Acoustically Sensitive Large Assembly Spaces at School:

An Elementary School Retrofit and Expansion

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Abstract

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This thesis argues for prioritizing the acoustic dimension of design and embracing an attitude of “acoustic delight” rather than “do no harm.” The thesis investigates three approaches to shaping the acoustic experience of large assembly spaces in schools: fixed acoustics, variable acoustics, and acoustic microclimates. The acoustic retrofit and expansion of a typical double-duty gymnasium/cafeteria is studied, motivated by improving the health and wellness of students and staff. Design options are evaluated using acoustic simulations with quantitative metrics for reverberation time, speech intelligibility, overall sound levels, and quieter areas within the large assembly space. The study explores preliminary acoustic design methods and tools to add to the architect’s toolkit. Architects can design creatively with qualities of sound, just as they do with qualities of light. It is time for architects to engage the full variety of sensory experiences that support a child’s social and emotional development.

Six supplementary sound recordings are included as MPEG/WAV files. They illustrate acoustic experiences at three large assembly spaces and commons areas: the existing study site, a site with sub-optimal acoustic experience, and a newer school designed with high priority on acoustics.

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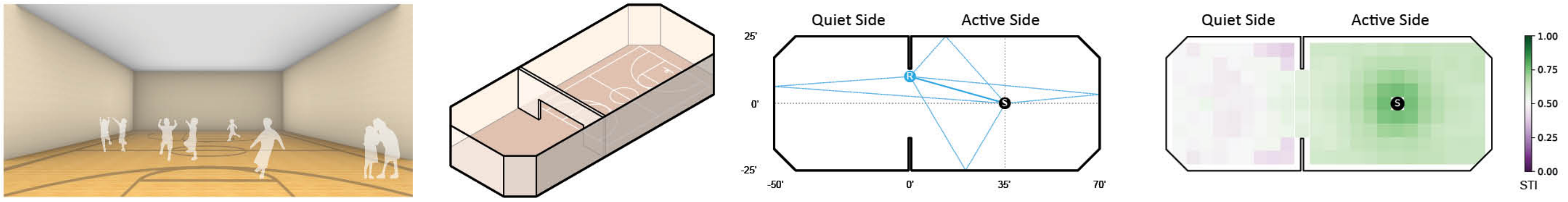

Gayle Ayers Elam

Figure i. Design images and quantitative data.

"The restoration of the body [in architecture] means, first and foremost, the restoration of the sensory-sensual - of speech, of the voice, of smell, of hearing. In short, of the non-visual."

- Henri Lefebvre, *The Production of Space*

"The mobility of the listener seems to have a deep effect on the experience of listening—choosing what to listen to, where to listen from, and experiencing sound as something to be explored rather than simply received."

- Vanessa Tomlinson, sound artist

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0. Introduction

Motivation
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Methodology
Case study school: Rockwell Elementary

This thesis investigates the process of designing the acoustic experience within large assembly spaces in schools such as gymnasiums, cafeterias, and commons areas. I work through this process by way of a research study and a design problem as case study of a specific school. The design problem is the acoustic retrofit and expansion of a typical double-duty gymnasium/cafeteria with a focus on acoustic microclimates. This is motivated by improving the health and wellness of students and staff. The workflow begins with an assessment of acoustic experience at the elementary school, continues with acoustic analysis and quantitative data, and leads to schematic design options.[1]

Motivation

This work is motivated by two primary beliefs. The first belief is that sound is an important part of the experience of a space. Sound connects us to our surroundings and to each other, to things near and far, seen and unseen, and it can also overwhelm us. Children especially need some control to choose their auditory experience during lunchtime and other social learning times. Too often the acoustic experience is overlooked or an afterthought to a design rather than an integral part of the design process.

The second belief is that an appropriate acoustic environment is essential for the health and wellness of everyone at school. In rooms with the right acoustic qualities, students understand what their teachers say without extra repetition, teachers do not strain their voices by talking extra loudly trying to be understood, everyone's hearing is protected, and stress and anxiety are reduced because learning is easier and less fatiguing.[2] However, in many older schools, the large social spaces such as the gymnasium are extremely loud rooms where people have trouble understanding each other and teachers strain their voices.[3] A multi-purpose gymnasium/cafeteria poses special acoustic challenges because the different functions have different acoustic needs. A gymnasium can be acoustically lively, but a cafeteria should be less lively so that children can talk freely and grow socially rather than sitting in enforced silence. If the room is too reverberant it gets too loud with multiple talkers, and they have trouble understanding each other.

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[1] See Figure i (title page) for a design image (large top image) and previews of quantitative data displays (smaller images).

[2] (The Collaborative for High Performance Schools (CHPS) 2018) "Washington Sustainable Schools Protocol" (WSSP)

[3] Bill Stewart, managing partner of SSA Acoustics says this is problem they encounter weekly in their office (May 1, 2020, personal communication).

Fixed acoustics, variable acoustics, acoustic microclimates

This thesis explores three approaches to shaping the acoustic experience of large assembly spaces in schools: fixed acoustics, variable acoustics, and acoustic microclimates. *Fixed acoustics* are permanently installed acoustic treatments that never change, such as wall panels and ceiling baffles. *Variable acoustics* are features that change to adapt the room to different activities within the space, such as opening and closing doors, moving partitions, and opening and closing curtains. *Acoustic microclimates* are a variety of acoustic conditions (microclimates) that exist within a large space, such as quieter or more active areas so that people can choose the environment that suits them best. Fixed acoustics are essential to establishing healthy acoustic environments overall, and variable acoustics and microclimates give people choices to customize their personal experience of sound by changing a feature of the room or their location within the room.

Methodology

This is investigation has four major parts. The first part is characterizing the acoustic experience at the case study school, Rockwell Elementary. The school is introduced in the next section, and sound recordings later in this chapter establish the need for an acoustic retrofit of the gymnasium/cafeteria and attached outdoor play area.

The second part is a research study (Chapter 3). This is a study of twenty-four typical gymnasium and/or cafeteria room volumes that explores the impact of room geometry and ceiling material on reverberation times.[4] Reverberation time is calculated by Sabine's equation.[5] This is general research that can be used to understand the expected reverberation time of a simple gymnasium or cafeteria given its size[6] and ceiling material. The calculations show that ceiling height and ceiling materials have more influence on reverberation time than different floor areas configurations.

The third part of the investigation applies the Sabine equation to the case study school (Chapter 4). The reverberation time for various design options of the double-duty gymnasium/cafeteria are

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[4] Reverberation time is a key acoustic metric that describes how long sound energy persists in a room once the signal producing the sound has stopped.

[5] The Sabine equation is a standard equation developed in 1895 that defines the relationship among room volume, total room absorption from the surface materials of a room, and reverberation time.

[6] The rooms are simple rectangular volumes defined by height, width, and length.

calculated using the Sabine equation. Fixed acoustic treatments and variable acoustic treatments (doors and curtains) are considered.

The fourth and final part of the investigation uses acoustic simulations to get more detailed information about design options for the case study design (Chapter 5). Acoustic simulations are performed using a 3D design software package (Rhino) with an emerging tool for acoustic analysis (the plug-in software package Pachyderm Acoustics). These acoustic simulations provide quantitative metrics for reverberation time, speech intelligibility, and overall sound levels on a five-foot grid of the room. The results of these quantitative data are shown in plan view as color-coded heatmap displays. The heatmaps to show location-specific information about the room, including acoustic microclimates within the space, such as quieter areas within the large assembly space.

Case study school: Rockwell Elementary

This investigation uses a neighborhood elementary school as a case study for developing an acoustic design process. The case study school is Rockwell Elementary, built in 1981 (see Figure 1 and Figure 2). It is a one-story suburban school located on a large property in Redmond, Washington on Seattle's Eastside.[7] The gymnasium/cafeteria and attached covered play area have a higher roof and a 20-foot ceiling height.

The design problem is the acoustic retrofit and expansion of the existing double-duty gymnasium/cafeteria. The school's only large assembly space was designed to serve as cafeteria during lunchtime and as gymnasium and assembly space the rest of the time. When it opened in 1981, the combined space was adequate for the 400 students, but the student body has grown to 550 to 650+ students. Now the students do not fit in two lunch periods, and more classes need to use the gymnasium for physical education. Expanding into the covered area might solve the capacity part of the design problem. But why is an acoustic retrofit needed?

We mentioned earlier that in many older schools the gymnasium is an extremely loud room. This is true for Rockwell Elementary. The walls, ceilings, and floors are made of hard surfaces only (concrete masonry walls, wood ceiling, vinyl floor). Both experience and analysis indicate that the current spaces are too loud and reverberant.

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[7] The school is not near any major roads, so traffic noise intruding into the building is not a primary acoustic issue.

Acoustic renovation and expansion of an elementary school’s typical CMU double-duty gymnasium and cafeteria.

What is the problem?

1. Rockwell Elementary’s existing double-duty gymnasium and cafeteria (built 1981) is too small to serve the current student body.
2. The current spaces (indoor and outdoor) are too loud and reverberant.

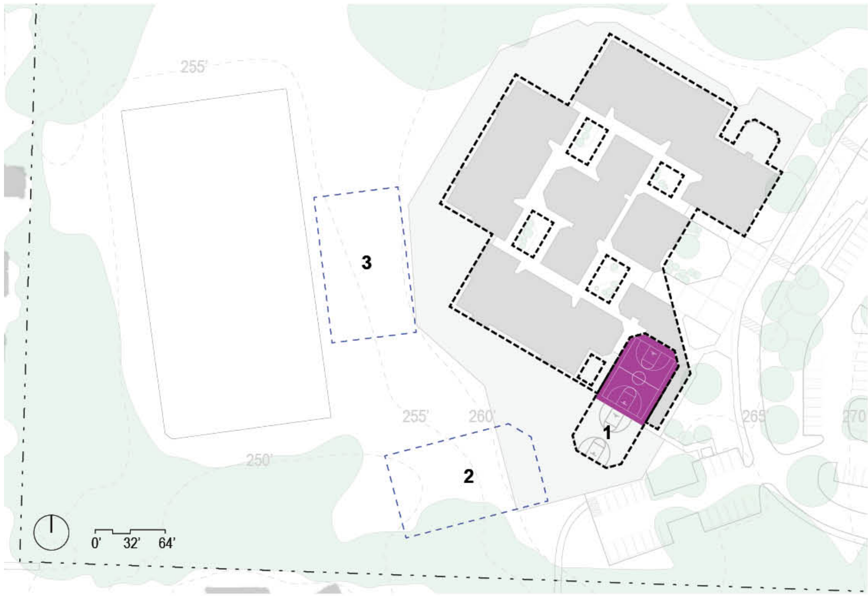
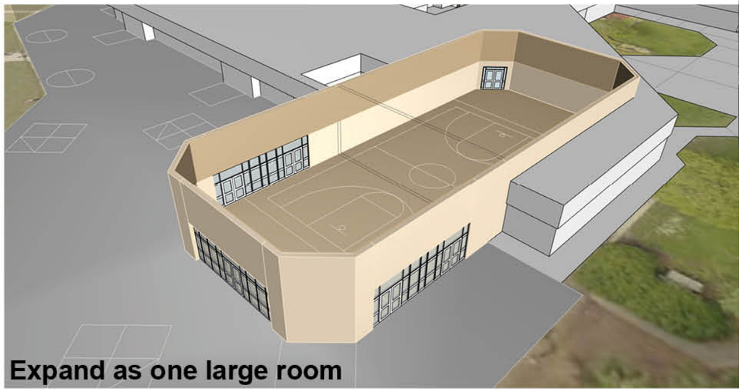
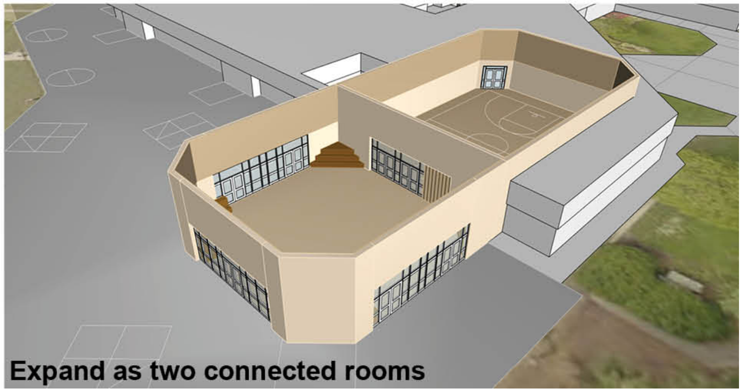


Figure 1. Design problem as case study, Rockwell Elementary.





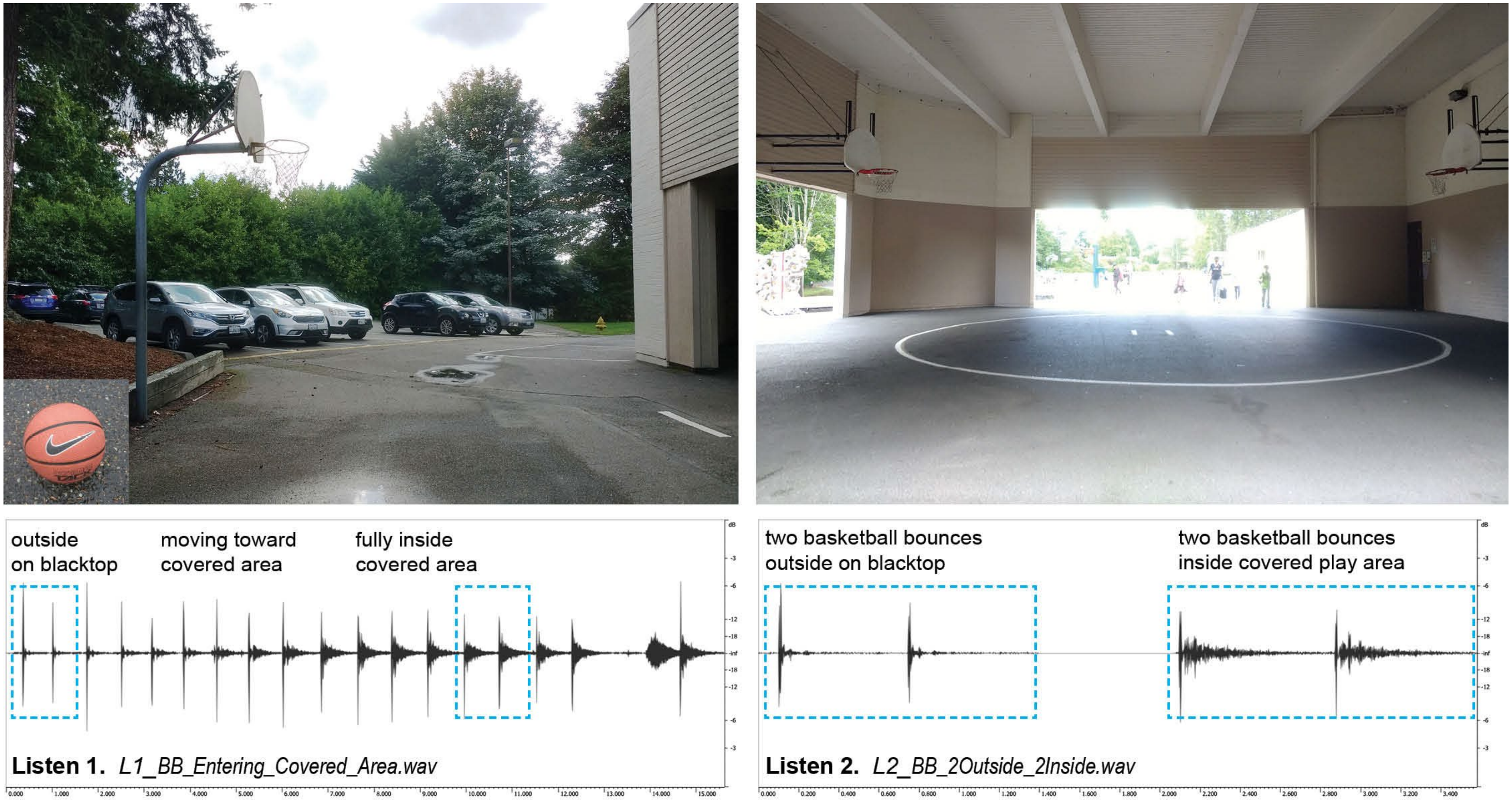


Figure 2. Sound experiences of existing covered play space at Rockwell Elementary. Site of **Listen 1-3** (basketball & voice).

Listen 1. L1_BB_Entering_Covered_Area.wav (basketball)
Listen 2. L2_BB_2Outside_2Inside.wav (basketball)
Listen 3. L3_Voice_Echo_Rockwell.wav (voice)

Sound is an important part of the experience of a space and it affects our well-being. These recordings made at the covered outdoor play space at Rockwell Elementary illustrate the importance of sound to how people the experience a space. The architectural characteristics of this covered play area combine to produce a dramatic effect. However, it is an unintentional consequence of the geometry of the space and the finish materials, not an effect crafted to enhance the play experience. Listen to what happens to the sound generated by the dribbling of a basketball on an open court and then within the covered play area (Listen 1 & Listen 2). Then listen to what happens to the sound of my voice inside the covered area (Listen 3). This is just one basketball and one voice and the acoustic experience is loud and reverberant. What would it be like with twenty or more children playing there because they want to avoid the rain during recess?

Look at the waveform images to see what happens to the sound produced by the basketball bounces in the two conditions. Comparing the waveforms, you can see that the sound level is greater and lasts longer when dribbling the basketball inside the covered area than outside (there is more black area). The sound energy of the basketball doesn't die off as quickly in the covered area as it does outside because the covered area captures the sound energy and bounces it around with reflections off the hard surfaces. The energy adds up, and it gets loud in there.

Clearly the acoustic experience was not taken into consideration at the time of design (1981). The covered play space does provide a dry place to play out of the rain, but it is not always the best play environment. Sometimes it is too loud for children to play there comfortably. This is especially true for kids with sensory issues or kids who are tired kids as well as for kids who react poorly to overstimulation.

Architects already design for experiences with light (daylighting, task lighting, variety) because it is integrated into their design process. They have tools and workflows that help them model, test, and analyze using both quantitative and qualitative data. Similar attention to the acoustical experience is vital to the experience of students and teachers as well as their health and safety, but it is not yet integrated into the architect's workflow.

Acoustics is complex and typically the realm of acoustic consultants, but with the right knowledge and mindset and the right tools in their toolkit, the design team can ask questions and help develop rich sound experiences for students and teachers. This thesis explores some methods and tools to help bridge the gap, adding preliminary acoustic design methods and tools to the architect's toolkit so that they can be more involved in the acoustic design process and explore similar questions about the acoustic qualities of a space to the questions they currently address about lighting and energy. For example, Figure 3 shows quantitative data for sound pressure level (loudness) and speech intelligibility (STI) displayed as heatmaps on a plan view, connecting numerical data to what a person would experience in the space, such as quieter and noisier areas, in other words, the acoustic microclimates. In collaboration with experts, architects can start to ask more and better informed questions that help them design more positive acoustic experiences and better performing buildings.

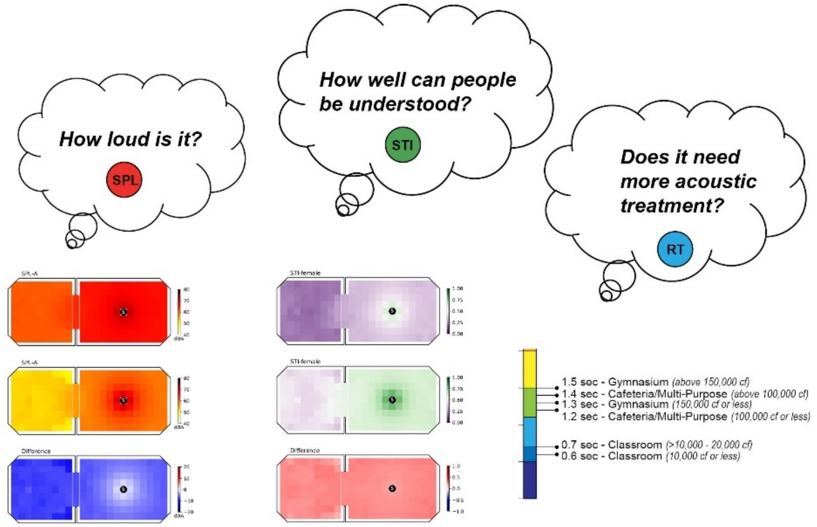


Figure 3. Questions architects and designers can ask about acoustics and quantitative data that can help answer them.

1.

Experiencing sound

Architects are most facile at designing spaces based on the sense of vision, but they would be well advised to design for the sense of hearing as well. Sound is an immersive experience that affects the body and the mind. How a space sounds plays a large role in the mood or atmosphere of a place. The acoustic properties of a space can have a significant effect on how a place feels, contributing to whether it is perceived as a pleasant or unpleasant place to be. People's comfort is affected if a room is too loud, too reverberant, has echoes, or distorts sound in some other way. Architects typically treat sound and noise as problems to be solved rather than design opportunities. When the stakes are high enough they call on acoustic consultants to solve technical problems of sound levels and acoustic performance. The performing arts center at a high school is carefully crafted to enhance the listening experience, but the acoustic experience of the cafeteria is neglected.

Phenomenology and sound

Before we dive too deeply into a purely technical approach to acoustics, one that relies on measurements and numeric quantification, please keep in mind that numbers alone do not address the fundamentally embodied experience of how people receive and respond to sound. Philosophers and thinkers in the tradition of phenomenology view the body and the body's perception through the senses as essential to the experience of place and emotion. The key phenomenological experience for this study is the phenomenology of the sense of hearing and how sound affects the body. Artists whose medium is sound also provide insight into how people experience sound. The examples and frameworks considered deepen the understanding of how sound is experienced and how it is tied to memory, mood, and positive/negative bodily responses. After all, health is fundamentally a bodily experience.

Hearing and listening are richly layered experiences that change dynamically moment by moment, independent of whether we are actively listening to human speech, music, sounds of nature, or sounds from manmade sources. In addition, there are inevitably other sounds present that are not the primary focus of our attention, and our attention may shift focus between the sounds at any point.

Indoor assembly places in use

Consider a conversation taking place in an indoor public place. During the conversation, we listen to the people we are talking to, but there are usually other people nearby having their own conversations. Add to those other conversations the sounds of people laughing, coughing, shifting in their chairs, turning pages, walking around or climbing stairs, doors opening, doors slamming shut, phones ringing, laptop keys clacking, mugs clinking onto tables, coffee machines whirring, refrigerators whining, air blowing, and many more incidental sounds. All of these sounds, the spatial configuration, and the material properties of the space combine together to create the sounds we hear and the atmosphere and experience of a place. The surrounding sound environment is the backdrop for our conversations, phone calls, lunch breaks, studying, reading, people watching, and daydreaming.

The three listening examples below illustrate some sound environments of indoor public places just described. Listen 1.1 and Listen 1.2 were recorded at Gould Hall Court (University of Washington, College of Built Environments) at two different times, the first relatively quiet and second quite active. Listen 1.3 was recorded at Shorewood High School Commons (Shoreline WA), moderate activity level with about twenty people present.

Listen 1.1.	L1-1_Gould_Court_91.wav	(relatively quiet)
Listen 1.2.	L1-2_Gould_Court_98.wav	(active)
Listen 1.3.	L1-3_Shorewood_Commons.wav	(moderate)

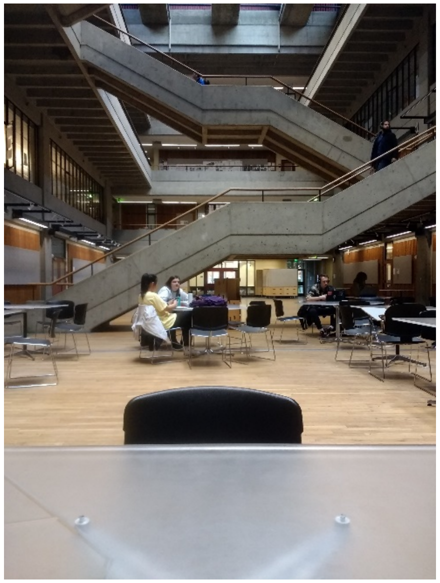


Figure 1.1. Gould Court, site of **Listen 1.1** & **Listen 1.2**.

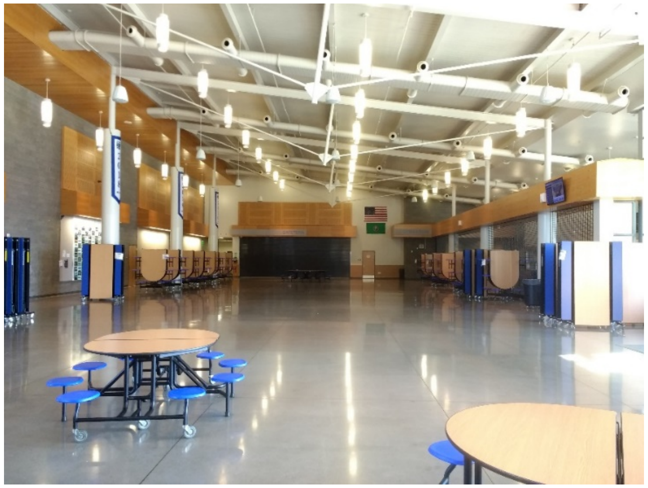


Figure 1.2. Shorewood High Commons, site of **Listen 1.3**.

These three examples of the sounds of indoor public places in use by real people illustrate that the same basic situation can be a very different experience and invoke quite different moods and emotions in people. For example, imagine that you were to start a new conversation in the relatively quiet Gould Court. It would be easy for you and your conversational partner to hear each other, but your conversation might disturb someone else who was reading or studying in the formerly quiet space, and that would feel awkward.

