66(S1), pp.S52-S52.

Rossing, Thomas D., et al. *The Science of Sound*. Addision Wesley, 2002.