Now imagine you were to start a new conversation in the active Gould Court. You and your conversational partner would have to speak up and listen carefully to be able to hear each other, but because your conversation would be only one of many noisy activities it probably would not change the character of the sound environment very much. People reading or studying there are probably already wearing headphones to block out the sounds around them, so your conversation is not likely to disturb them. Other people who were in Gould Court when it was relatively quiet may have left once their tasks were no longer compatible with the more active environment. These examples illustrate that depending on the task you were engaged in and your personal preference and/or tolerance for sounds, you could either feel comfortable or extremely uncomfortable in a relatively quiet Gould Court or in an active Gould Court. It could be a healthy environment for you, or an unhealthy one, and your body and your emotions will let you know.

Terminology

“Sound is when you mow your lawn, noise is when your neighbor mows their lawn, and music is when your neighbor mows your lawn.”
- Arjun Shankar, acoustic consultant[8]

Up to this point I have freely used the terms *sounds*, *conversations,* and *noisy activities* in my descriptions, but I have deliberately held off using the terms *signal*, *noise*, *speaker* and *listener* even though they are common terms used in acoustics and linguistics to describe the priority of sounds and the roles of participants in a conversation. *Sound* is a relatively neutral term, while *signal* indicates the high priority sound, the message, the focus of attention. *Noise* is sound that interferes with the signal, the unwanted sound, the low priority sound. *Speaker* and *listener* seem clear enough, but people trade off the role of speaker and listener throughout a conversation, and they can even be both speaker and listener simultaneously. The terms *signal/noise* and *speaker/listener* all presuppose a specific point in time and an individual with a

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[8] (Bosker 2019)

specific point of view or focus of attention. The terms can be hard to apply to real-world examples because people shift their listening priorities or judgments frequently.

Perhaps additional terminology used by artists and scientists can bring greater clarity to our understanding of experiencing sounds. Pauline Oliveros, a composer and activist, highlighted the difference between *hearing* and *listening* as it relates to attention and experiencing sound. Oliveros advocated for "deep listening" as a way to explore "the difference between the involuntary nature of hearing and the voluntary, selective nature – exclusive and inclusive — of listening." [9]

The sound artist Vanessa Tomlinson categories sounds not as *signal* and *noise* but rather as a three-way distinction between *intentional sounds*, *interruptive sounds*, and *masking sounds*.[10] This three-way distinction is a more experiential way of looking at sounds that acknowledges people's changes in attention and listening behavior. Intentional sounds are the focus of attention (like signal), while interruptive sounds and masking sounds are more specific than the single category of noise. Interruptive sounds grab our attention in an unpleasant and often involuntary way (they become foregrounded for a time whether we like it or not), while masking sounds interfere with hearing the intentional sounds that we would like to listen to. Tomlinson credits the listener as most often making the decision about what is most important to be heard, the *listening priority*, out of what is available to be heard, the *listening environment*. In other words, the listener chooses what to listen to and when to listen.

Sounds and environment

Due to its physical properties, sound interacts with the environment and is shaped by the environment, and our ears and brains are highly sensitive to these details. Sounds dissipate quickly in an open field because there is nothing to reflect the sounds back to a listener. Walls, ceilings, and floors made of hard, reflective materials reflect sounds back to a listener, possibly causing an echo or a distortion of the sounds depending on the geometry of the space. Soft or absorptive materials capture some of the sound energy rather than reflecting it, and irregular or convex shapes distribute the sound energy.

Sound is an immersive medium that surrounds us whether we

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[9] (Center for Deep Listening at Rensselaer n.d.)
[10] (Tomlinson 2019)

like it or not. And hearing is a powerful sense of perception. Hearing and listening, like vision and looking, have the power to inform us about many details of our environment if we attend to the messages. Sound can reach us from distances further than we can see, and it can warn us that someone is approaching from behind and how fast. Sound reinforces the experiences of interior and exterior, enclosed and open, active and still. Sounds can contribute to feelings of pleasure or disgust.

Typology of listening experiences

Sound artist Vanessa Tomlinson also outlines a typology of musical listening experiences based on listeners having various levels of control over their ability to choose when to listen and what to listen to. According to Tomlinson, the three types of listening environment are the "Theater of Listening," the "Museum of Listening," and the "City of Listening."[11] Tomlinson explains that listeners either follow the typical concert conventions of sitting in their assigned seat or choose a more personal experience by moving through a space to suit themselves. She says, "Reflected in these listening activities is the way in which humans navigate through their listening environments, making decisions to physically go towards or away from sounds." These choices reflect their listening priorities with respect to their listening environments. This listening typology transfers well to non-musical listening experiences as well and could have been written to describe a large assembly space at school.

Tomlinson explains the "theater" as the canonical performance for an audience. A stage marks what is to be listened to, the concert hall is designed to enhance the sound of the event, and listeners stay in their seats for the entire performance. The "museum" offers a variety of performances that the listeners can choose amongst. Listeners stay for as long or as short a time as they wish, and listeners are free to move around the venue during the event to tune their personal listening experience for content, volume, and proximity to the performances. The "city" listening experience is an even more choose-your-own-adventure style of listening experience. The museum concept of listening is a powerful concept, giving people agency and control over their listening experience. Deliberately creating acoustic microclimates within a larger assembly space would help people personalize their listening experience.

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[11] (Tomlinson 2019)

Takeaways

“Memory attaches itself to sites, whereas history attaches itself to events.” – Pierre Nora[12]

Pauline Oliveros teaches us that when we pay attention to sounds, we remember them better, and we build memories of that sound, in that place, and in that time. She commends us to pay attention to the beautiful sounds of the world.[13] Elaine Scarry, American essayist, literary critic, and professor of English, argues for the value of beauty in the world and its role in stimulating perception and alertness.[14] These thinkers inspire us to use what we know as beautiful in our designs of places for people, including in the auditory realm. We can’t see the beauty of acoustics, and it is hard to see on plans, but designers need to explicitly design for acoustics in schools, not just leave it to chance or hand it off to experts.

The school environment has strong components of both involuntary hearing of extra sounds and listening for instruction. It is important that designers seek ways to nurture children’s bodily experiences as well as their minds during the school day. Students and teachers as moving away from the “theater” style sound experience (students as audience in their seats listening to the teacher) more toward a “museum” style of interaction in which students move around to work or visit with other students in the classroom or at lunch. Designers should strive to include design strategies such as acoustic microclimates that provide students and teachers more control and personal choice during the day, especially during social activities such as lunch and other group experiences.

It is time for architects to move beyond the current approach of “do no harm” acoustics to a more ambitious goal of “acoustic enhancement of well-being.” This is not a new idea,[15] but in this ever noisier world it becomes more urgent that children and adults alike understand that there are sounds to listen to and enjoy in the world, and that architecture affects the sonic experience of space. It is time to tune in to the acoustic dimension of design and embrace an attitude of “acoustic delight,” to paraphrase Lisa Herschong’s

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[12] (Nora 1989)

[13] (Oliveros 2016), (O’Brien 2016)

[14] (Scarry 2001) “It is as though beautiful things have been placed here and there throughout the world to serve as small wake-up calls to perception, spurring lapsed alertness back to its most acute level. Through its beauty, the world continually recommits us to a rigorous standard of perceptual care; if we do not search it out, it comes and finds us.” *On Beauty and Being Just,* p. 81.

[15] (Rasmussen 1962), *Experiencing Architecture;* (Pallasmaa, The Eyes of the Skin: Architecture and the Senses 2012)*;* (Erwine 2017)*, Creating Sensory Spaces*

concept of “thermal delight.”[16] We can incorporate sound in interesting ways into school spaces such as sound gardens. We can pay attention to the sound footsteps make on different types of flooring in different size rooms, and use that sound detail in the design of an entry sequence or a quiet restful place.[17] We can design spaces where people can hear each other well for learning and for enjoying social interactions. We can design spaces where people find acoustic respite and acoustic delight. We just need to know more about it and make it a priority in our designs.

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[16] (Herschong 1982)

[17] (Rasmussen 1962); (Pallasmaa, The Eyes of the Skin: Architecture and the Senses 2012); (Erwine 2017)

2.

Acoustics in classrooms and learning spaces

Disciplines with expertise in acoustical requirements of schools
Acoustic standards & acoustic metrics
Research methodologies
Takeaways

Chapter 1 focused on the experience of sound and the importance of designing for acoustic comfort and delight. Chapter 2 is a technical approach to acoustics as it applies to speech communication and best practices regarding acoustics in schools. This chapter describes key acoustic measures and metrics, numeric quantification, and research methodologies. All of the measures and metrics try to quantify what a good acoustic environment is and how well people can understand each other speak and how well they can learn in different acoustic environments.

Disciplines with expertise in acoustical requirements of schools

Several disciplines and a wide range of expertise relate directly to the acoustic requirements of school classrooms and core learning spaces, and the literature reflects those different approaches. The main disciplines are architecture and architectural/room acoustics, psychoacoustics (the perception of sounds), speech communication, and education. The disciplines have different research approaches for how to define and measure high quality acoustics in school learning spaces but they have a common goal of sound not being an impediment to learning and teachers do not having to strain their voices to be heard. Architectural acoustics measures room responses to sound (reverberation time, for example), while the fields of speech communication, psychoacoustics, and education, measure how people respond to sounds. They measure how well people understand a spoken message (speech intelligibility) or how well they perform on certain tasks under different sound conditions. They also investigate how sound affects concentration/distraction, comfort/discomfort, and vocal damage (speech pathology).

Acoustic standards & acoustic metrics

Acoustic metrics are quantifiable data that are collected, calculated, or generated to describe the acoustic characteristics of a room or environment. Acoustic standards are codified requirements to protect human health and establish good learning environments in schools. Compliance with acoustic standards are verified with quantifiable measurements of built projects in the real world. Many of these metrics can also be modeled or estimated to guide the design process. In the United States the national standard is ANSI/ASA standard S12.60 Parts 1 & 2.[18] These national acoustic standards set requirements for new construction and provide guidance for remediation of older schools. In Washington State, state-assisted major school construction projects are also required to meet a green building standard, either the Washington Sustainable Schools Protocol (WSSP) or the Leadership in Energy and Environmental Design (LEED) standard, which also include acoustic requirements.[19]

There are two acoustic standards that are requirements for schools:

- Requirement 1: 35 dBA is the maximum allowable background noise level in a core learning space. (See Figure 2.1.)
- Requirement 2. Classrooms must have reverberation times of 0.6 seconds or 0.7 seconds, depending on the size of the classroom. Washington Sustainable Schools Protocol also has Improved Acoustic Performance criteria for gymnasiums and cafeterias. (See Figure 2.2.)

To understand these two requirements we will have to understand background noise level and how to measure it as well as reverberation time and how to measure it.

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[18] (Acoustical Society of America 2015), (Acoustical Society of America 2014), (Acoustical Society of America 2015), (Technical Committee on Architectural Acoustics of Acoustical Society of America 2003), (Technical Committee on Speech Communication of the Acoustical Society of America 2002)

[19] (The Collaborative for High Performance Schools (CHPS) 2018)

Requirement 1.

35 dBA is the maximum allowable **background noise level*** in a core learning space (classroom, gymnasium, commons).

Use NC-35 standard, per WA code.

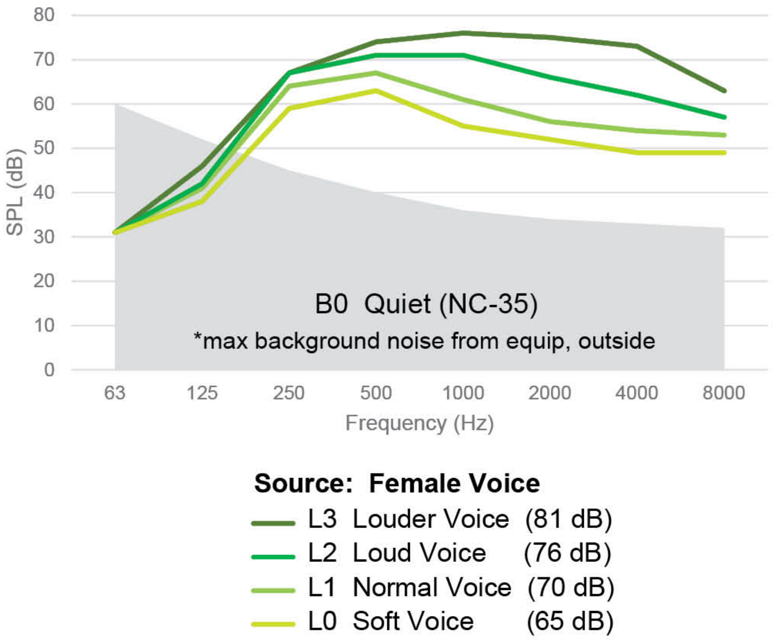


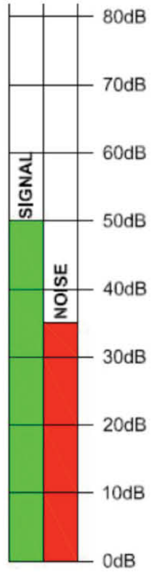
Figure 2.1. Acoustic standards: Background noise level requirement. Data on left shows the NC-35 curve for background noise compared to four levels of vocal effort.[20]

SPL *How loud is it?*

STI *How well can people be understood?*

A signal-to-noise ratio of at least 15 dB is required for good **speech intelligibility**.

50 dB (teacher) - 35 dB (noise) = 15 dB



67 dB Signal
Normal speaking voice
at 3 feet away

50 dB Signal
Teacher's normal speaking voice
at back of classroom

35 dB Noise
background noise level

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[20] See Appendix C for data values and sources. Signal-to-noise graphic and information from (Acoustical Society of America 2015) "Classroom Acoustics for Architects".

Requirement 2.

Classrooms must have RTs of 0.7 sec or 0.6 sec.

ANSI recommendations and WSSP points for gyms, cafeterias, and commons depend on the volume of the room (in cf).

Improved Acoustic Performance
WSSP IEQ4.1
(1 point each for Gym/Cafeteria)

Minimum Acoustic Performance
WSSP IEQ4.0
(Required for classrooms)

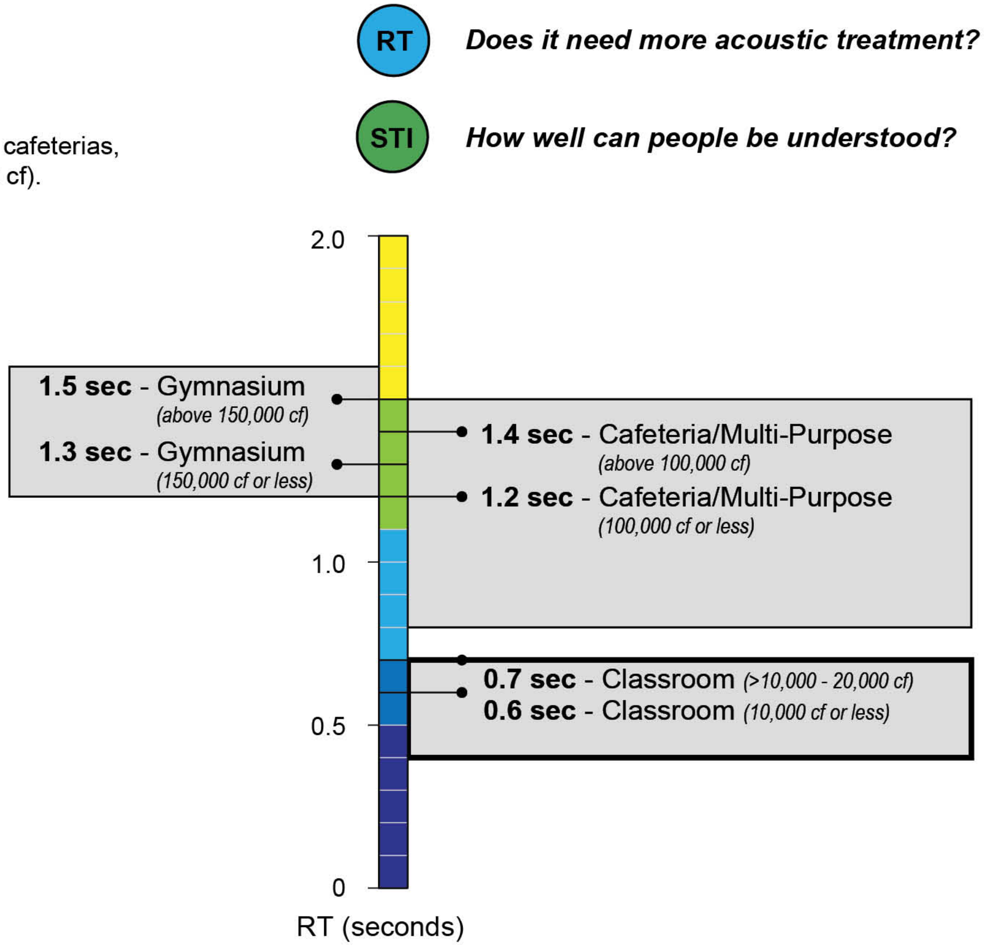

Figure 2.2. Acoustic standards: Reverberation time requirements. The classroom requirements are both ANSI and WSSP requirements, and the gray box surrounding them includes ASA recommendations to architects of suitable RTs. Gymnasium WSSP improved acoustic performance are shown on the left of the chart. Cafeteria targets are shown on the right of the chart. The gray box surrounding them respectively includes ASA recommendations to architects.[21]

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[21] (Acoustical Society of America 2015) “Classroom Acoustics for Architects”; (The Collaborative for High Performance Schools (CHPS) 2018)

Background Noise and Sound Pressure Level (SPL)

To understand Requirement 1, we need to know what background noise means and how sound pressure levels are measured. Background noise comes from environmental noise outside the school (road noise, airplanes, mowing, playground, etc.) as well as noise from inside the school (HVAC equipment, plumbing, mechanical rooms, other building equipment, and noises from adjacent spaces such as corridors). Background noise is measured as a sound pressure level (SPL) in decibels (dB) by a sound level meter. Decibels are the units of a logarithmic ratio of a given sound pressure to a reference sound pressure. Changes of 1 dB are imperceptible to the human ear, a 3 dB change is the minimum perceptible difference, and a 5 dB change is clearly noticeable.[22] A 10 dB change is a substantial change that is perceived as twice as loud, for example the increase from 50 dB to 60 dB or from 60 dB to 70 dB. A 20 dB increase equals a quadrupling of loudness.[23]

Sound pressure level is also affected by the distance between the source and receiver and by the number and intensity of sound sources. Doubling the distance between a sound source and a listener results in a 6 dB decrease in sound pressure level, and halving the distance results in a 6 dB increase.[24] To find calculate the combined dB of individual sound sources, the decibels have to be added logarithmically or approximated using decibel addition tables. For two identical sound sources, the sum is 3 dB more than the sound level of a single source, a minimally perceptible difference. For three identical sources add 5 dB, for 10 identical sources add 10 dB (a doubling in loudness), for 15 identical sources add 12 dB, for 20 identical sources add 13 dB, for 50 identical sources add 17 dB, and for 100 identical sources add 20 dB (a quadrupling in loudness). For non-identical sound sources, the resultant dB depends on the difference between the two levels to be added. For a difference of 1 dB, add 3 dB to the higher level. For a difference of 2-4 dB, add 2 dB to the higher level. For 5-9 dB difference, add 1 dB to the higher level, and for a difference of 10 or more, add 0 dB to the higher level.[25] Figure 2.3 shows the sound pressure level of common sounds and the subject impression of loudness from faint to painful. Figure 2.3 also shows a sample of the

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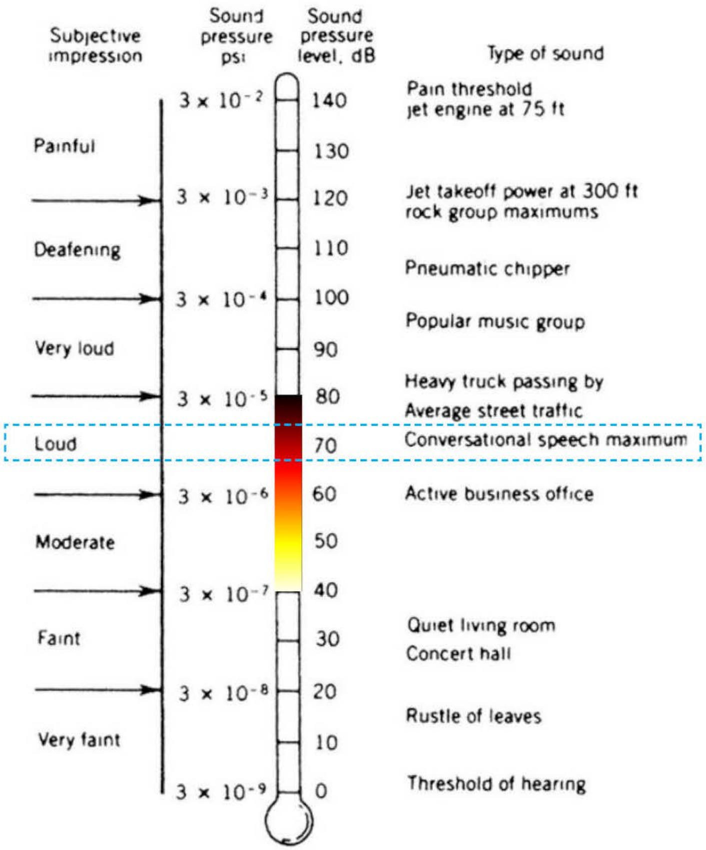
[22] (Mehta, Johnson and Rocafort 1999)

[23] (Doelle 1972, 15-16)

[24] (Mehta, Johnson and Rocafort 1999, 18, 22)

[25] (Mehta, Johnson and Rocafort 1999, 14-15)



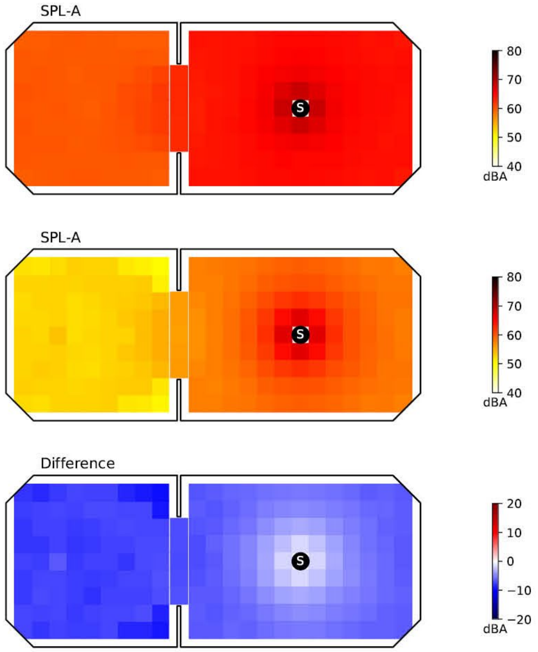
From William J. Cavanaugh "Acoustics-General Principles" in Encyclopedia of Architecture: Design, Engineering, and Construction, ed. Joseph Wilkes, Wiley & Sons, Inc.1988.

Figure 2.3. How loud is it? graphic from Cavanaugh. Color code overlay corresponds to dBA scale used to display case study simulation results (see Chapter 5 for details).

SPL ***How loud is it?***

80+ dBA can cause hearing damage if people are exposed for too long

70+ dBA can be perceived as "annoyingly loud" to some people



Washington State code limits sound exposure levels.[26]

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[26] Sound exposure to levels 80+ dBA is limited by WA state code.

ANSI/ASA S12.60-2010 specifies that the greatest allowable background noise level in a classroom is 35 dBA. Mehta explains that dBA is a dB value as weighted for sound frequency bands to adjust for different sensitivity of human hearing at different frequencies.[27] To achieve the 35 dBA maximum background noise value inside a classroom requires noise control for the building.[28] Washington state building code specifies the NC-35 standard. The noise control component of the standard provides direction based on the measured external noise level and the internal noise sources. It provides direction on the kinds of assemblies to be used for the building envelope to achieve adequate noise control and determines whether natural ventilation by operable windows in the classroom is allowable. It also provides direction on the kinds of assemblies to be used for internal walls, ceilings and floors to achieve appropriate noise separation for building internal noise sources.

A classroom background noise level of 35 dBA means that a teacher talking with a normal voice is loud enough to the heard over the background noise level. A normal speaking voice is about 67 dB at 3 feet and reduces to about 50 dB at the further parts of the room as the sound energy reduces with distance from the source.[29] At 50 dB, with a maximum background noise level of 35 dB, the teacher's voice is at least 15 dB higher than the background noise, and that 15 dB difference is generally accepted as a good signal-to-noise ratio to provide good speech intelligibility,[30] but some research studies find that is not universally true.

The signal-to-noise ratio or the speech-to-noise ratio (SNR) refers to the difference between the speech level and the noise level. Since both speech levels and noise levels are expressed in decibels, speech-to-noise ratio is also expressed in decibels. In the example above, with speech at 50 dB and noise at 35 dB, the signal-to-noise ratio is 15 dB.

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[27] (Mehta, Johnson and Rocafort 1999) p. 28-29

[28] (Long 2014, 2006)

[29] (Acoustical Society of America 2015)

[30] (Acoustical Society of America 2015)

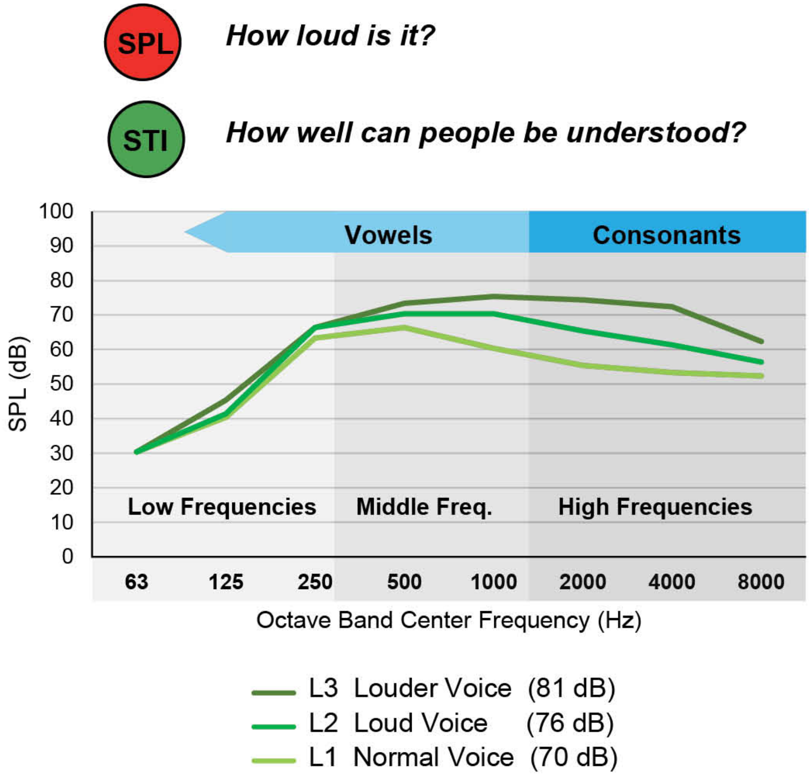

Figure 2.4. Speech intelligibility: speech signal. Vowels and consonants energy levels by frequency band.[31]

Figure 2.4 shows the sound pressure level (SPL in dB) for vowels and consonants at octave band center frequency (in Hz). The octave band center frequencies (Hz) are the way that signals and noise are describe in acoustic analyses and calculations. The y-axis shows the sound pressure level (SPL) which shows how much energy is present at the different frequencies.

The meaning of the speech signal is carried predominantly in the middle and high frequency bands. [32] The values for 500 Hz, 1000 Hz, and 2000 Hz are the most important in calculations such as Speech Transmission Index (STI) that indicated how well speech would be understood by a listener in the room.

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[31] Figure based off a figure in (Acoustical Society of America 2015) “Classroom Acoustics for Architects”. Voice spectrum data from Pachyderm Acoustic values (see Appendix C).

[32] (Mehta, Johnson and Rocafort 1999); (Long 2014, 2006); (Acoustical Society of America 2015)

Reverberation Time (RT or T_{60})

The second acoustic criterion set by ANSI/ASA S12.60-2010 is the maximum reverberation time (Figure 2.2). "Reverberant" is a term used to describe a space in which sound energy reflects around a space instead of being absorbed quickly. Reverberation time refers to the time that it takes for an impulse noise such as a hard clap to die down to inaudible (to decay by 60 dB). The maximum allowable reverberation time for classrooms is 0.6 seconds or 0.7 seconds for larger classroom. Speech becomes less intelligible with reverberation times longer than 0.6 seconds because clearly understandable speech depends upon being able to distinguish each sound and syllable from the next. Longer reverberation times means longer times that the speech sounds persist as sound energy, and those older sounds begin to interfere and mask the understanding of the current speech sounds.

The WSSP criteria set requirements to achieve "improved acoustic performance" in gymnasiums, cafeterias, and multi-purpose rooms of different volumes. Suitable reverberation times are determined empirically, informed by studies of student performance on various tasks.[33]

The reverberation time component of ANSI/ASA S12.60-2010 provides direction on the surface finishes within the classroom with respect to how much they absorb or reflect sound and the overall volume of the room. The exact materials and their distribution are left to the design team and acoustical consultant. Some basic rules of thumb are provided in "Classroom Acoustics for Architects"[34], such as providing sound absorption equal to the floor area. This absorption can be on the ceiling, but it need not all be in the ceiling. Appendix E of that publication gives suggested guidelines for absorptive treatments in school classrooms and gymnasiums.

Absorption (A) and the Sabine equation

Developed in 1895 by Wallace Clement Sabine, the Sabine equation defines the relationship among room volume, reverberation time, and total absorption provided by room surface materials.

$A_t = 0.05\ V/RT$ and $RT = 0.05\ V/A_t$

$$\mathrm{RT} = \mathrm{T}_{60} = \frac{0.05\ \mathrm{V}}{\mathrm{A}_\mathrm{t}}$$

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[33] (The Collaborative for High Performance Schools (CHPS) 2018)

[34] (Acoustical Society of America 2015)

Total room absorption (A_t) is inversely related to reverberation time (RT) and directly related to room volume (V) in cubic feet as given by the Sabine equation $A_t = 0.05\ V/T_{60}$. Total absorption includes absorption provided by room boundary surfaces, people, furniture, air, etc. Given one of A or RT, the other can be computed.[35] Detailed examples of RT calculations using Sabine equation with absorption coefficients are given in Chapter 3.

Speech Intelligibility & Task Performance Metrics

Various metrics are used to quantify speech intelligibility and task performance in speech communication, psychoacoustics, and education. The gold standard measure of speech intelligibility is Articulation Index (AI). The articulation index of a room can only be determined in an existing space with live talker and listeners. The procedure for determining AI of a room is a field test with a live talker and a few listeners. The talker speaks words or sentences and the listeners write down what they hear. The test material must contain all critical speech sounds. The percentage of correctly identified responses is the articulation index.[36]

Two of the most common metrics for speech intelligibility are computed based on the signal and the background noise. They are Speech Transmission Index (STI) and Rapid Speech Transmission Index (RASTI). Speech Transmission Index (STI) is an objective measurement that is a predictor of how the intelligibility of a speech signal is affected by the background noise level and reverberance. A Speech Transmission Index (STI) or Rapid Speech Transmission Index (RASTI) of 1.0 means the speech signal is perfectly intelligible and has no speech privacy. An STI of greater than 0.8 is excellent intelligibility and between 0.65 and 0.80 is very good intelligibility. An STI of less than 0.5 is fair to bad intelligibility but has better speech privacy. STI can be estimated in models or measured in existing spaces.[37]

Definition (D_{50})

Definition is a measurement of the early-to-arrive sound energy (direct sound or early reflection sound arriving in the first 50 ms) to the total sound energy. This measure correlates with speech intelligibility computation such as STI.[38]

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[35] (Mehta, Johnson and Rocafort 1999, 428), (Sato and Bradley 2008)

[36] (Mehta, Johnson and Rocafort 1999, 309)

[37] (Astolfi, Bottalico and Barbato 2012), (Sato and Bradley 2008), (Ermann 2014), (Siebein, Gold, et al. 2000)

[38] ISO 3382 Standard

Research methodologies

The research techniques used in school acoustics research depend upon the focus of the researcher. Most of the research papers in my survey were correlational research; they correlated acoustic measurements with survey data collected in actual classrooms. The next largest group of papers involved experimental research that tested subjects in controlled noise environments rather than in actual classrooms. The smallest set of research papers involved simulation research or other computational modeling.

The research studies involved many variables: unoccupied vs. occupied classrooms, room geometry and surface finishes, background noise level (observed vs. controlled), background noise level / ambient noise level / classroom noise level, student age/grade level, task complexity, classroom activities, and number of talkers.

Correlational Research – Field Measurements of Classrooms

Most of the research papers in my survey involved measurements and observations of actual classrooms, both occupied and unoccupied. Correlational studies are very important for connecting field observations with computational models and for verifying whether adopted acoustic standards are meeting the needs of students.

Architectural acoustics oriented researchers measure unoccupied and/or occupied classrooms for sound level and reverberation time. Some of them make rules of thumb based on correlations between numerical metrics and architectural correlates of ceiling height, quantity of glazing, and presence of hard vs. soft materials.[39] For example, according to Siebein et al, ceiling height should be limited to 9-12 feet or treated with extra absorption to control reverberation.

Professor of Acoustics Bridget Shield and her associates conducted a comprehensive survey of actual conditions in 185 unoccupied spaces in 13 secondary schools in England and found that newer schools complied with the new noise requirements for schools (similar to the ANSI requirements in the United States).[40] This large correlational study found significant correlations between many factors. They measured both unoccupied and occupied classrooms and were able to show that room height and the amount of glazing were related to the unoccupied reverberation time, and

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[39] (Siebein, Gold, et al. 2000), (Siebein 2004), (Shield, et al. 2015), (Sato and Bradley 2008), (Bradley and Sato 2008), (Aguilar and Tilano 2019)

[40] (Shield, et al. 2015)

that unoccupied acoustic conditions affect the noise levels occurring during lessons. Room acoustic parameters and STI were calculated from impulse responses captured on a sound analyzer. The data I found most compelling from this study compared to other similar studies was the categorization of the activities observed during lessons (lectures, group, quiet testing, one-on-one help). Lectures were 50% of the time, making it essential that the acoustic design enhances speech intelligibility throughout the classroom so that speech can be understood by all students. However, the classroom noise levels were highest during group work. They also demonstrated that the overall lesson noise is affected by both the unoccupied ambient noise level and the reverberation time; the higher the ambient noise level, the higher are the equivalent background noise levels during lessons. Similarly, the longer the reverberation time the higher are the lesson noise levels. These results demonstrate that measuring unoccupied classrooms inform the performance of occupied classrooms, and that controlling the background noise level and the reverberation time has a real effect on classroom noise levels.

Another especially strong correlational study comes from elementary classroom measurements in Ottawa, Canada. In a pair of studies, Bradley and Sato did linear regression analyses and mathematically modelled many acoustic parameters.[41] They found a predictable linear regression relationship between the total sound absorption for occupied classrooms and unoccupied classrooms and were able to calculate the absorption per child of 0.28 m^2. They create a mathematical model that suggests that the ideal RT for these young students is about 0.3 seconds rather than 0.6 seconds, with similar results from 0.2 s to 0.5 s. They also found evidence for the *Lombard effect*[42], the involuntary raising of the voice to improve the speaker's signal-to-noise ratio. Whitlock and Dodd also found evidence of the Lombard effect in their study.[43] They also found that a signal-to-noise ratio of 15 dB was not sufficient for the young students to perform well on the speech comprehension task. These findings that young students did not in fact perform well on tasks with the RTs and signal-to-noise ratios adopted in the acoustic standards

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[41] (Bradley and Sato 2008), (Sato and Bradley 2008)

[42] The Lombard effect is also referred to the cocktail party effect. Once the background noise level of other people talking reaches a certain level, people automatically raise their voices, talking louder to try to be heard above the background noise, which raises the background noise level.

[43] (Whitlock and Dodd 2006)

means that meeting a standard does not mean that a room can be classified as having high quality acoustics for all students. For my design problem in elementary school, this result makes it seem likely that young children will be especially vulnerable to not being able to understand other talkers the multi-talker gymnasium and cafeteria. For young students an appropriate reverberation time is probably much lower than even the WSSP improved acoustic performance criteria.

Experimental Research – Testing in Controlled Environments

Some of the research papers in my survey use experimental research to test speech intelligibility and task performance in controlled environments such as simulated classrooms or controlled noise environments using recorded stimuli with controlled samples of speech and noise. Some researchers simulate classroom conditions and vary the acoustic parameters of background noise level and reverberation time and measure student performance on certain comprehension or concentration tasks. From the performance of students in controlled conditions they make estimations or predictions of ideal criteria to be used as standards to ensure better classroom conditions.

Simulation Research and Computational Modeling

Simulation research was not well represented in my survey, but there were a few papers giving numeric models of predicted noise levels based on number of speakers and other factors. Sato and Bradley[44] established many different mathematical equations as predictions as discussed above, and Whitlock and Dodd[45] established a predictive mathematical model for the activity noise in a classroom based on the base voice level, the number of children speaking, the starting level for the Lombard effect, the volume of the classroom, and the reverberation time of the classroom.

Expert Opinions

One of the papers in my literature is based on result of a survey sent to teachers of students with autism.[46] The teachers all observed students covering their ears (97%). This behavior was interpreted as sound being a negative experience for these students at least some of the time.

A few of the papers present design guidelines in which experts sharing their observations of best design practices based on

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[44] (Sato and Bradley 2008)

[45] (Whitlock and Dodd 2006, 425)

[46] (Kanakri, et al. 2017)

professional experience.[47] Siebein et al provides ten ways to improve acoustics in schools after their comprehensive correlational study of 56 Florida classrooms that they believe represents 5000 similar classrooms in the state. Their suggestions include:

- carefully choose and plan the HVAC system because those contribute the primary noise to classrooms.
- limit the ceiling height to 9-12 feet or be prepared to add additional absorbent material to control reverberation
- provide sound-absorbing surfaces approximately equal to the floor area
- noisy rooms (above NC-40) require background noise controls as well as absorption control to reach acceptable speech intelligibility values (Rapid Speech Transmission Index)
- carpeting controls the noise of fidgeting (but could cause other problems)
- emphasize classroom furniture arrangements that reduce the distance between the teacher and the students such as sitting around a round table for a reading session and circling the teacher's chair for story time (only a 4 dB drop with an excellent STI of 0.82, compared to a 9 dB drop and a fair STI of 0.45 in standard lecture style seating
- select and design the overall site plan wisely to avoid excessive external environmental noise and avoiding acoustical "hot spots" of loud activities or busy corridors near classrooms
- design for good sound isolation between classrooms
- include consultants who have expertise in classroom acoustics.

The advice of experts based on professional experience is extremely valuable for setting and updating acoustic standards.

Takeaways

Classroom acoustics has been researched from many different perspectives – external noise control, optimal signal-to-noise ratio, optimal reverberation time for speech intelligibility, and actual classroom activity and internal noise levels. The basic room geometry and distribution of absorptive material for the conventional classroom are well documented. However, the ANSI/ASA standards that set the requirements for background noise and reverberation time and are best applied to the single-talker/lecture mode. The background noise level standard is set so that a teacher can be

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[47] (Siebein, Gold, et al. 2000), (Acoustical Society of America 2015), (Acoustical Society of America 2015), (Acoustical Society of America 2014)

heard above the background noise, but it specifically does not address background noise from students talking at the same time as the teacher or the multi-talker/collaboration mode of a classroom in which many people are talking at the same time. That is, extra speech within the classroom or learning space in not currently addressed by the standards, but it is extremely common. This extra speech noise within the classroom is beginning to be well documented, but there is not agreement on how best to compensate for this architecturally or with furnishings. There are conflicting opinions about whether adding more absorption is helpful or harmful.

It is very important to keep in mind who you are designing for because students are not all alike. Younger students have lower levels of mastery of the language and they understand language in a noisy environment less well than older students and adults.[48] Second language speakers also have different levels of mastery of the language than native speakers, and they to have more trouble understanding in noisy environments with high levels of background noise.[49] Children with hearing impairment also have more trouble understanding speech in noisy environments.[50] There are students on the autism spectrum who are more sensitive to noise and auditory stimulation. There are also individual differences in people who for various reasons are sensitive to noises.[51] Any of these factors can influence speech intelligibility in the classroom (and whether the 15 dB difference is great enough) or whether the room is too noisy to be able to concentrate on a task.

Although the results of many of these research areas have been incorporated directly into national design standards and guidelines, it is still the case that research studies frequently disagree on the exact numerical results (e.g. for reverberation time) that support good communication and good learning because students are individuals with individual needs. This means that meeting the acoustic standards for background noise level and reverberation time may not be as helpful for speech intelligibility as one might like. We can aspire to go beyond the minimum standards to improve the acoustic experience, especially for some student populations, including young elementary age children.

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[48] (Yang and Bradley 2009), (Bradley and Sato 2008)

[49] (Nelson and Soli 2000)

[50] (Crandell and Smaldino 2000)

[51] (Schnitta 2016)

3. Research study - Method 1, Sabine equation

Sabine equation for reverberation time
Effect of room geometry and ceiling materials on reverberation time
Test set: 24 gym/cafeteria room volumes with 6 ceiling types

As discussed in the introduction and in Chapter 2, reverberation time (RT or T_{60}) is measured in an existing room to determine compliance with an acoustic standard such as WSSP. Recall that the reverberation time is the time in seconds it takes for sound to decrease by 60 dB in a room. We also saw that reverberation time could calculated using the Sabine equation from knowing the total room volume and the total room absorption from surface materials. In this chapter we will take a deep dive into the Sabine equation and explore how to use it as a modeling tool to compare the predicted behavior of a set of rooms with controlled room dimensions and ceiling materials.

The idea that reverberation time was a quantifiable characteristic of a room originated with Wallace Clement Sabine, an American professor of physics at Harvard University[52]. Sabine was tasked with correcting a problem of unintelligible speech in a lecture hall at Harvard in 1895. Sound would persist in that room for over five seconds, making it impossible for most of a speaker's words to be understood. Sabine systematically added and arranged varying amounts of different absorptive materials to the room, especially cushions from a nearby theater. His solution to the problem of unintelligible speech added enough absorption to bring the reverberation time down to about one second[53]. By continuing his experiments and measurements in many rooms of many different types he determined an empirical relationship between reverberation time and room parameters. Thanks to Sabine's work, in addition to being measured directly in the field, reverberation time can also be calculated by the empirical formula called the **Sabine equation**:

$$\mathrm{RT} = \mathrm{T}_{60} = \frac{0.05\ \mathrm{V}}{\mathrm{A_t}} = \frac{0.05\ V}{\sum_{i=1}^{n}(S_i\alpha_i)}$$

T_{60} = reverberation time (seconds), the time it takes for sound to decrease by 60 dB in a room

V = volume of the room (cubic feet)

$\mathrm{A_t}$ = total absorption in the room (sabins)

$$= \sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{S_i}\alpha_\mathrm{i}) = \mathrm{S}_1\alpha_1 + \mathrm{S}_2\alpha_2 + \mathrm{S}_3\alpha_3 + \cdots + \mathrm{S_n}\alpha_\mathrm{n}$$

The Sabine equation is a numerical model of reverberation time. It is a function of two room parameters: room volume and room absorption. It is directly proportional to room volume V and inversely

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[52] (Mehta, Johnson and Rocafort 1999)

[53] (Long 2014, 2006)

proportional to total absorption in the room A_t. Increasing room volume raises RT and increasing the absorption in the room lowers RT. Total absorption is computed by adding up the contributions of every room surface based on the surface area and the material's absorption coefficient. The contribution of a surface is equal to the surface area multiplied by its absorption coefficient ($S_i\alpha_i$). An absorption coefficient of 0 means the surface is completely reflective, and an absorption coefficient of 1 means it is completely absorptive.

There are a few background assumptions or limitations to be aware of before using the Sabine equation. The Sabine equation assumes a perfectly diffuse sound field, which means that reverberation time does not change in space. In other words, there are no room modes or standing sound waves that amplify or diminish the sound energy at a specific frequency through wave addition. Because room modes are frequency dependent, perfectly diffuse sound fields can only exist in certain frequencies and not others. "Schroeder's frequency" tells us which frequencies are likely to set up standing waves based on the size of the room.[54] Specifically Sabine's equation is only valid for frequencies above Schoeder's frequency. Because these gymnasiums and cafeterias are quite large, Schroeder's frequency is quite low, and the Sabine equation is valid at the frequencies we are considering.

Now let us use the Sabine equation to calculate the reverberation time for the simple rectangular room shown in Figure 3.1. The room measures 20' x 100' x 50' and has distinct materials for the ceiling, walls, and floor. We use a spreadsheet to complete the calculations once we know the room geometry and the materials (see Figure 3.2).

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[54] (Long 2014, 2006)

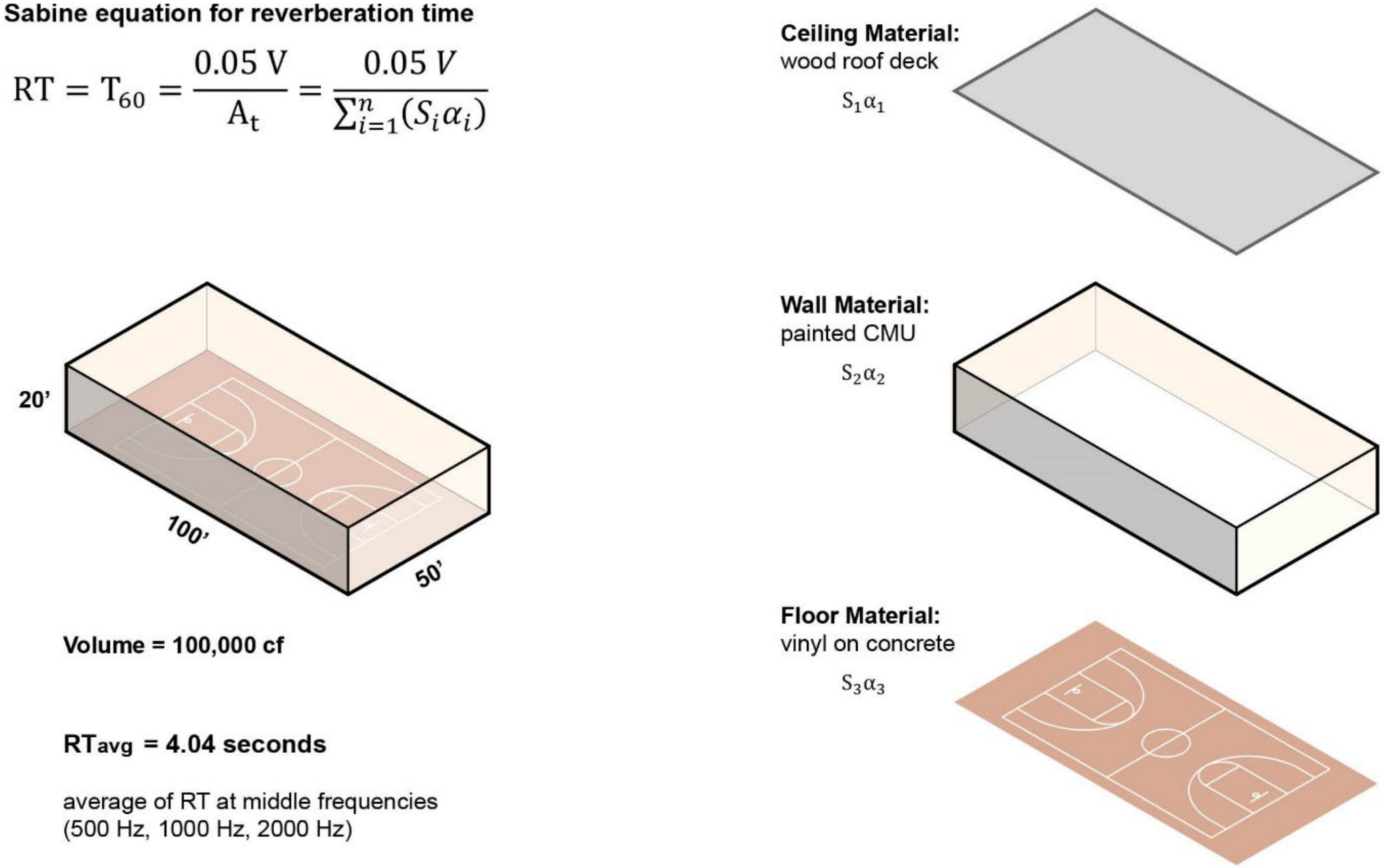
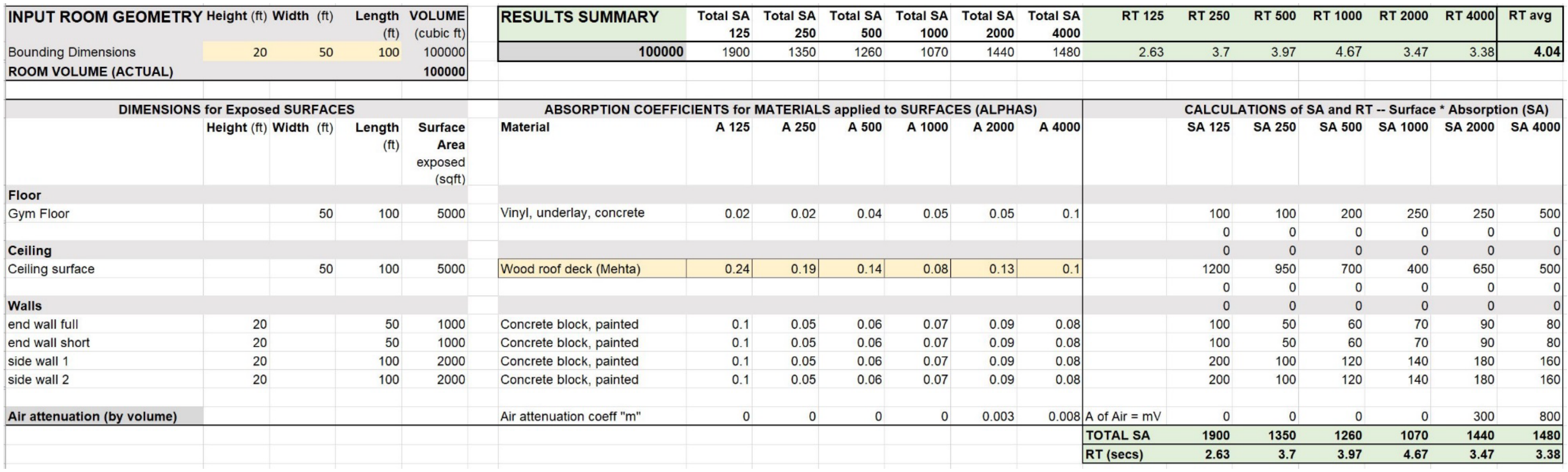


Figure 3.1. Calculating the average reverberation time for a simple rectangular room measuring 20’ x 100’ x 50’, a simplified version of a small gymnasium.

The first step in calculating the reverberation time with the Sabine equation is to determine the surface area in square feet for each of the three materials that appear in the room. As we see in Figures 3.1 and 3.2, for the ceiling, the surface area s_1 of wood roof deck is 5000 sf (100’ x 50’). For the walls, the total surface area s_2 of painted CMU is 6000 sf (2 x 50’ x 20’ + 2 x 100’ x 20’). For the floor, the surface area s_3 of vinyl on concrete is 5000 sf (100’ x 50’).



INPUT ROOM GEOMETRY	Height (ft)	Width (ft)	Length (ft)	VOLUME (cubic ft)
Bounding Dimensions	20	50	100	100000
ROOM VOLUME (ACTUAL)				100000

RESULTS SUMMARY	Total SA 125	Total SA 250	Total SA 500	Total SA 1000	Total SA 2000	Total SA 4000	RT 125	RT 250	RT 500	RT 1000	RT 2000	RT 4000	RT avg
100000	1900	1350	1260	1070	1440	1480	2.63	3.7	3.97	4.67	3.47	3.38	4.04

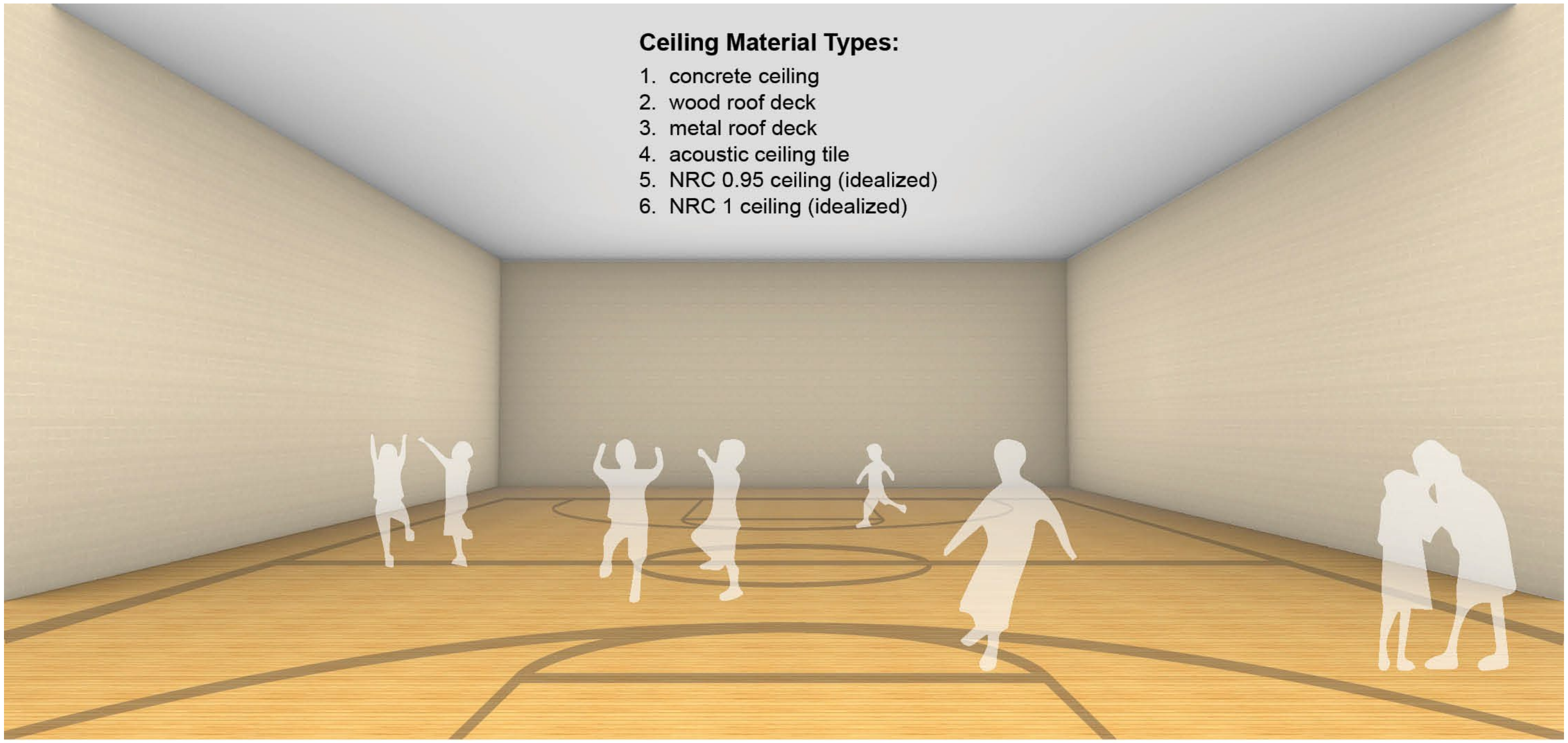
DIMENSIONS for Exposed SURFACES					ABSORPTION COEFFICIENTS for MATERIALS applied to SURFACES (ALPHAS)							CALCULATIONS of SA and RT -- Surface * Absorption (SA)						
	Height (ft)	Width (ft)	Length (ft)	Surface Area exposed (sqft)	Material	A 125	A 250	A 500	A 1000	A 2000	A 4000		SA 125	SA 250	SA 500	SA 1000	SA 2000	SA 4000
Floor																		
Gym Floor		50	100	5000	Vinyl, underlay, concrete	0.02	0.02	0.04	0.05	0.05	0.1		100	100	200	250	250	500
													0	0	0	0	0	0
Ceiling													0	0	0	0	0	0
Ceiling surface		50	100	5000	Wood roof deck (Mehta)	0.24	0.19	0.14	0.08	0.13	0.1		1200	950	700	400	650	500
													0	0	0	0	0	0
Walls													0	0	0	0	0	0
end wall full	20		50	1000	Concrete block, painted	0.1	0.05	0.06	0.07	0.09	0.08		100	50	60	70	90	80
end wall short	20		50	1000	Concrete block, painted	0.1	0.05	0.06	0.07	0.09	0.08		100	50	60	70	90	80
side wall 1	20		100	2000	Concrete block, painted	0.1	0.05	0.06	0.07	0.09	0.08		200	100	120	140	180	160
side wall 2	20		100	2000	Concrete block, painted	0.1	0.05	0.06	0.07	0.09	0.08		200	100	120	140	180	160
Air attenuation (by volume)					Air attenuation coeff "m"	0	0	0	0	0.003	0.008	A of Air = mV	0	0	0	0	300	800
												TOTAL SA	**1900**	**1350**	**1260**	**1070**	**1440**	**1480**
												RT (secs)	**2.63**	**3.7**	**3.97**	**4.67**	**3.47**	**3.38**

Figure 3.2. Calculating the average reverberation time for a simple rectangular room measuring 20' x 100' x 50'. This is the same small gym illustrated in Figure 3.1.

Each of these materials has a characteristic set of absorption coefficients ("alphas"), one coefficient for each of six frequency bands (125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz). There is also a small absorption contribution for air at 4000 Hz. Figure 3.2 shows the spreadsheet used to calculate the RTs based on this room geometry and these materials. The results summary section in green at the top of the spreadsheet shows the RT for each frequency and an average RT (for 500 Hz, 1000 Hz, and 2000 Hz). This is how to compute reverberation time with the Sabine equation.

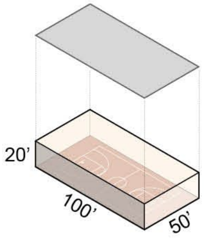
The computed average reverberation time for this room with a wood roof deck ceiling is 4.04 seconds, well above the recommended reverberation time for a small gymnasium. This room would need acoustic treatment in the form of added absorptive materials to fall within the ASA recommended range of 1.2 seconds to 1.6 seconds or to meet WSSP's improved acoustic performance requirement of a maximum reverberation time of 1.3 seconds.

The first part of this research study concerns the impact ceiling types on reverberation time, such as metal roof deck and acoustic ceiling tile. To that end we compute reverberation time for the same room with six different ceiling types, as seen in Figures 3.3 and 3.4.



Ceiling Material Types:

1. concrete ceiling
2. wood roof deck
3. metal roof deck
4. acoustic ceiling tile
5. NRC 0.95 ceiling (idealized)
6. NRC 1 ceiling (idealized)



Volume = 20' x 100' x 50' = **100,000 cf**

Ceiling Material: varies (1-6) $S_1\alpha_1$
(Wood roof deck is the existing condition of the case study school.)

Wall Material: painted CMU $S_2\alpha_2$

Floor Material: vinyl on concrete $S_3\alpha_3$

A_t = total absorption $= S_1\alpha_1 + S_2\alpha_2 + S_3\alpha_3$

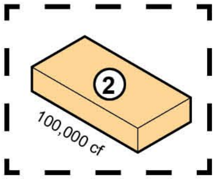
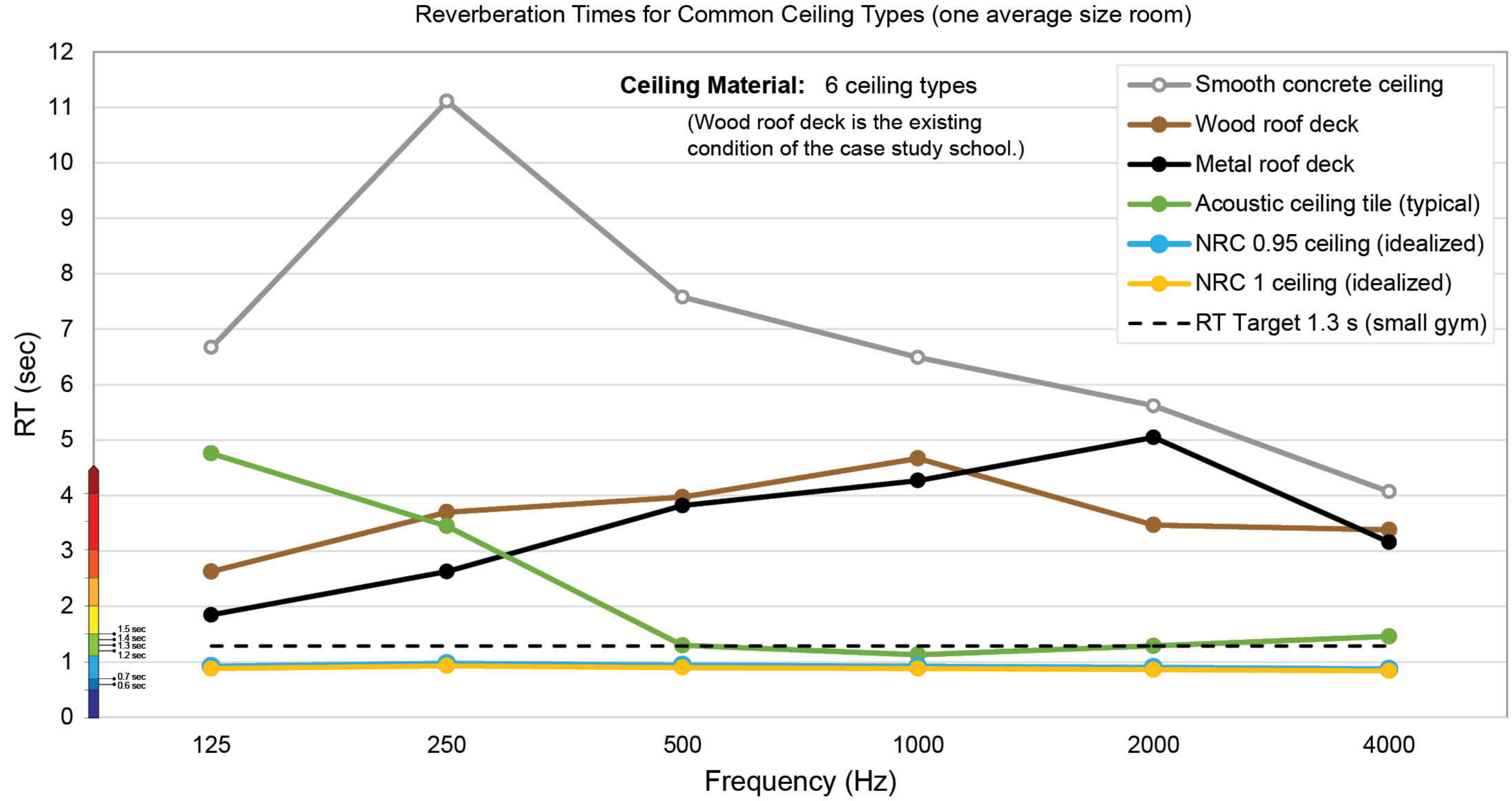
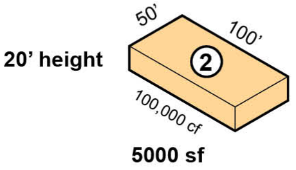


Figure 3.3. Interior view of the simple rectangular gym room measuring 20' x 100' x 50'. Compute Sabine reverberation times for six different versions of the same basic room. Keep the same wall material (painted CMU) and floor materials (vinyl on concrete), but change the ceiling material each time (choose one of six different common ceiling types).





Volume = 20' x 100' x 50' = **100,000 cf**

Wall Material: painted CMU

Floor Material: vinyl on concrete

Figure 3.4. Reverberation times for six different ceiling types of the simple rectangular gym measuring 20' x 100' x 50'.

Figure 3.4 shows that the reverberation time of this large room with highly reflective walls and floor is highly influenced by the material properties of the ceiling. The wood roof deck ceiling and the metal roof deck ceiling have similar RTs, and the concrete ceiling has an even higher RT. The three versions with absorptive ceilings nominally meet the reverberation time requirement of 1.3 seconds.

The second part of this research study concerns the impact of both ceiling materials and room geometry on reverberation time. The Sabine equation tells us that larger room volumes increase RT, and more absorption decreases RT, but it does not explicitly address any surface-to-volume effects associated with changing room dimensions. To that end I designed a test set of twenty-four potential gym/cafeteria room volumes to test with different ceiling types. The room dimensions explore typical room footprints in school gyms and cafeteria, from small elementary school gyms to a single court high school gymnasium, and a variety of ceiling heights suitable for cafeterias and gyms, but they are also applicable to other similar large rooms such as restaurants and meeting halls.

Two widths (50’, 75’) and three lengths (75’, 100’, 125’) combine to make six different room footprints as seen in Figures 3.5 and 3.6. Figure 3.6 shows each footprint 1-6 sorted from the smallest square footage (3750 sf) to the largest (9375 sf). Footprint size is color coded by color intensity, starting with a pale tint for the smallest size and moving up to a saturated shade for the largest size.

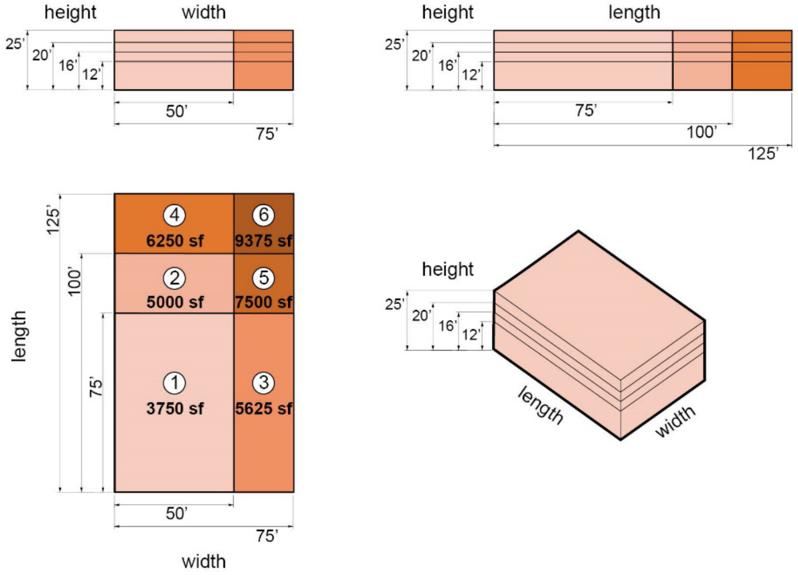


Figure 3.5. Test set of 24 room volumes is described by three room parameters: width, length, and height. Two widths (50’, 75’) and three lengths (75’, 100’, 125’) combine to make six different room footprints (1-6). Each footprint 1-6 appears in four different heights (12’, 16’, 20’, 25’).

Ceiling height is color coded as well. Each ceiling height has its own color: blue for 12’, green for 16’, yellow for 20’, and orange for 25’. Taken together, the color-coding scheme shows both the footprint size and ceiling height for each of the 24 room volumes.

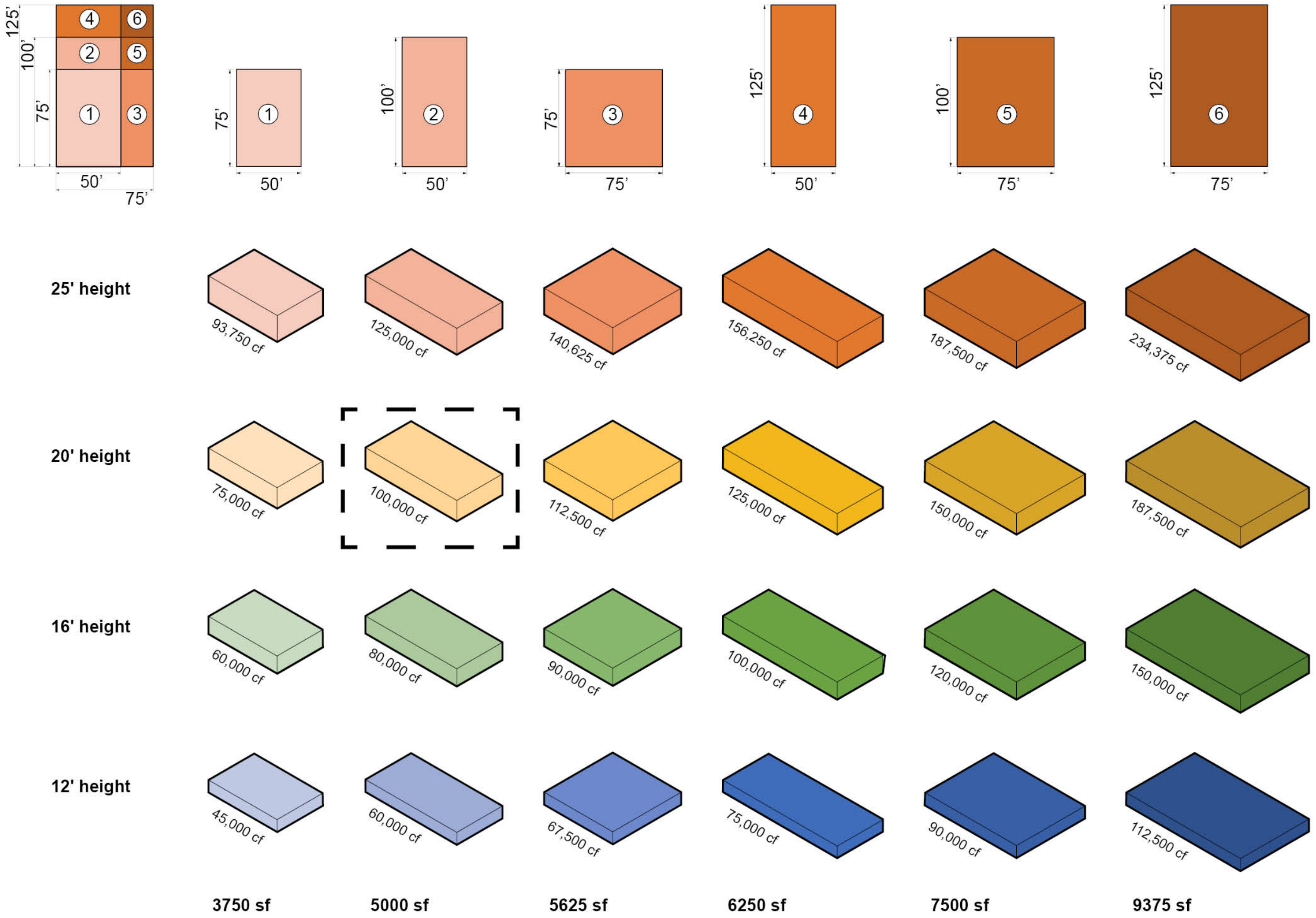


Figure 3.6. Test set of 24 room volumes are sorted and color coded by floor area (footprints 1-6, from 3750 sf to 9375 sf) and ceiling height (12', 16', 20', 25'). Each footprint 1-6 appears in the four heights. The dashed rectangle around the second volume in the 20' height row highlights the 20' x 50' x 100' room considered previously.

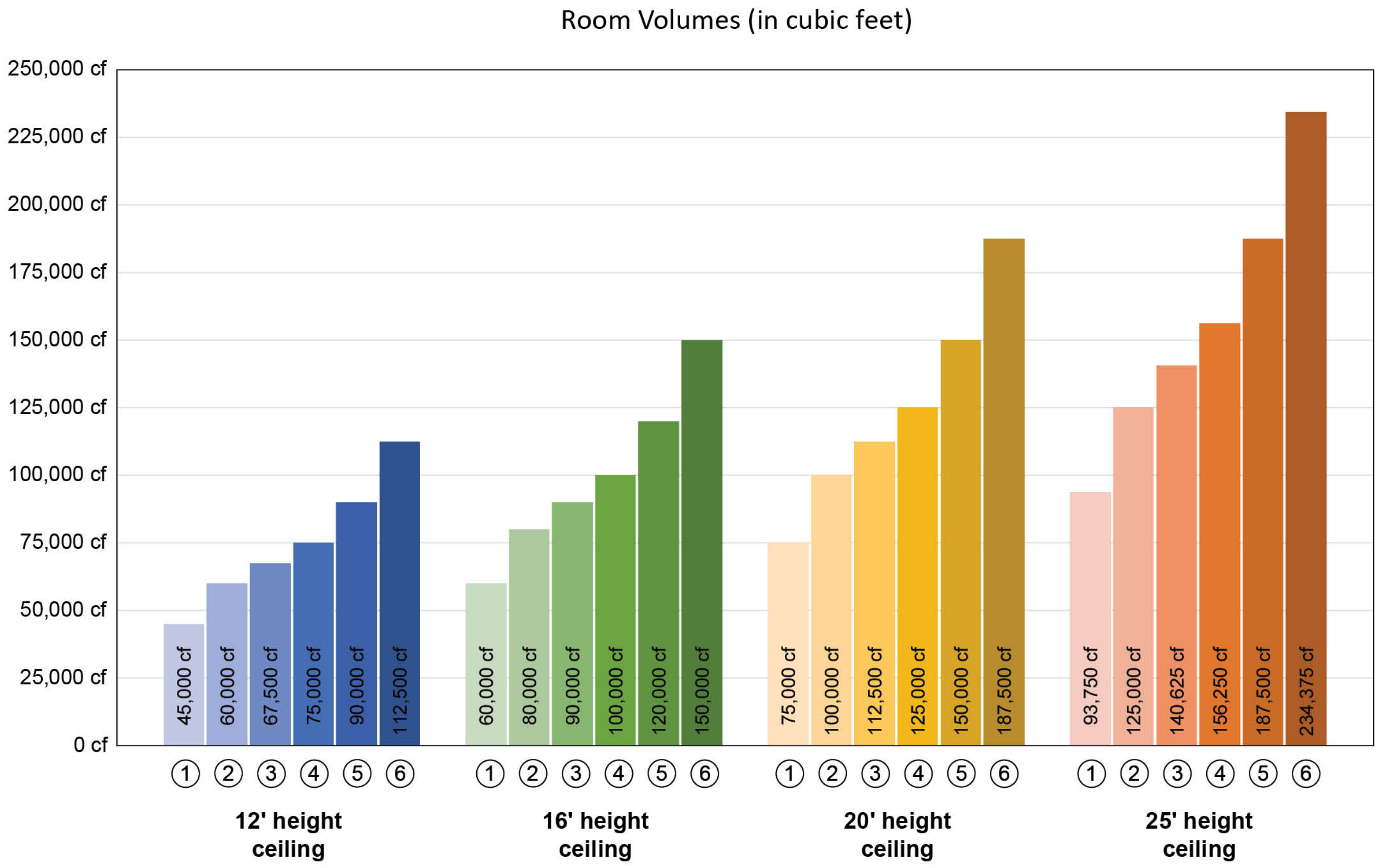


Figure 3.7. Total room volumes (in cubic feet) of the test set of 24 room volumes, sorted and color coded by ceiling height and footprint (1-6). Note that the room volumes overlap among the four ceiling heights. For example, the largest 12’ high room (blue 6) has a larger room volume than the smallest 25’ high room (orange 1). The average room volume is 114,062 cf, and the median room volume is 106,250 cf. The standard deviation is 45,447 cf. Yellow number 2 (100,000 cf) is the 20’ x 50’ x100’ room considered previously. It is very close to the mean and average room volumes.

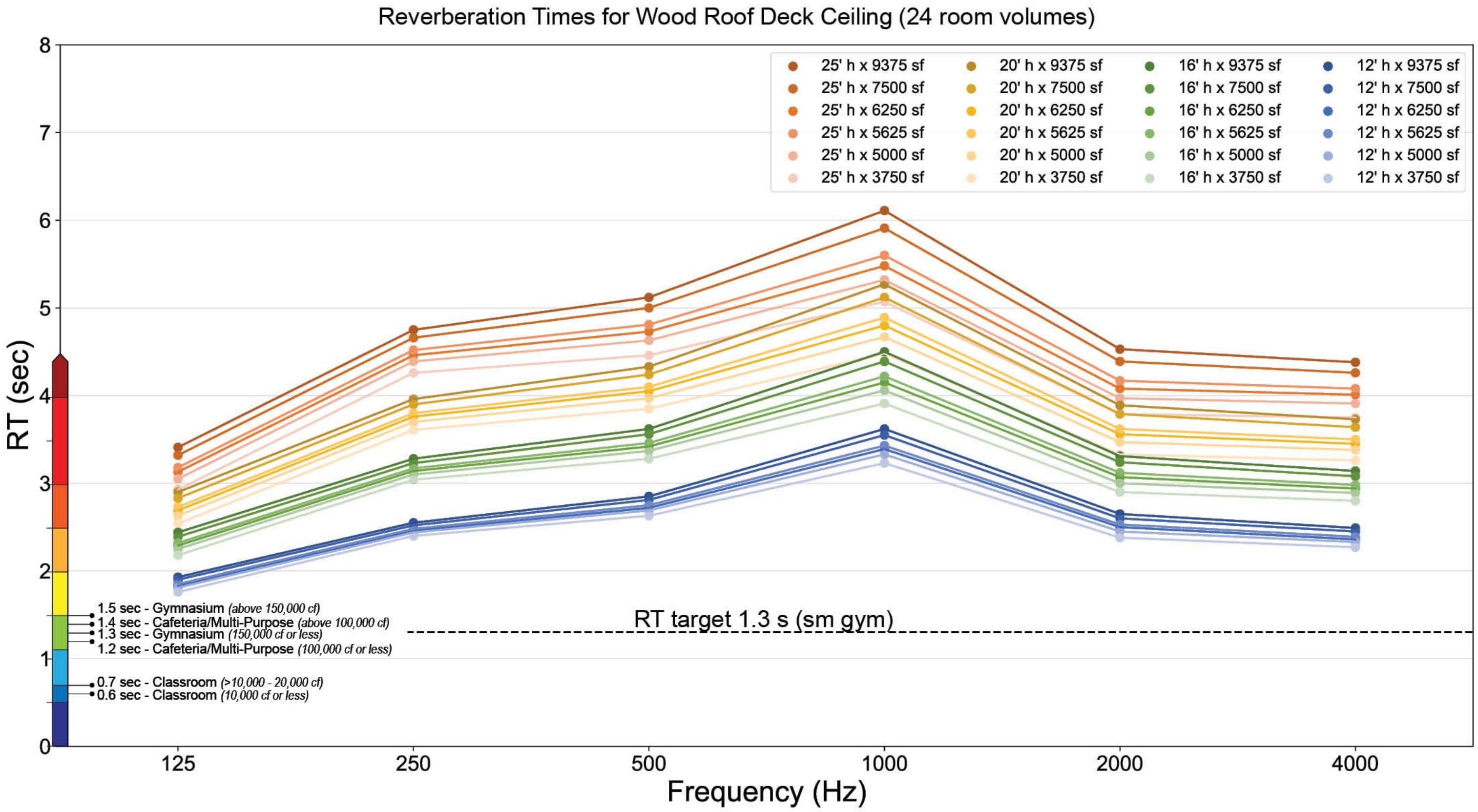


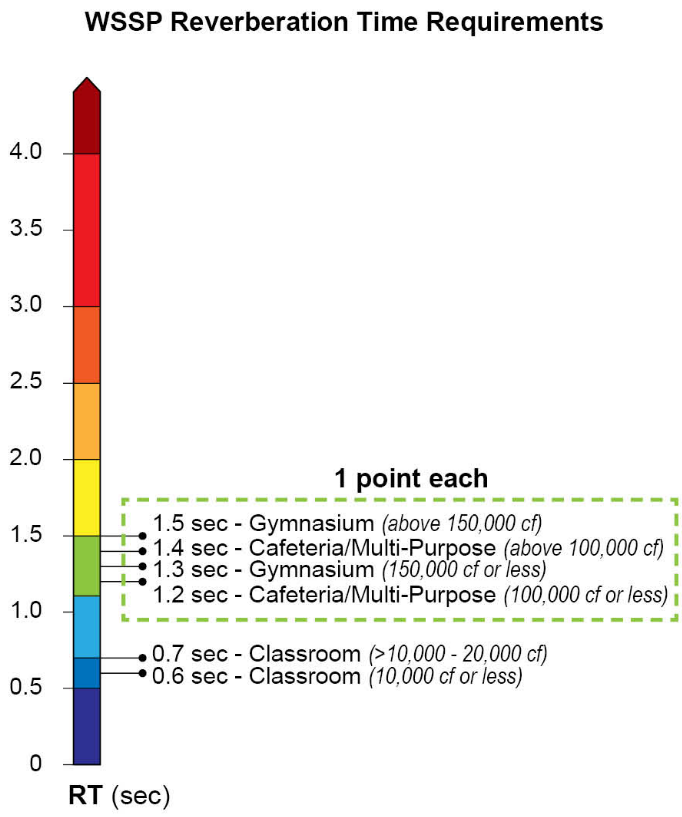
Figure 3.8. Reverberation times for wood roof deck ceiling, all 24 room volumes.

Figure 3.8 shows the results of the Sabine equation reverberation time calculations for rooms with wood roof deck ceilings, for all 24 combinations of footprint size and ceiling height. We see that the wood roof deck has a characteristic shape to the RT response curve. Both footprint size and ceiling height show up in this plot, but ceiling height has a larger impact on the results than footprint/ceiling surface area.

If room volume were the most important factor in determining reverberation time, then based on the room volumes data in Figure 3.7 we would expect to see significant overlaps in the four height conditions in Figure 3.8. Recall, for example, that the largest 12’ high room (blue 6) has a larger room volume than the smallest 25' high room (orange 1). However, what we see instead in Figure 3.8 is a clear separation of the reverberation times based on ceiling height. There is very little overlap in RT between the four ceiling heights. In general, the RT results increase from smallest to largest room volume within each ceiling height group, and then by ceiling height. All of the 12' height ceiling rooms (in blues) are below all of the 16' height ceiling rooms (in greens). There is a small amount of overlap in reverberation times between the largest 20' height ceilings (in yellow) and the smallest 25' ceiling heights (in orange). But the largest 12' high room (blue 6) has a much shorter reverberation time than the smallest 25' high room (orange 1).

The full results for the reverberation time plots of all 24 room volumes for the full set of six ceiling types (smooth concrete, wood roof deck, metal roof deck, acoustic ceiling tile, NRC 0.95 ceiling, and NRC 1.0 ceiling) can be found in Appendix A. We saw in Figure 3.4, the comparison of ceiling types for a single room volume, that the ceiling type has a very strong impact on the reverberation time of a typical size room. This is expected because the different ceiling materials have very different absorption coefficients. Just as the 20' x 50' x 100' room volume (yellow 20' h x 5000 sf) falls in the middle of the results in Figure 3.8 for wood roof deck, the same is true for the other ceiling types (see Appendix A).

Looking at six different plots for six different ceiling types is instructive, but it is easier to see the interacting impacts of ceiling type, footprint/ceiling size, and ceiling height when the reverberation time data are summarized as RT average (500 Hz, 1000 Hz, 2000 Hz), the frequencies most important to speech communication. Figure 3.9 shows both the wood ceiling and a generic "idealized" absorptive ceiling ("Ideal ceiling NRC 0.95"; see Appendix B). The 24 room volumes are sorted and arranged as before, but this time the rooms are color coded for RT to show how each room compares to WSSP RT requirements. For the wood ceiling material, even the smallest rooms with 12' ceilings would require additional acoustic treatment to meet acoustic standards for gyms or cafeterias. By contrast, for the ideal NRC 0.95 ceiling, the smallest rooms with 12' ceilings seem to nominally meet even the more stringent classroom standards, with reverberation times under 0.6 seconds, and the largest rooms with 25' ceilings seem to nominally meet the gym/cafeteria WSSP improved acoustic performance requirements.



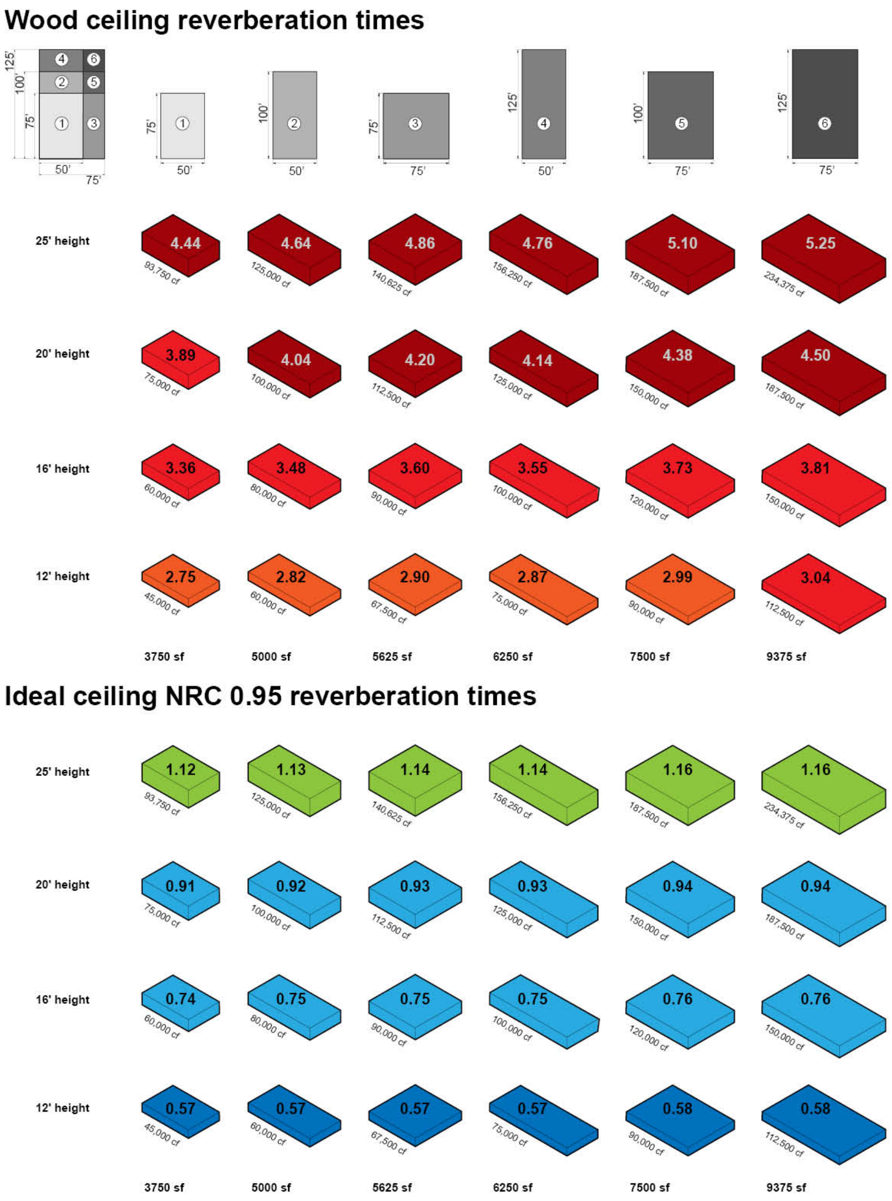
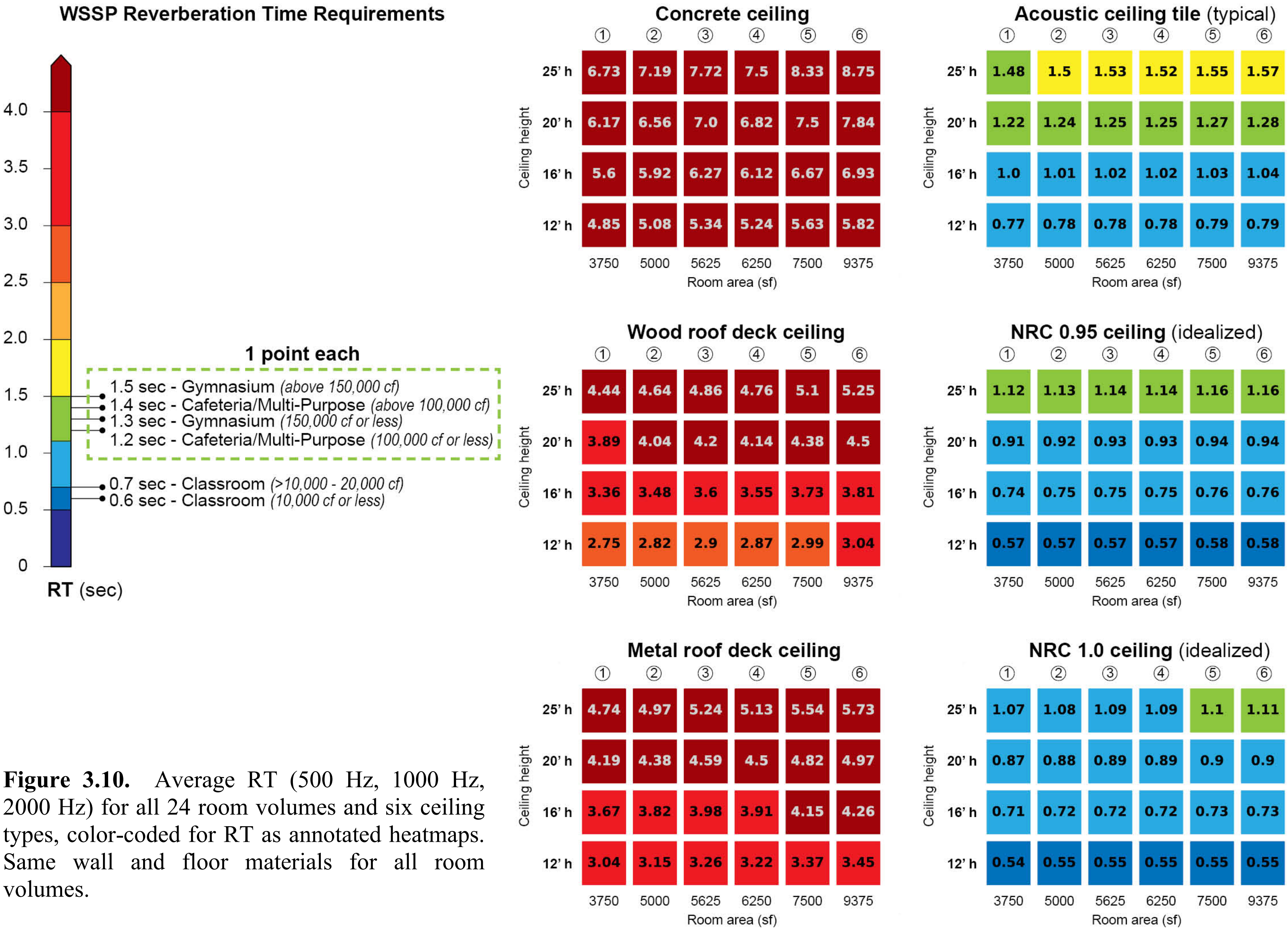


Figure 3.9. Average reverberation times for all 24 room volumes, color-coded for RT, arranged by footprint and height as before. Colors show how each room compares to WSSP reverberation time requirements. Note that none of the test cases with wood ceiling come even close to meeting the WSSP reverberation time requirements for gymnasiums and cafeterias, not even the smallest rooms with the lowest ceilings.



Concrete ceiling

Ceiling height	① 3750	② 5000	③ 5625	④ 6250	⑤ 7500	⑥ 9375
25’ h	6.73	7.19	7.72	7.5	8.33	8.75
20’ h	6.17	6.56	7.0	6.82	7.5	7.84
16’ h	5.6	5.92	6.27	6.12	6.67	6.93
12’ h	4.85	5.08	5.34	5.24	5.63	5.82

Room area (sf)

Acoustic ceiling tile (typical)

Ceiling height	① 3750	② 5000	③ 5625	④ 6250	⑤ 7500	⑥ 9375
25’ h	1.48	1.5	1.53	1.52	1.55	1.57
20’ h	1.22	1.24	1.25	1.25	1.27	1.28
16’ h	1.0	1.01	1.02	1.02	1.03	1.04
12’ h	0.77	0.78	0.78	0.78	0.79	0.79

Room area (sf)

Wood roof deck ceiling

Ceiling height	① 3750	② 5000	③ 5625	④ 6250	⑤ 7500	⑥ 9375
25’ h	4.44	4.64	4.86	4.76	5.1	5.25
20’ h	3.89	4.04	4.2	4.14	4.38	4.5
16’ h	3.36	3.48	3.6	3.55	3.73	3.81
12’ h	2.75	2.82	2.9	2.87	2.99	3.04

Room area (sf)

NRC 0.95 ceiling (idealized)

Ceiling height	① 3750	② 5000	③ 5625	④ 6250	⑤ 7500	⑥ 9375
25’ h	1.12	1.13	1.14	1.14	1.16	1.16
20’ h	0.91	0.92	0.93	0.93	0.94	0.94
16’ h	0.74	0.75	0.75	0.75	0.76	0.76
12’ h	0.57	0.57	0.57	0.57	0.58	0.58

Room area (sf)

Metal roof deck ceiling

Ceiling height	① 3750	② 5000	③ 5625	④ 6250	⑤ 7500	⑥ 9375
25’ h	4.74	4.97	5.24	5.13	5.54	5.73
20’ h	4.19	4.38	4.59	4.5	4.82	4.97
16’ h	3.67	3.82	3.98	3.91	4.15	4.26
12’ h	3.04	3.15	3.26	3.22	3.37	3.45

Room area (sf)

NRC 1.0 ceiling (idealized)

Ceiling height	① 3750	② 5000	③ 5625	④ 6250	⑤ 7500	⑥ 9375
25’ h	1.07	1.08	1.09	1.09	1.1	1.11
20’ h	0.87	0.88	0.89	0.89	0.9	0.9
16’ h	0.71	0.72	0.72	0.72	0.73	0.73
12’ h	0.54	0.55	0.55	0.55	0.55	0.55

Room area (sf)

Figure 3.10. Average RT (500 Hz, 1000 Hz, 2000 Hz) for all 24 room volumes and six ceiling types, color-coded for RT as annotated heatmaps. Same wall and floor materials for all room volumes.

Figure 3.9 shows average RTs for all 24 rooms of all 6 ceiling conditions in tabular heatmap form, arranged by footprint and ceiling height in the same order as before. The color-coding makes a clear distinction between the rooms with ceiling conditions that are highly reflective (smooth concrete, wood roof deck, and metal roof deck) and ceiling conditions that are highly absorptive (acoustic ceiling tile, NRC 0.95 idealized ceiling, NRC 1.0 idealized ceiling). It also shows the trend of higher RTs for larger volumes, from the smallest rooms in the lower left corner to the largest rooms in the top right corner. It also shows the strong impact of ceiling height, over and above room volume alone.

The rooms with ceiling conditions that are highly absorptive demonstrate the strong contribution of ceiling material to rooms of all volumes and ceiling heights from 12' to 25'. The rooms with reflective ceilings paired with the already reflective painted CMU walls and vinyl on concrete floor clearly need additional acoustic treatment that add absorption to the room in order to meet any acoustic guidelines or standards requirements. The data also suggest that wood roof deck ceiling is a slightly better surface from the standpoint of acoustics than metal roof deck, and substantially better than a concrete ceiling. it would need much more absorptive ceiling reduces the number of absorptive panels that would need to be applied to the walls and ceilings.

In summary, both footprint size and ceiling height show up in these data, but volume shows up even less directly. Ceiling height has a larger impact on the results than footprint/ceiling surface area. A typical size gym with a wood roof deck at 20' to 25' ceiling height has a reverberation time of around 4 seconds, and it clearly would not meet the reverberation time requirements of current acoustic standards. Even the smallest room volumes with 12' height wood ceilings would require additional acoustic treatment to meet current acoustic standards.

4.

Case study - Method 1, Sabine equation

Case study school: Rockwell Elementary
Design problem: Acoustic renovation and expansion of double-duty gymnasium/cafeteria
Sabine equation reverberation time calculations of case study design options

This chapter begins with a description of the case study school and sets the context for the design problem: the acoustic retrofit and expansion of the existing double-duty gymnasium/cafeteria. The Sabine equation is the first method we use to evaluate design options. Reverberation times are calculated for two expansion options: expansion as a single large room and expansion as two connected rooms. Reverberation times for variable acoustic options are also calculated, such as doors open and doors closed between the two rooms and no curtains versus curtains covering the windows.

Case study school: Rockwell Elementary

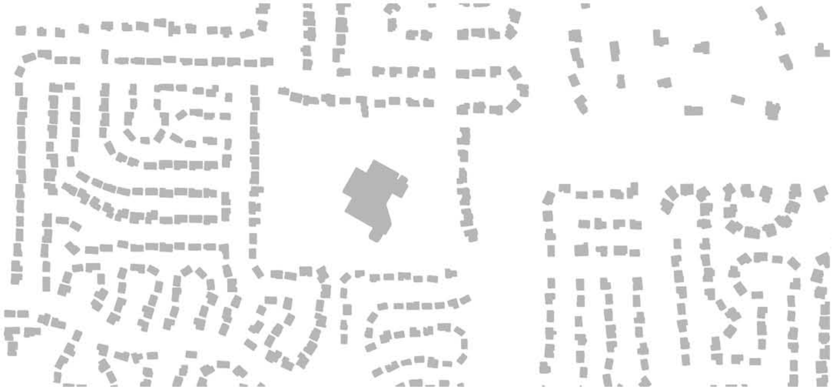
As you know, the case study school is Rockwell Elementary, and the design problem is the acoustic retrofit and expansion of the existing double-duty gymnasium/cafeteria. It was chosen for being a very typical situation with the dual-purpose space. Norman Rockwell Elementary is one of 29 neighborhood elementary schools in the Lake Washington School District. It is a suburban school located in Redmond, Washington on Seattle's Eastside. As you can see in Figure 4.1, Rockwell Elementary is a single-story building on a large property in a neighborhood of single-family homes. The building is 50,025 ft^2 on a 577,605 ft^2 site (13.26 acres). Most of the school is standard single-story height, but the gymnasium/cafeteria area is a double height volume with a 20' ceiling (see Figure 4.2).

When it opened in 1981, Rockwell was designed for about 400 students. Because of rapid population growth in the greater Seattle area during the last ten years, Rockwell Elementary has sometimes had a student body of more than 650 students. About 550 students attended Rockwell during the 2019-2020 school year.

The school's only large assembly space was designed to serve dual purposes: as cafeteria during lunchtime and as gymnasium and assembly space the rest of the time. However, what worked for 400 students is inadequate for 550-650+ students. The space is too small to seat all the students in two shifts at lunchtime, let alone fit everyone for all-school assemblies or performances for families.

Although the current school building is strained past capacity in some spaces, especially in the gymnasium/cafeteria, it is well-loved because of its strong connection to nature and the outdoors and the culture that the outdoor connection has fostered. Every classroom opens either directly to the outside or onto one of four open-air interior courtyards. The courtyards and outdoor places provide overflow space to host some of the most memorable school events.

Figure 4.1. Aerial view and figure-ground map of Norman Rockwell Elementary, 11125 162nd Ave NE, Redmond WA. (Google 3D image, from the south). Lake Washington School District owns the 50,025 ft^2 building and the 577,605 ft^2 property (13.26 acres).



Due to the rapid population growth in the last ten years, the Lake Washington School District has grown to become the second largest school district in the state of Washington. At the beginning of the 2019-2020 school year more than 31,000 students were enrolled in 56 schools, with 15,379 elementary students in grades K-5 in 33 schools (29 neighborhood schools and four choice schools).[55] With the rapid growth in the school district has come changed economic circumstances and changed values concerning sustainable building practices.

Rockwell Elementary had originally been scheduled for demolition and replacement when it turned 35 years old in 2016. However, in 2008 taxpayers began rejecting a bond measures that would have funded the previous policy of automatic age-based school replacements. The original Rockwell Elementary still exists today, while four of the five nearby schools built just a few years earlier than Rockwell were replaced under the old policy and funding model. The taxpayers forced the school district to change to a more fiscally responsible policy that identifies and addresses renovation needs rather than scheduling automatic school replacements.

For Rockwell Elementary, I recommend the renovation and addition model of construction as the most cost effective and sustainable way to address the school's need to serve the increased student population. This is a top performing school with a strong culture and sense of place, and the existing building is in good condition. Renovating the undersized gymnasium/cafeteria rather than demolishing the existing school and building a bigger new school recognizes the inherent value of the existing building and school culture. The school community benefits from improvements that minimize unnecessary changes, the environment benefits from a lower consumption of resources and smaller waste stream, and the school district benefits from a lower overall project cost.[56]

The building reuse approach provides the opportunity to expand the capacity of the large assembly space and to fix the previously described acoustic defects of the current gym/cafeteria and covered play area. The large site presents opportunities to expand the school to a campus experience through additions if needed, while retaining the advantages of the existing site plan. An analysis of renovation and addition options are presented in the next section.

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[55] (Lake Washington School District: About Us 2020)

[56] (Merlino 2018)

Figure 4.2. The existing condition of Rockwell's covered play area with 20' ceiling height. This is the site of the sound recordings **Listen 1 - Listen 3** from the introduction.

The image in the lower left shows the current exterior wall of the gymnasium/cafeteria.[57] A single metal door is currently the only access between the interior and exterior spaces.

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[57] This is very typical construction in the school district. The exterior walls are made of concrete masonry units (CMU). A single masonry unit is 16" wide x 8" deep x 4" high. The units are laid two layers back to back (for 16" thick walls).

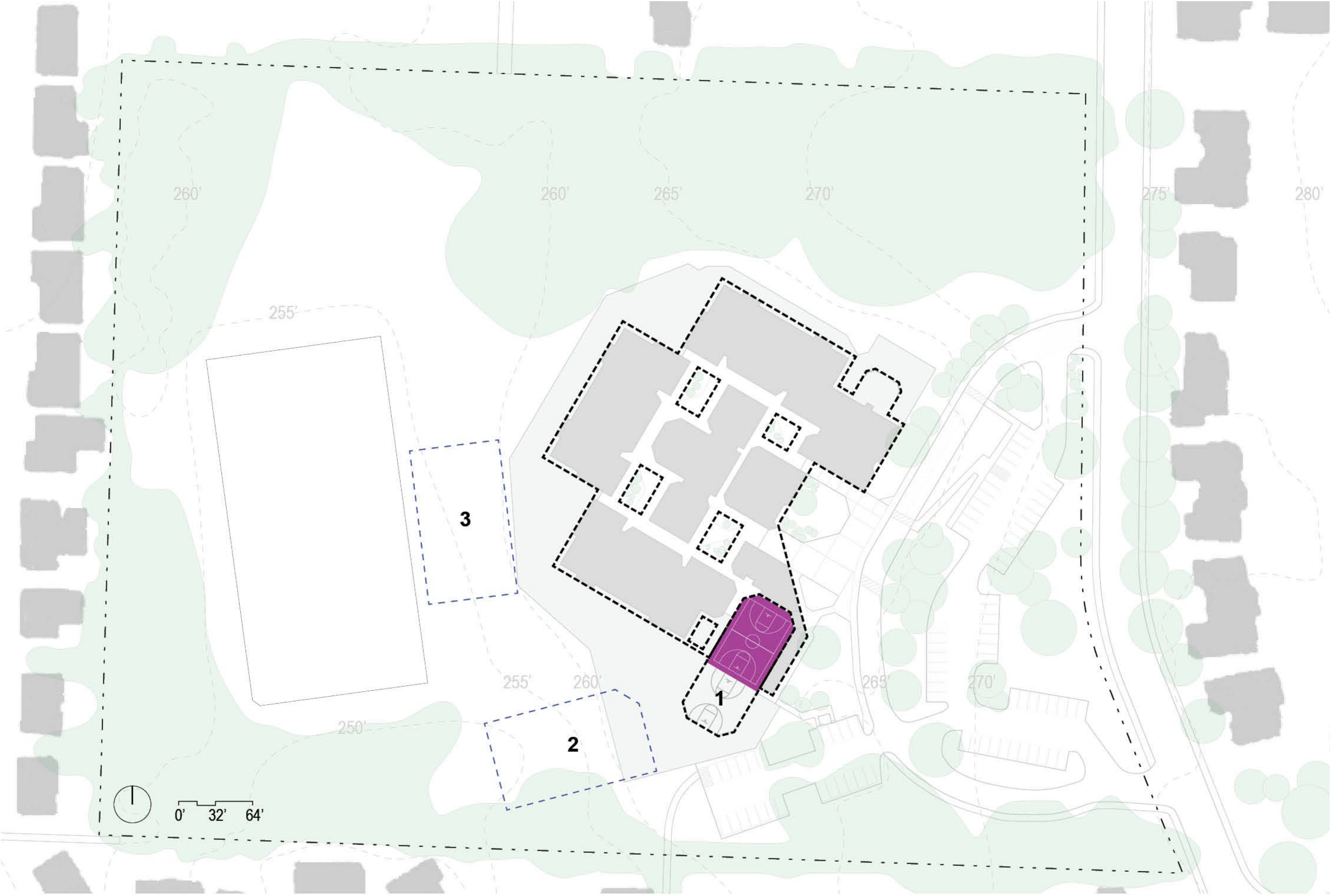


Figure 4.3. Site plan of Rockwell Elementary with three possible gymnasium/cafeteria expansion opportunities.

Enclose attached covered play area and renovate (site 1). New build cafeteria (site 2). New build gymnasium (site 3).

Design problem: Acoustic renovation and expansion of Rockwell Elementary's double-duty gymnasium/cafeteria

Rockwell Elementary needs more space for students than the current double-duty gymnasium/cafeteria provides. It also needs to solve the acoustic problems in the existing indoor and outdoor spaces. This section outlines the main options for adding needed large assembly space capacity and the pros and cons of each approach. We will begin the analysis of the renovation and addition options by recapping the design problem and listing desirable features in a design solution. Ultimately renovating and expanding within the existing footprint (site 1 of Figure 4.3) is the logical and most cost effective option.

What is the problem?

1. The school's existing double-duty gymnasium and cafeteria is too small to serve the current student body.
2. The current spaces (indoor and outdoor) are too loud and reverberant.

What could be?

1. Building reuse with improved indoor/outdoor connections.
2. A big enough large assembly space with appropriate acoustics to improve health and wellness.
3. Variety of acoustic conditions to allow individual choices and to accommodate groups of different sizes and activity levels.

The lowest cost option is to expand the gymnasium/cafeteria within the existing footprint of the building by enclosing the attached covered play area (site 1 of Figure 4.2). A more expensive option is to add a new building to the site, either a new cafeteria (on site 2) or a new gymnasium (on site 3). Each option has advantages and disadvantages.

Expanding within the footprint (site 1) is the least cost with the lowest impact on the site. It keeps the current kitchen, and the gym could have improved access to the outside. Two connected rooms can be a starting point for creating acoustic microclimates for active and less active spaces. The main disadvantages are that it is still a double-duty gymnasium/cafeteria and there are fewer design opportunities for acoustic microclimates in a renovation.

Building a new cafeteria (site 2) is more expensive but has several advantages. There could be separate rather than shared spaces for the active gymnasium and the less active cafeteria. The acoustic experience could be designed from the ground up to include the acoustic priorities of a cafeteria and large assembly space as well as strategies for creating acoustic microclimates. The main disadvantages are that it is more expensive and would still require acoustic treatment of the existing gym and covered play area.

Building a new gymnasium (site 3) and renovating the existing space as a cafeteria is the least desirable option. The current gym is probably big enough for elementary sports, but the cafeteria is not big enough, so it would still require an expansion and renovation. The ceiling is also much higher than necessary for a cafeteria. Site 3 is a very promising site for an addition to the campus because of its potential to mediate the 10-foot grade change between the main school and the lower big field and large backyard area, but it would require planning beyond the scope of this thesis.

After consideration of the advantages and disadvantages of building a new cafeteria or gymnasium compared to renovation and expansion of the existing gymnasium/cafeteria, I recommend renovation and expansion within the existing footprint. While a new addition has some advantages, it is much more expensive, and the existing spaces still require acoustic treatment to make them healthy spaces that are not too loud and are good places for people to talk to each other and be well understood.

Given the decision to expand within the footprint, the next major design decision is whether to expand as one large room or as two connected rooms. At this point in the investigation we turn to the Sabine equation as a tool to get valuable data concerning the different possible design options: relative reverberation times, absorption requirements, and how to treat the room(s) to achieve the target reverberation times. The next section discusses that process and calculation results.

Sabine equation RT calculations of case study design options

In this section the Sabine equation is used as a tool to evaluate reverberation time and needed additional absorption for design options under consideration. We follow the same methodology for the Sabine equation calculations in this case study room as we did in the research study of 24 rooms in Chapter 3. We start by calculating the room volumes and identifying all the surfaces and their materials for the design options. The results are calculated using a spreadsheet as before. The spreadsheet contains the relevant room geometry (volume and surface areas by material type) and calculates the total room absorption and the reverberation time.

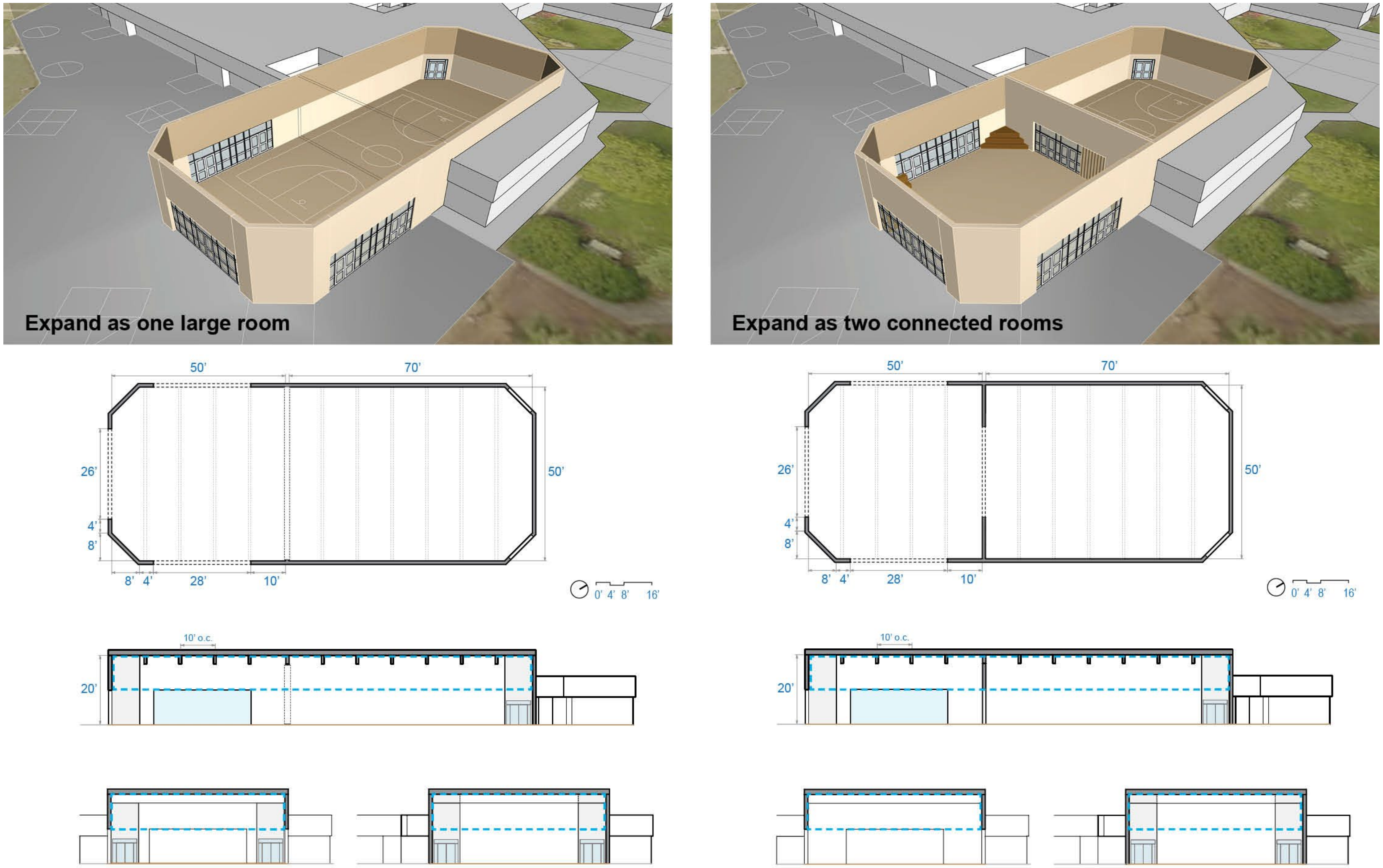


Figure 4.4. Two options are considered for expansion of the gymnasium/cafeteria: as one large room and as two connected rooms. Plans and sections give dimensions. Blue dashed lines show location of wall absorption considered (from 10' to 20').

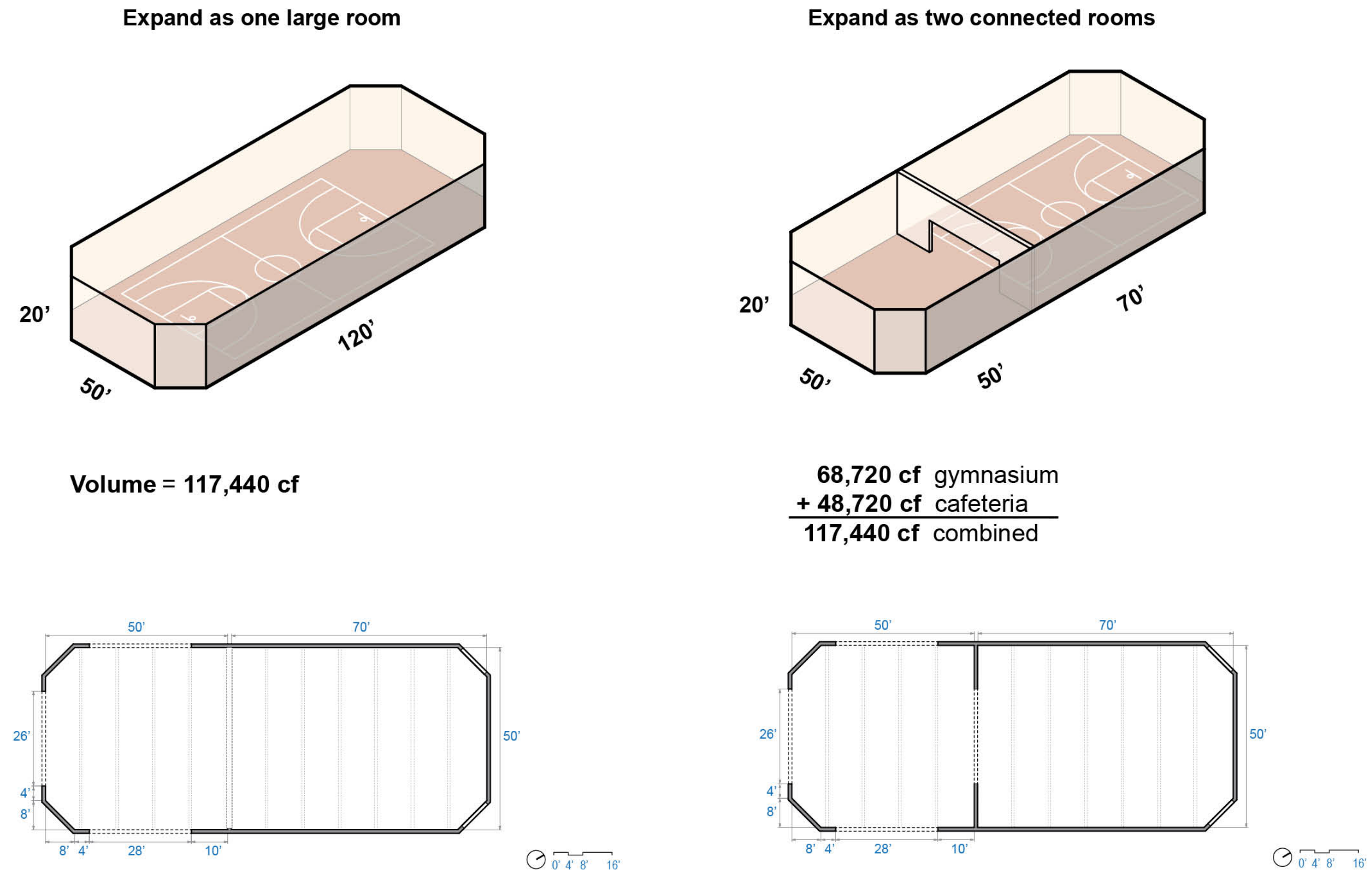


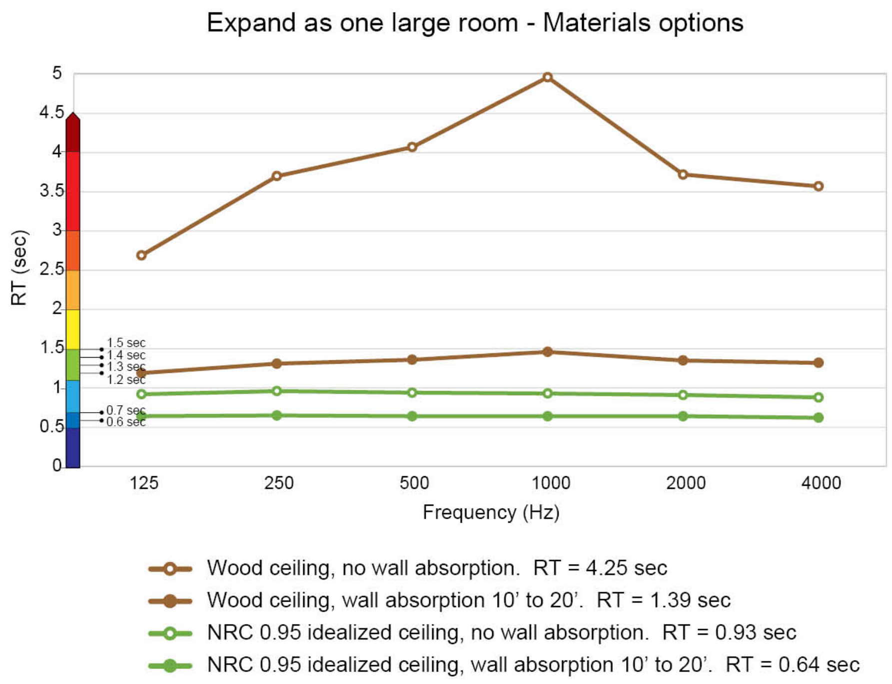
Figure 4.5. Two options for expansion: one large room and two connected rooms.

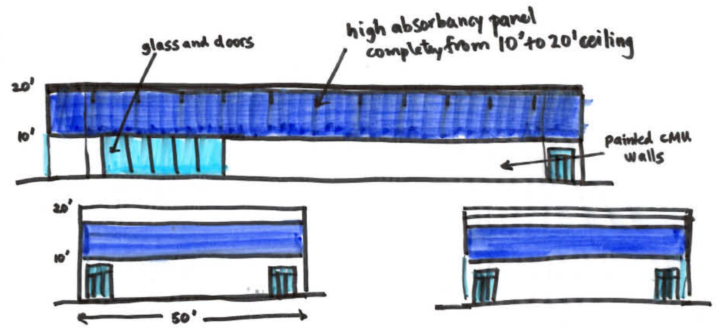
Figures 4.4 and 4.5 show the two options under consideration for the expansion of the gymnasium/cafeteria. The first option is expansion as one large room, and the second option is expansion as two connected rooms. In both options the attached covered play area is converted to interior space by adding glass windows and doors to fill the 26’ and 28’ wide openings (all openings are 10’ high). In the first option, the entire existing exterior gym wall is removed (see Figure 4.2, dashed lines). In the second option, only a 26’ wide by 10’ high portion of the existing exterior end wall is removed to connect the two rooms. Plans and sections show the room details with interior dimensions marked.

We start by calculating the reverberation times for the first option, expanding as one large room. This room has a wood roof deck ceiling, a 20’ ceiling height, and a footprint of 50’ x 120’ minus the chamfered corners (5872 sf). The walls are CMU, and the windows and doors are treated as double glazing which are also quite reflective surfaces. The total room volume is 117,440 cf (Figure 4.5). This case is very similar to rooms in the research study in Chapter 3, so we expect similarly high reverberation times of approximately four seconds for the acoustically untreated room.

Figure 4.6 shows the results of the Sabine equation calculation for this large room. It shows the base condition with the wood roof deck ceiling and no acoustic treatment and three treatment possibilities. As expected, the untreated room has an average RT of 4.25 seconds. By adding wall treatments equivalent to acoustic panels that cover the entire top half of the walls (above 10’ up to the 20’ ceiling), the average RT decreases to 1.39 seconds. This is very close to the WSSP IEQ4.1 Improved Acoustic Performance criteria (1.4 sec for Cafeteria above 100,000 cf and 1.3 sec for Gymnasium 150,000 cf or less). The Sabine calculation suggests that this is a simple way to reach compliance, purely by adding enough absorption to bring the reverberation time into line.

What the Sabine equation calculations do not tell us, however, is whether it is actually a good solution in the real world. That would have to be verified, and it is in fact likely that some of the absorption would have to be added to the ceiling in order to break up standing wave reflections between the floor and ceiling. The Sabine equation also tells us that if the entire ceiling were absorptive, the average RT would be 0.93 seconds, a value that may be even more appropriate for a cafeteria. A mix of wall and ceiling treatment is likely best.





Ceiling Material:	wood roof deck	$S_1\alpha_1$
Wall Materials:	painted CMU	$S_2\alpha_2$
	double pane windows	$S_3\alpha_3$
	treatment panels	$S_4\alpha_4$
Floor Material:	vinyl on concrete	$S_5\alpha_5$

Volume = 117,440 cf

$$\mathrm{RT} = \mathrm{T}_{60} = \frac{0.05\ \mathrm{V}}{\mathrm{A}_t}$$

$$\mathrm{A}_t \quad = \text{total absorption} \quad = S_1\alpha_1 + S_2\alpha_2 + S_3\alpha_3 + \cdots + S_n\alpha_n$$

Figure 4.6. Reverberation time calculations for versions of the one large room option.

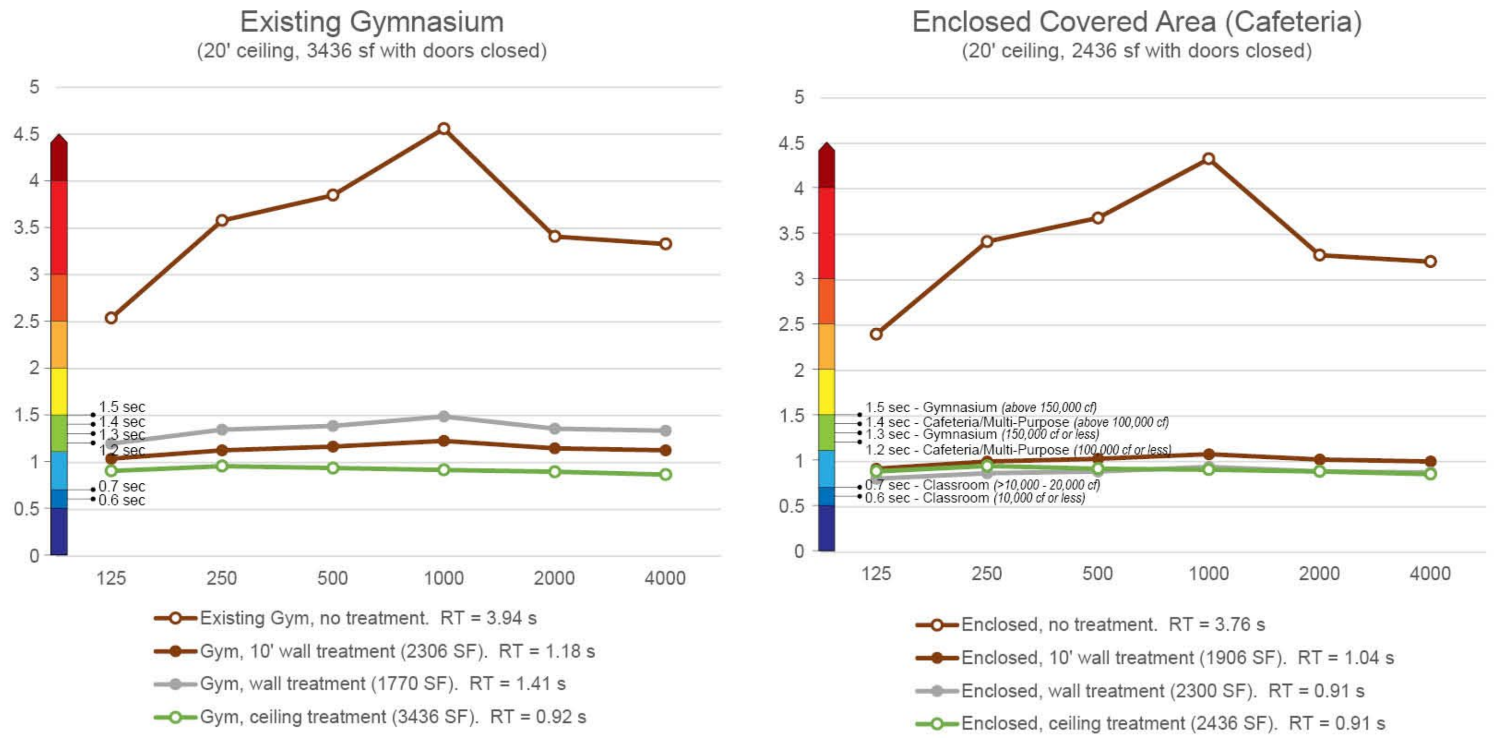


Figure 4.7. Reverberation time calculations for second option, two connecting rooms with doors closed between them.

Next we calculate the reverberation times for the second option, expanding as two connected room. This option includes a variable acoustics approach of being able to switch the two rooms between being connected to each other (doors open) or separate from each other (doors closed, here treated as double glazing). The one large room calculations are a very rough approximation to the doors open condition, but we need different calculations to understand the two rooms separately. Again they have wood roof deck ceiling, 20' ceiling height, CMU walls, and glass windows and doors. The total room volume is 68,720 cf for the existing gym and 48,720 cf for the enclosed covered area/cafeteria expansion (Figure 4.5). Figure 4.7 results show that with the doors closed and the volumes are smaller, the same amounts of absorption result in lower average RTs, which is a big advantage when trying to create a smaller, quieter room.

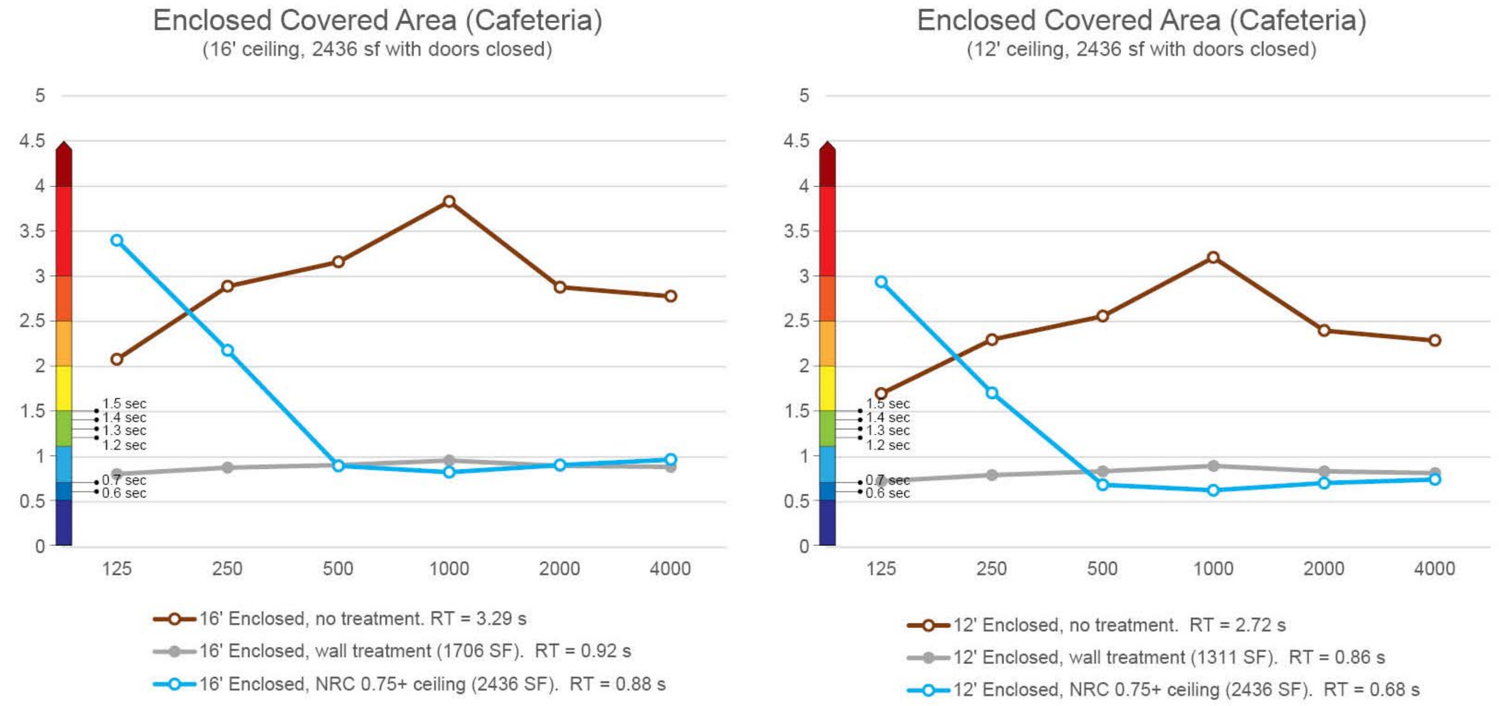


Figure 4.8. Reverberation time calculations for lower ceiling heights in the enclosed covered area/cafeteria (16’ and 12’ ceilings).

Next we calculate the reverberation times for the second option if we were to have a ceiling height lower than 20’ in the enclosed covered area/cafeteria expansion. Figure 4.8 shows us that if an NRC 0.75+ drop ceiling[58] were installed in the smaller area at a height of 16’ or 12’ and the doors were closed, the average RT would be getting close to classroom values of 0.7 seconds for large classrooms (0.88 seconds for 16’ ceiling height or 0.68 seconds for 12’ ceiling height, in blue). This could be very useful if the smaller room were to put to use as something resembling a large classroom or small lecture room.[59]

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[58] An NRC 0.75+ ceiling could be acoustic tile, acoustic panels, perforated metal, or other absorptive ceiling type.

[59] For example, as an extra “classroom” to meet social distancing requirements for a larger group of students or a teacher meeting. It would work better as a classroom than a standard gymnasium.

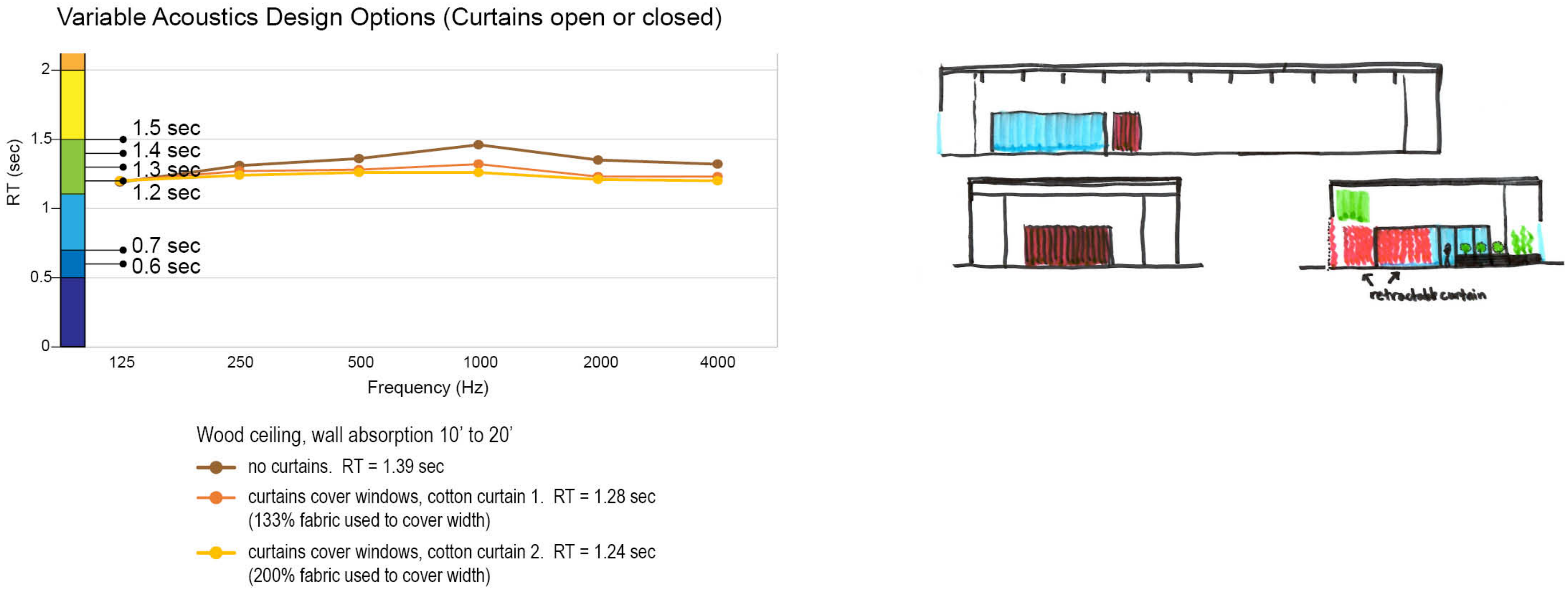

Figure 4.9. Reverberation time calculations for curtains as a variable acoustic design option.

The final set of reverberation time calculations I present here are for the variable acoustic contribution of fabric curtains. Curtains can be an adjustable element for both lighting and sound, giving people some control over their environment. Curtains can be open or closed (covering the glass windows). For this room they make about a 0.1 second difference in reverberation times. That is not a large change, but it probably is significant, given that the WSSP requirements make 0.1 second increments in the requirements.

The Sabine equation makes it easy to calculate predicted room level reverberation times using schematic design levels of specificity for room geometry and materials. A spreadsheet with area takeoffs can give non-specialists a basic starting point for understanding the implications of room volume, ceiling height, and ceiling type, as well as wall construction type. However, the Sabine equation is limited to room level averages of RT and absorption. For information about local conditions (acoustic microclimates), or measures of speech intelligibility or loudness we need another tool in our toolkit, such as simulations, as we see in Chapter 4

5. Case study - Method 2, Geometric acoustic simulation

Advantages & disadvantages: Sabine equation & geometric acoustic simulation
Room acoustic metrics: T_{30}, SPL, STI, D_{50}
Method 2 process: 3D model, run simulation, analyze results
Applying simulations to case study design options
Conclusions

In Chapter 2 we introduced several acoustic metrics used for characterizing the acoustic properties of a space. In Chapters 3 and 4 we used the Sabine equation as a method to calculate one of those acoustic metrics, reverberation time (RT or T_{60}). In this chapter we will use geometric acoustic simulation[60] as a method to calculate four room acoustic metrics. These metrics are *reverberation time* (T_{30}), *sound pressure level* (SPL), *speech transmission index* (STI), and *definition* (D_{50}). We will compute these metrics for several design options, as we did in Chapter 4 for reverberation time. We will use those metrics to investigate the impact of design decisions (room geometry and material choices) on a more granular scale to see the variations within the larger space. The overarching goal is to use this method to get information about both the overall acoustic character of the case study room as well as more localized acoustic microclimates.

Advantages & disadvantages of the two methods

As we have discussed in detail in Chapter 3, the Sabine equation is a simple and powerful method for calculating the reverberation time for a room based on its room geometry and surface materials. It is also used to estimate the total room absorption needed to achieve a target reverberation time. [61] Its simplicity is a great advantage because it enables easy calculations of reverberation time by hand or with a simple spreadsheet to quickly compare rooms with each other. However, it has no spatial details about the relationship of the various surfaces because it assumes a perfectly diffuse sound field, and it gives only a single number for the whole room. Because reverberation time is used in the acoustic standards requirements for schools,[62] it is an extremely important number, making the Sabine equation method of calculating reverberation time a very useful tool for preliminary acoustic design.

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[60] Geometric acoustic simulation is computationally intensive software modeling associated with a three-dimensional model of a space. This thesis uses Rhino 6 for the 3D modeling and the plug-in extension Pachyderm Acoustic for the acoustic simulations.

[61] Reverberation times must be measured in the field to certify that a room as built meets the acoustic standards. A calculated value cannot be used as final validation of a design's acoustic performance (see for example the WSSP requirements for RT). (The Collaborative for High Performance Schools (CHPS) 2018).

[62] Recall that reverberation time is used because it is strongly correlated with speech intelligibility, and the goal is to design spaces that support good speech communication.

Geometric acoustic simulation tools, including the one used for this thesis, are complex software packages that perform calculations that rely extensively on the spatial details of a room or connected set of rooms. It is not possible to do these calculations by hand or in a spreadsheet. *Pachyderm Acoustic* for Rhino uses both an analytical technique called "ray-tracing" and the "image source" method to mathematically model sound propagation around the room. These two methods work together to determine a more accurate model of sound propagation over time. This is a "source-path-receiver" model of how sound moves from a source to a receiver within a room. This is very useful for modeling large rooms because the sound can go directly from the source to the receiver, and it can arrive indirectly by bouncing off room surfaces. The "direct sound" arrives quickly because it follows the shortest path, the straight line-of-sight path between the source and the receiver. This is best modeled by the image source method. The "indirect sound" reflects off one or more surfaces before it arrives at the receiver. The reflected sound energy arrives later (and even much later in a large and reverberant space). Ray-tracing is better suited for the later reflections.

Geometric acoustic software is used to model large rooms because it can calculate complex time-dependent details of sound propagation, like early- and late-arriving sound. In addition to being able to calculate reverberation time (T_{30}), geometric acoustic software is also capable of reproducing the *impulse response*[63] and therefore most of the ISO 3382-1 room acoustic parameters,[64] including sound pressure level (SPL), speech transmission index (STI), and definition (D_{50}). The relationship of early direct sound to later indirect sound is important for the character of the sound, which influences the experience of listening to sounds in the space. This is of course the point of music performance halls, but it is also important in other large assembly spaces such as gymnasiums, cafeterias, and commons areas in schools.

This computational method provides access to much more detailed information about the room than one summary number for reverberation time. This power comes with a cost in computing

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[63] The impulse response is the "temporal evolution of the sound pressure observed at a point in a room as a result of the emission of a Dirac [sound] impulse at another point in the room." In other words, the time dependent sound energy curve as measured at a receiver point that came from a source sound signal. (ISO 2009)

[64] Room acoustic parameters = acoustic measurements = metrics

time.[65] It also requires a time investment to learn how to use the software package and how to interpret the data. Once things are set up though, the 3D modeling workflow is a familiar to architects. It is straightforward to test different design options by changing materials and room geometry and to test source signals at different locations within the room.

Ray-tracing is an agreed upon analytical modeling technique that models many things well, but it does have limitations. Ray-tracing treats the source signal like a bouncing particle, so it misses some of the wave propagation details that require finite element analysis to model more accurately. For example, it does not model sound going around corners well, so the “acoustic shadow” can be exaggerated in size and shape.[66] As always, models are useful to make predictions and compare different options, but the results must be checked to make sure they make sense.[67]

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[65] Computation times depend on complexity of geometry, number of receivers, reverberation time, number of rays traced, and cutoff time. These numbers also have a big influence on the accuracy of the simulation.

[66] An exaggerated acoustic shadow shows up in my results.

[67] When possible, take acoustic measurements of the existing space and calibrate the simulation tool by making adjustments to the model or the simulation control parameters until the results are a good match to real conditions.

Method 2 process: 3D model, run simulation, analyze results

We now move from acoustic simulation in general to the specific details of how I used this approach in this project. As the flowchart in Figure 5.1 shows, there are four major steps to get from a 3D model of a space to a visualization of the room acoustic metrics.

Step 0: Install the software packages: *Rhino 6*, the *Pachyderm Acoustic* plug-in for Rhino, *Excel*, *Python*, and *matplotlib*.

Step 1: Set up model data for simulation (surface geometry elements, materials, receiver locations, source location and power spectrum). Build a 3D model in Rhino. Organize your model by layers, one for each different material type. Assign a material type to each layer (Rhino command “PachyDerm_Acoustic”). See Appendix B for materials and absorption coefficients. I used a *Grasshopper* script to set the receiver locations, source location and source power spectrum (see Appendix E for a view of the user interface control panel, a Grasshopper script).

Figure 5.2 explains the details about the source and receivers. Each source and each receiver has an (X,Y,Z) location. Location points are evenly spaced 5’ x 5’ apart on the floorplan. There are 202 receivers and one source per simulation. The source signal is a female speaker, modeled as an omnidirectional source with a voice power spectrum from the Pachyderm Acoustic speaker values (see Appendix C for the dB values by frequency).

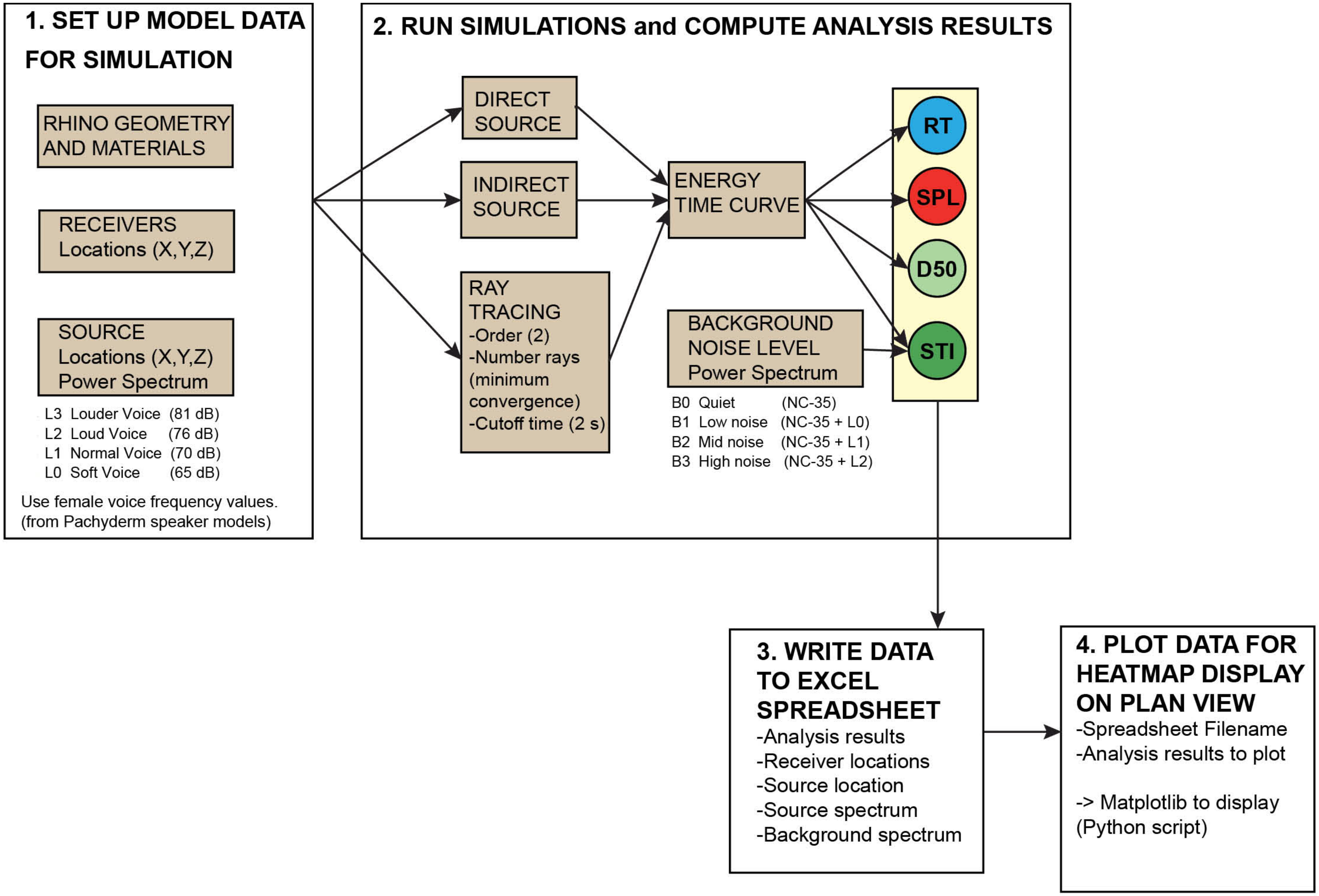
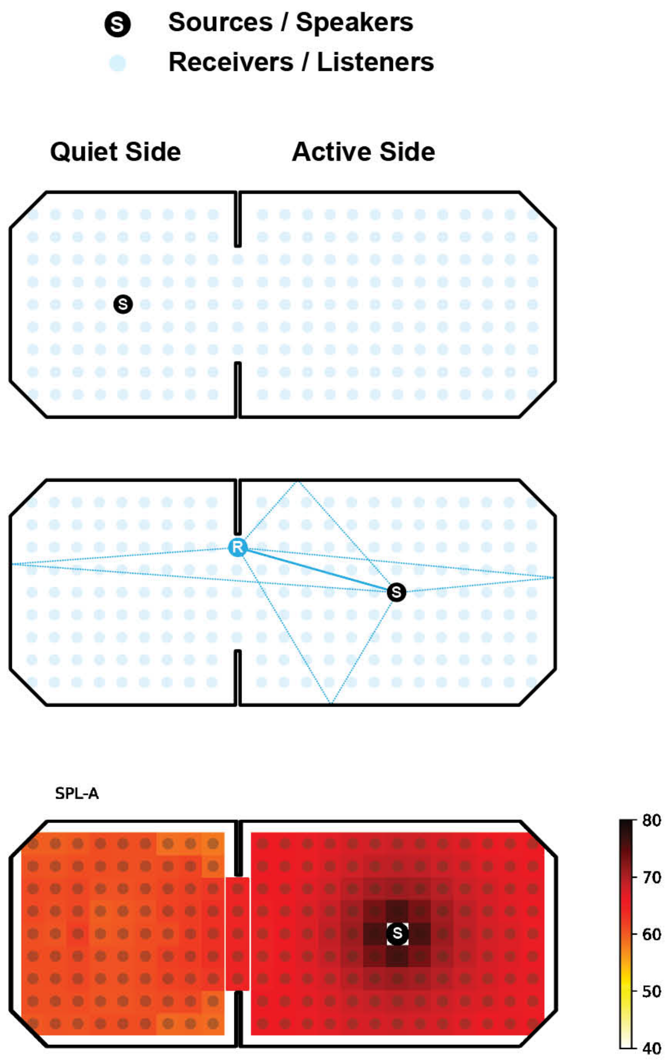


Figure 5.1. Flowchart of acoustic simulation workflow, from setting up the 3D model in Rhino, to running the simulation, to saving the results and finally displaying the room acoustic results as a heatmap display on a floorplan.



Location grid	Grid of points evenly spaced 5’ x 5’ apart on floorplan. (23 x 9 = 207 points with 4 removed at doorway wall) Total of 203 point locations used in simulations. 202 receivers + 1 source = 203 points
Receivers ●	202 receiver points, evenly spaced 5’ x 5’ apart (X,Y) coordinates for location on floor plan Z coordinate: 5’ above the floor
Source Ⓢ	1 source point per simulation (1 of 203 points) S1. Center of active side (gym) S2. Center of quiet side (cafeteria/commons) (X,Y) coordinate for location on floor plan Z coordinate: 5’ above the floor *(Future: sources for common situations* *lunch, gym class, assembly/performance)* *S3 (future). At a “quiet corner”* *S4 (future). At a stage near the short or long wall*
Source signal	Female speaker. Voice power spectrum from Pachyderm female speaker. (See Appendix C.) Omnidirectional source. L3 Louder Voice (81 dB) L2 Loud Voice (76 dB) L1 Normal Voice (70 dB) L0 Soft Voice (65 dB)

Figure 5.2. Location grid of points used for receivers and source locations, receivers, and source information for the simulations. Location points are evenly spaced 5’ x 5’ apart on the floorplan. There are 202 receivers and one source per simulation. Blue lines show the direct path between the source and one receiver (thick line) and first order indirect paths (thin, one reflection).

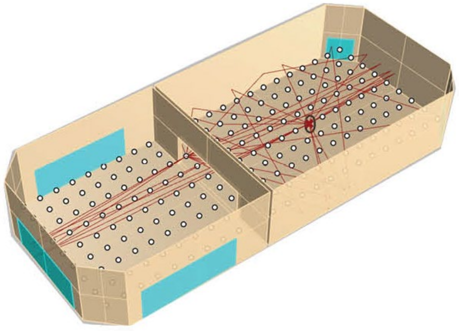


Figure 5.3. 3D view of Rhino model of two connected rooms version of Rockwell Elementary. The sound source is in the center of the active gym side and the 202 receiver locations are on a 5' x 5' grid. The red lines show the direct rays and second order indirect rays (two reflections) between the source location in the center of the gym/active area and one receiver location (in the doorway between the two rooms).

Step 2: Run simulation and compute analysis results for room acoustic metrics. Direct source and indirect source (2 reflections) are based on the room geometry and the source and receiver locations. The ray-tracing calculation is time consuming. I used the ray-tracing simulation parameters as follows:

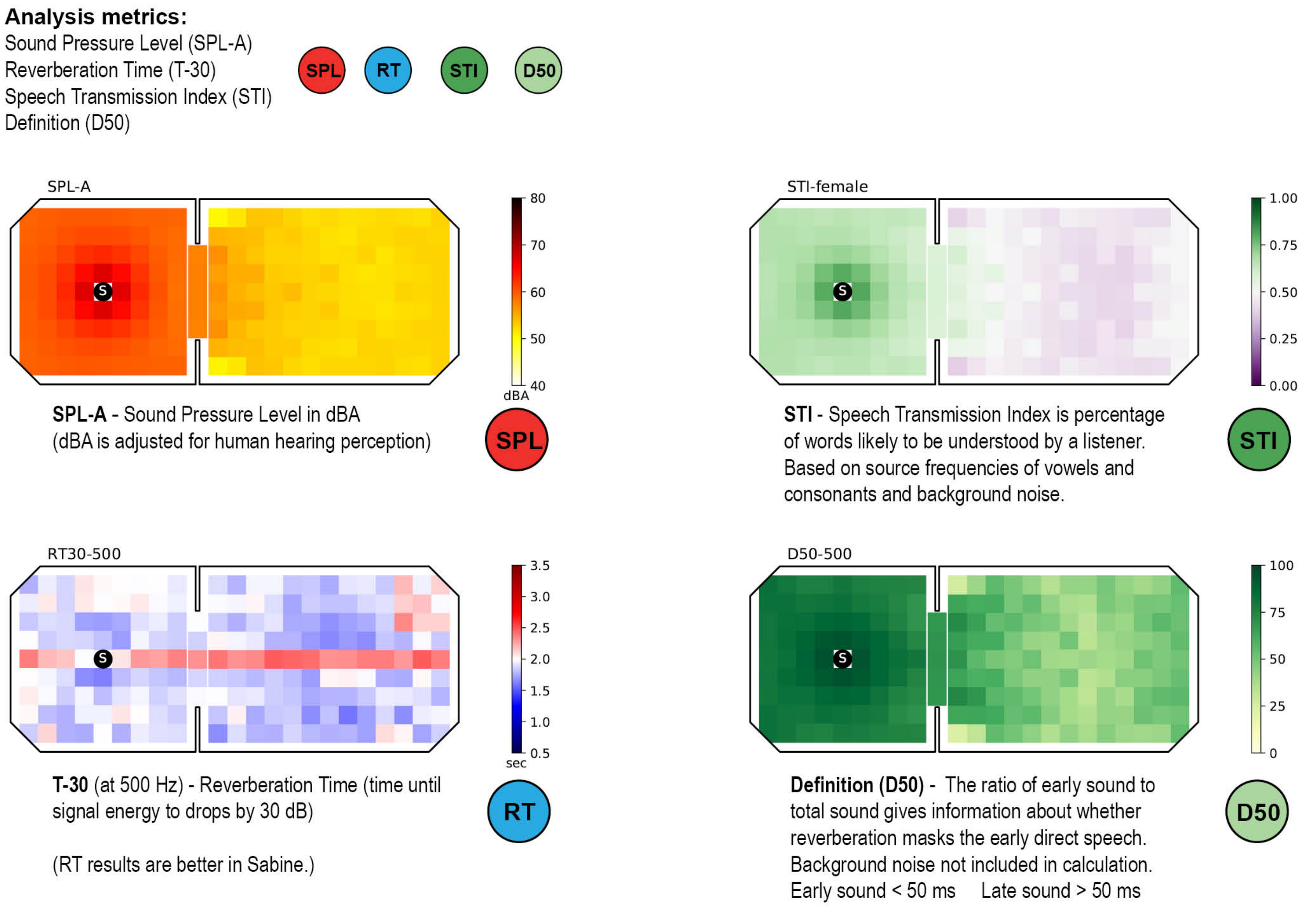
- number of rays: 10,000+, often 20,000+
  (“minimal convergence solution” setting)
- cut-off time: 2000 ms
- source image order: 2

The energy time curve (impulse response) is the combination of the direct source, indirect source, and the ray-tracing. Four room acoustic parameters are then computed from the impulse (T_{30}, SPL, STI, D_{50}).. Note that STI requires both the source power spectrum and a background noise level power spectrum (see Appendix C).

Step 3: Save the analysis results to a spreadsheet, one row per receiver location. Capture the input parameters describing the source, receivers, and background noise.

Step 4: Plot the analysis results as color-coded heatmap displays on the floorplan for data visualization and comparison. Choose between plotting the results of one simulation (all four acoustic metrics) or comparing one acoustic metric between two simulations (two input files, one metric).

Figure 5.4 shows an annotated example of the results of one simulation with all four metrics and a brief reminder of what they mean and how they are used in this analysis. Figure 5.5 shows examples of comparing one acoustic metric between two simulations to answer specific questions (first simulation, second simulation, and then the difference between the values at each location).



Analysis metrics:
Sound Pressure Level (SPL-A)
Reverberation Time (T-30)
Speech Transmission Index (STI)
Definition (D50)

SPL-A - Sound Pressure Level in dBA
(dBA is adjusted for human hearing perception)

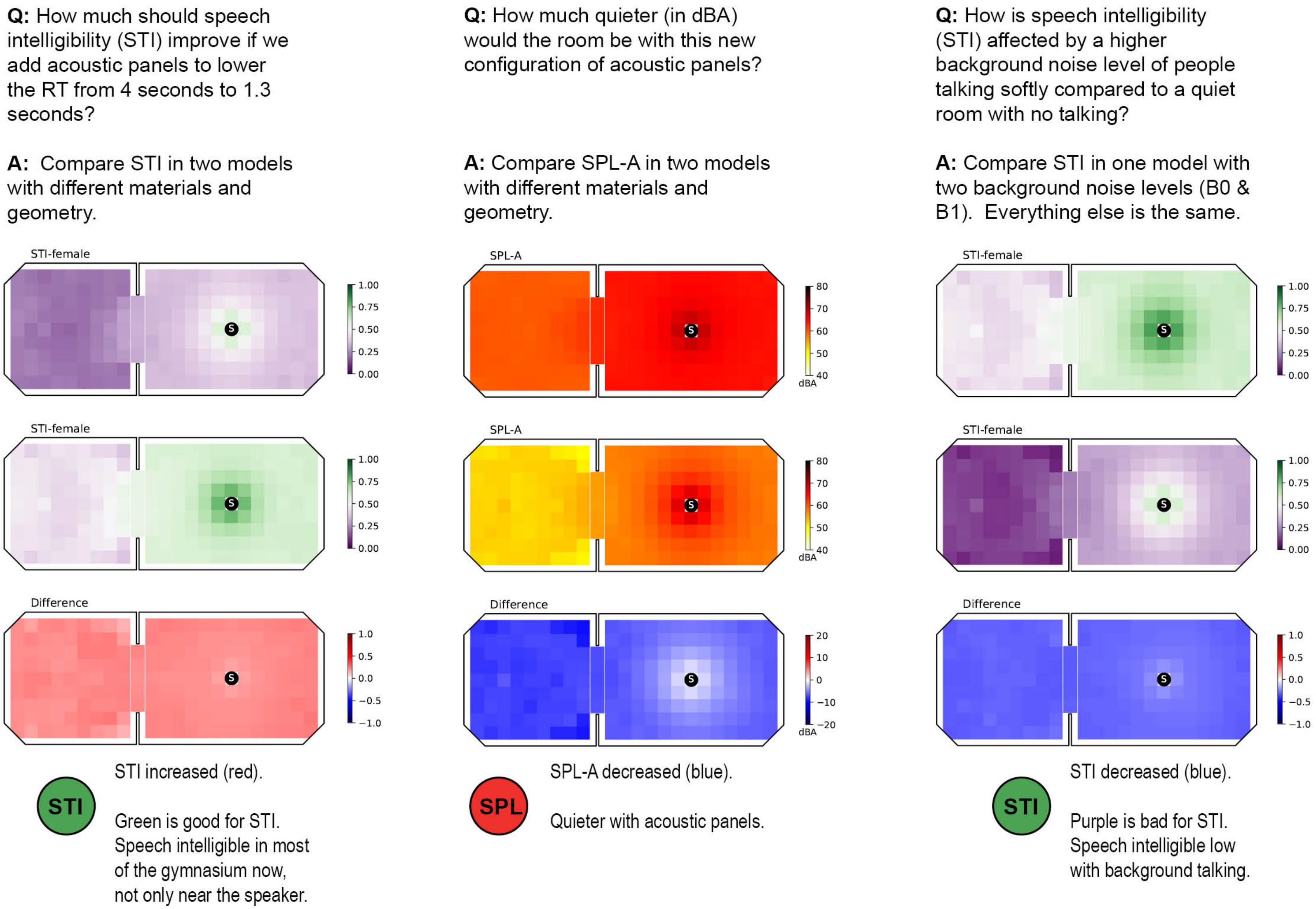
STI - Speech Transmission Index is percentage of words likely to be understood by a listener. Based on source frequencies of vowels and consonants and background noise.

T-30 (at 500 Hz) - Reverberation Time (time until signal energy to drops by 30 dB)

(RT results are better in Sabine.)

Definition (D50) - The ratio of early sound to total sound gives information about whether reverberation masks the early direct speech. Background noise not included in calculation.
Early sound < 50 ms Late sound > 50 ms

Figure 5.4. Four room acoustic analysis metrics (SPL-A, T30, STI, D50) are calculated at 202 receiver locations. The analysis results are first saved to a spreadsheet and then plotted on the floorplan (4 metrics, 202 data values). Data values are color-coded according to the scale shown to the right of each floorplan.



Q: How much should speech intelligibility (STI) improve if we add acoustic panels to lower the RT from 4 seconds to 1.3 seconds?

A: Compare STI in two models with different materials and geometry.

STI increased (red).

Green is good for STI. Speech intelligible in most of the gymnasium now, not only near the speaker.

Q: How much quieter (in dBA) would the room be with this new configuration of acoustic panels?

A: Compare SPL-A in two models with different materials and geometry.

SPL-A decreased (blue).

Quieter with acoustic panels.

Q: How is speech intelligibility (STI) affected by a higher background noise level of people talking softly compared to a quiet room with no talking?

A: Compare STI in one model with two background noise levels (B0 & B1). Everything else is the same.

STI decreased (blue).

Purple is bad for STI. Speech intelligible low with background talking.

Figure 5.5. Three questions that are answered by comparing between two simulations. From top: first simulation, second simulation, difference between values at each point. Red means the measure increased, and blue means the measure decreased.

Applying simulations to case study design options

So far in this chapter we have seen how a 3D model in Rhino can be used as to set up a geometric acoustic simulation that takes advantage of the spatial information, the materials information, and source information, and the background noise level. Much of this work is an extension of the thinking that we were doing in Chapter 4 when figuring out scenarios for the Sabine equation calculations. The difference for the simulations is that we specify the details on the 3D model itself instead in a list of surface areas. We have to be explicit in this method because each surface in the model is part of the simulation, so we have to model carefully. Build a simple model first and then add in details and change things as needed.[68]

This is a familiar workflow for designers who are used to 3D modeling software already. BIM software such as Revit have many details stored directly in the model. As students at the University of Washington we used Rhino with plug-ins and Grasshopper scripts to do daylight and thermal analyses and visualize the results as heatmap displays on floorplans or other model surfaces. What may not be as quite as familiar a way of thinking is the direct comparison "experiments" between two different conditions or design options. We are looking for data to inform our intuitions and hunches.

To return to the examples in Figure 5.5, the questions are set up to determine how much an acoustic parameter changes between two versions of the 3D modeled space (with and without acoustic panels). With the Sabine equation we figured out an approximate square footage of acoustic panels that would be necessary to lower the RT from 4 seconds to 1.3 seconds to meet the WSSP improved standards. With the acoustic simulation we can ask directly how the speech intelligibility (STI) should improve given the acoustic treatment, and indeed we see a huge improvement.

That was an example of fixed acoustics treatment for the room overall. Now we can try to design a cozy quieter corner within the larger room and look for evidence of the acoustic microclimate. The research question is "Do the acoustic treatments create microclimates that are quieter and offer higher intelligibility and more speech privacy for conversations as intended?" There are of course many different design strategies to accomplish this goal, but I will present one design option and the direct evidence and comparison-based evidence for it.

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[68] My advisor told me repeatedly to "build the wrong box," then fix it.

Consider the concept sketches in Figure 5.6 for design elements that might set up a cozy quieter corner. The overall room has the existing wood ceiling so we add wall absorption to get the reverberation time calculated by the Sabine equation down to less than 1.3 seconds. We then add a glass walled alcove to set aside a quieter corner for children who would appreciate that quieter experience during lunch. We have already run the simulation for the room without the alcove, and we experiment in the 3D model until we get something that we like and want to evaluate for evidence of a quieter microclimate.

In Figure 5.7 we see the results of the four room acoustic parameters. In the alcove corner the SPL-A display shows a quieter corner. The STI display shows a decrease in that corner, meaning that in the alcove one cannot understand the conversation in the main room very well, which is good for a quiet corner. The D50 display also seems to show less direct early sound in that corner. (It also shows a large region in the gym that looks like an acoustic shadow. It seems too extreme for a curtain.) Figure 5.8 shows the comparison evidence, and it is even clearer in the differences plots (all are blue for decrease).

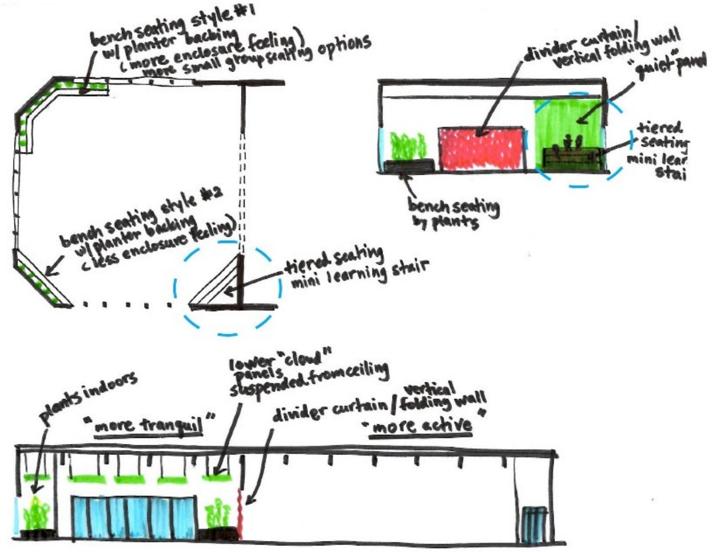


Figure 5.6. Sketches of possible features to set up a "more tranquil" cafeteria/commons addition in the footprint of the existing outdoor covered play area. Acoustic treatments on the walls and ceiling bring down the reverberation time. Curtains and doors can divide the two rooms into a "quiet side" and an "active side" or be open as one large space. We would like to have an even quieter experience in one of the corners of this space. One possibility is to create a glass walled alcove around one of the small learning stairs so that it is not as acoustically connected but still visually connected to the main space.

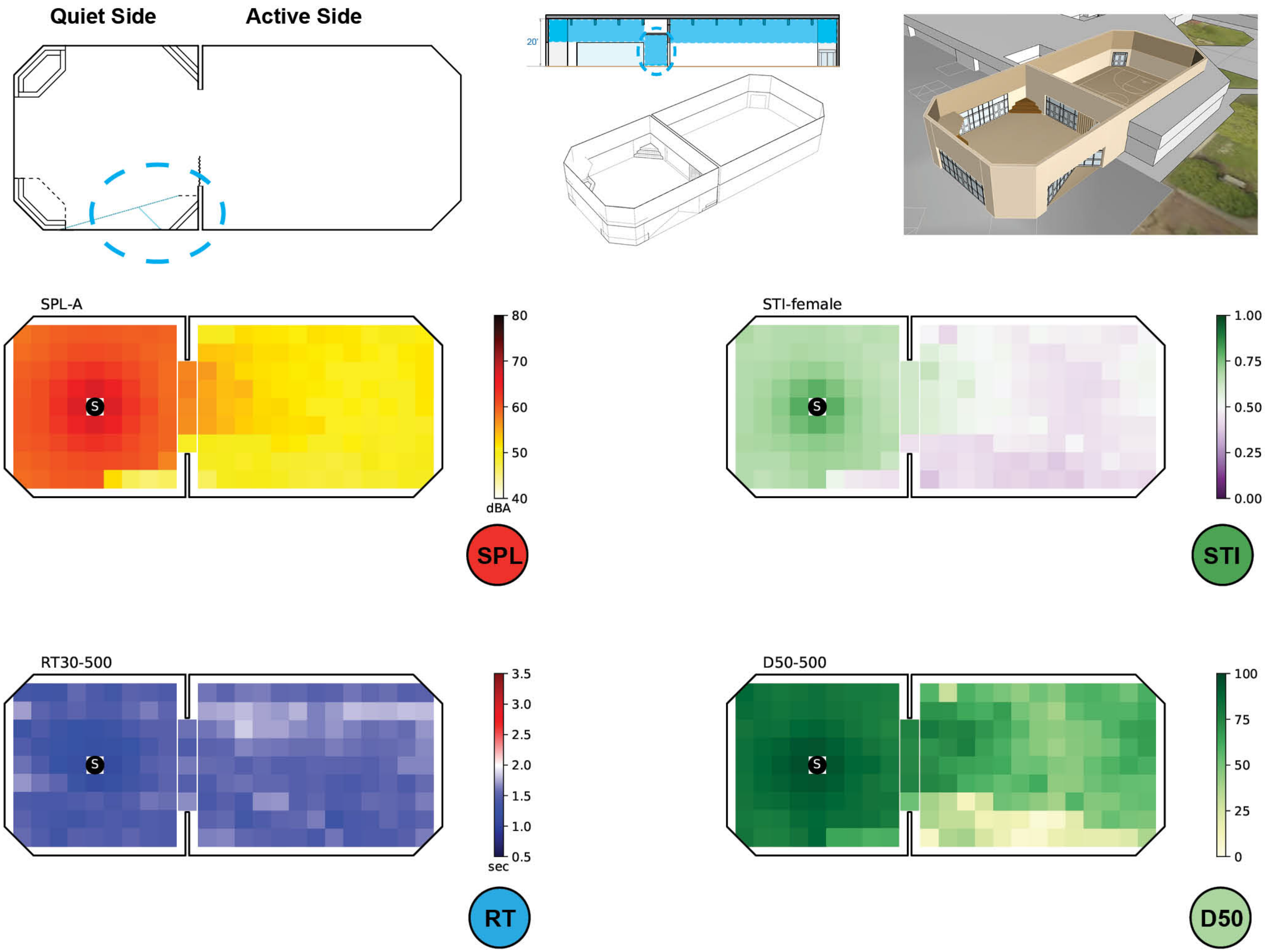
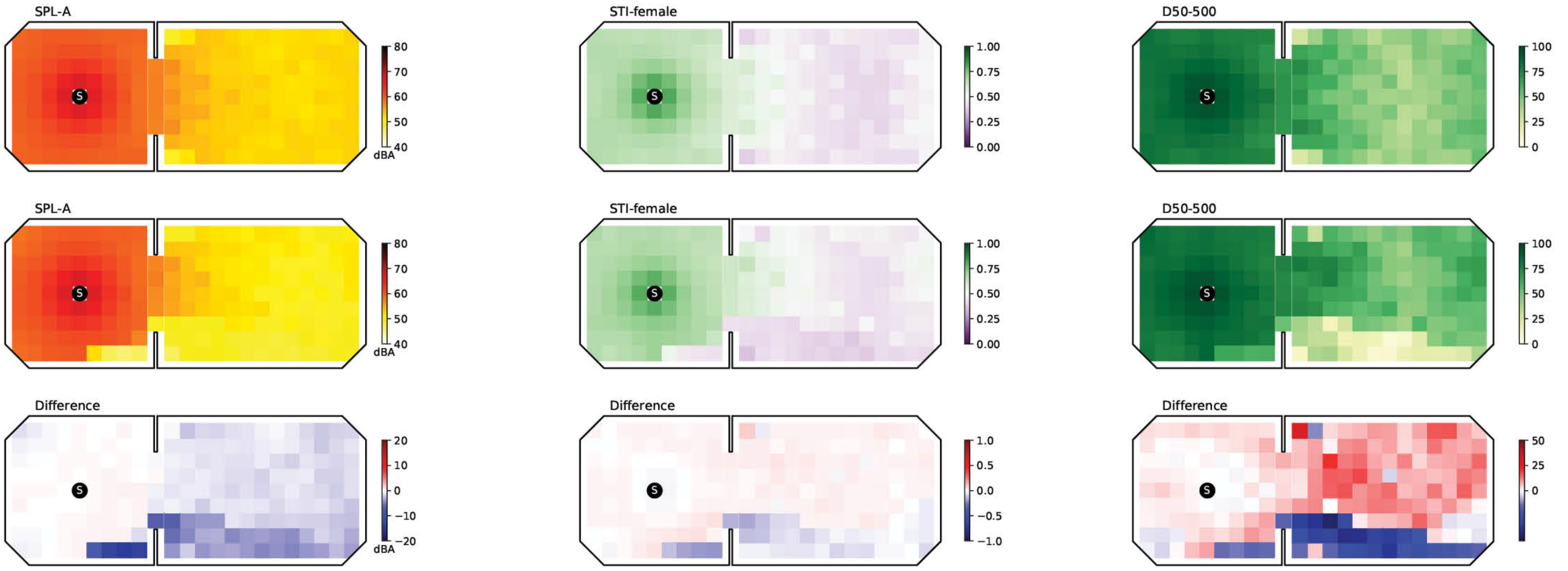


Figure 5.7. Evaluate microclimate treatment scenarios with simulations and acoustic analysis metrics.



SPL SPL-A decreased (blue).

Quieter in alcove corner.

STI STI decreased (blue).

Speech less intelligible (less intrusive) in alcove corner.

D50 D50 decreased (blue).

Less direct early sound in alcove corner and behind the curtain.

Figure 5.8. Comparison-based evidence for local acoustic microclimates in the glass alcove corner (and perhaps behind curtain). Research question: Do the acoustic treatments create microclimates that are quieter, high intelligibility / more private conversations as intended? Models have wood ceiling with wall absorption, with and without glass alcove and curtain. Sabine RT < 1.3 seconds. Source is the L3 female speaker, and the background noise level is NC-35.

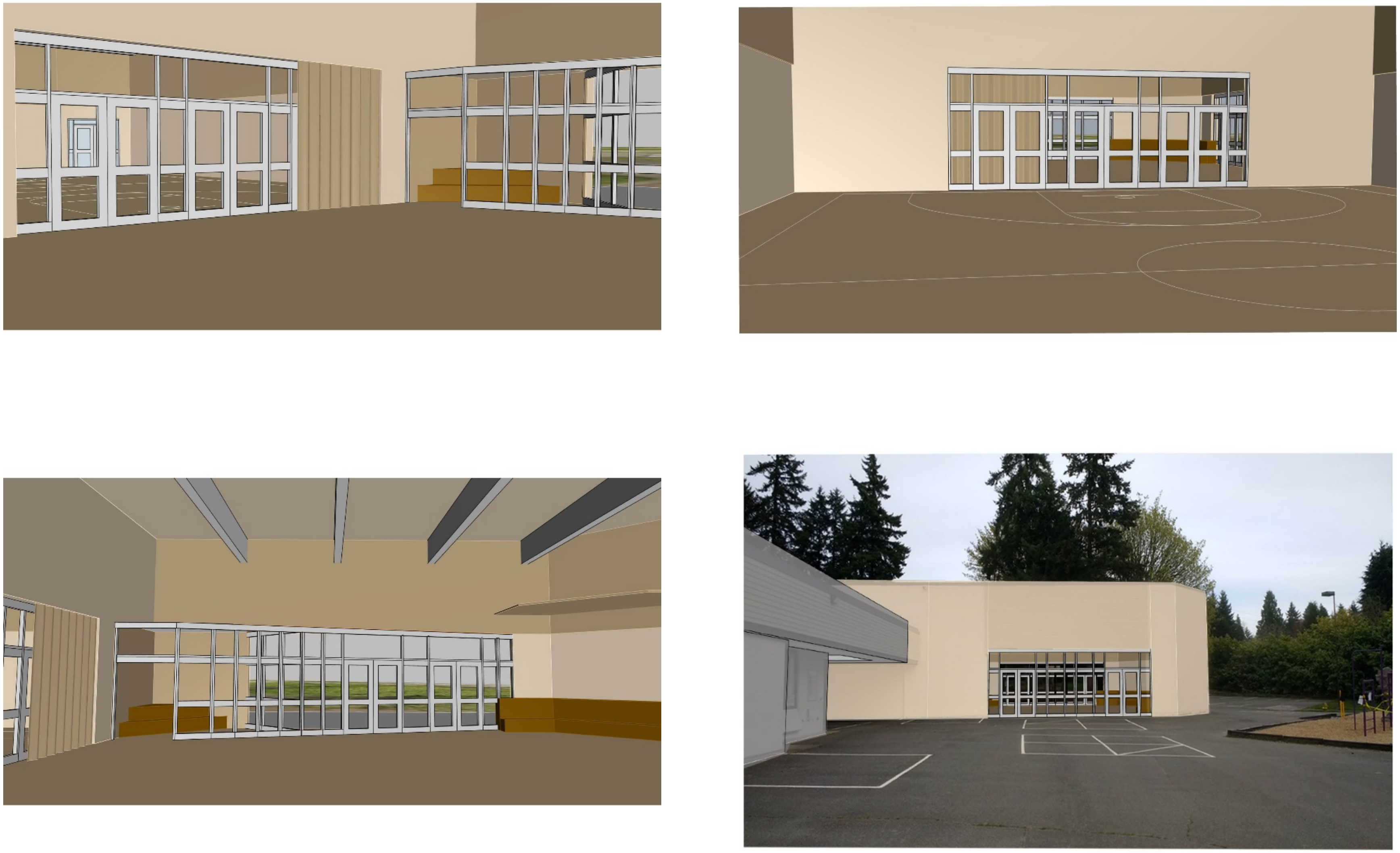


Figure 5.9. Views of the “quiet corner” alcove inside the proposed cafeteria addition for Rockwell Elementary.

Conclusions

The method of geometric acoustic simulations provides a lot of information about a room, including directly relevant information about how loud it is and how intelligible speech is likely to be in the room. Displaying multiple acoustic parameters simultaneously (for example SPL and STI) gives a much more complete profile of a room than one metric viewed separately. The comparison method of is a powerful tool for examining differences between two design alternatives. Designers can model design options and compare them to ask better and more informed questions than they may have in the past. They can use this kind of questioning that leads to modeling and simulations to grow their intuitions and enter into more informed conversations with their acoustical consultants.

Have I found a good solution to the design problem for my case study school, Rockwell Elementary? Yes, I think so. The acoustic defects of the existing covered play area and gymnasium are fixed. Calculations and acoustic standards guidelines suggest that the acoustic treatments that bring the reverberation time down from over four seconds to the WSSP improved acoustic performance level have significant health and experience improvements for students and teachers.[69] The gym teacher should be able to give instructions to the students more easily, the overall sound level should be reduced, and there is a new quiet alcove that can be used for respite from a busy day or to host small group meetings.

From the experience perspective, the expansion increases the seating capacity in a flexible way that can function as one larger room composed of two connected rooms or it can truly be two separate rooms when the connecting doors are closed. The new cafeteria expansion is built within the existing footprint, following the sustainable practice of building reuse. The existing gymnasium also gains an upgrade with better connection to the outdoors and views to the outside.

Have I come up with the best solution? No, I have not had a chance to work with a full design team and benefit from the exchange of ideas and the group collaborative process. I do feel that I have learned enough to be a strong team member who can talk knowledgably to an acoustic consultant and make good decisions. I also feel that I can be an advocate for the importance of including acoustic experience in the design of projects for children, especially

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[69] (The Collaborative for High Performance Schools (CHPS) 2018)

at the elementary school level where the research on classrooms shows that some kids need less reverberant rooms than the ANSI standards prescribe.

Do I believe that this design or one like it is worth doing and would improve the experience of students, teachers, and family members at Rockwell? Definitely, and I look forward to presenting these ideas to the principal when school reopens in the fall. And if some classes have to meet in the gymnasium because of physical distancing requirements in the time of COVID-19, then I would definitely recommend that the school move forward with an acoustic retrofit sooner rather than later so that learning has a better chance with less effort spent on trying to understand each other talk.

I believe that designers and architects who are not yet comfortable with the complexities of acoustics might be intrigued by seeing my sample questions and the color-coded results that start to answer those questions. They may find inspiration in this way of seeing acoustic information displayed on plans and start to think that maybe acoustics is not such an invisible and mysterious topic that only experts can engage with it. Acoustic experiences are for everyone, and designers are well positioned to join the conversation and add value, just as they are already doing with light and energy. What better place to start exploring and learning than at an elementary school?

6.

Conclusions and next steps

This thesis argues that it is important for architects to move beyond the business-as-usual approach to acoustics in which they meet the prescriptive requirements of acoustic standards by deferring to acoustic consultants. Architects should and can be much more involved in the acoustic qualities of the spaces they design. They can move beyond being satisfied with a “do no harm” approach. With improved awareness of the importance of acoustics to well-being and new tools in their toolkit, they should aspire to achieve much greater enhancement of acoustic well-being in our all-important educational facilities. Just as they design creatively with qualities of light and indoor-outdoor connections, it is time to add a measure of “acoustic delight” to each project, and to embrace the variety of sensory experiences that support a child’s social and emotional development.

Remember that all the acoustic codes and requirements about reverberation time and background noise level are fundamentally about improving the human experience and human health. They are about making the conditions right for good speech communication between students and teachers, making sure that they can understand each other, and that it is not too loud. But remember that the prescriptive code values are not the best values for all people, especially young children, second language learners, and children with sensory issues, who all do better with shorter reverberation times than those in the standards.

This thesis tries to balance understanding the human experience of an acoustic property with quantitative data that helps answer questions about the impact of a design decision on the acoustic experience in the space. No model is perfect, but a good model helps us explore answers to questions like the following:

- What is the acoustic experience for the people in the space?
- Is my cozy corner quieter than other parts of the room?
- What can I do as an architect to improve it?
- What can I do as an architect to give people agency over their acoustic environment?

These are the questions we need to be asking as a group of professionals. Use your insights as a designer and contribute to the lived sound experience. I hope that this thesis has inspired you to be more personally involved in designing for sound experiences and given you an idea of some tools that can help you understand acoustics better.

For me, next steps include more exploration of techniques for establishing acoustic microclimates within larger visually connected spaces. Heatmap displays of the results grid indicated the characteristics of acoustic microclimates within the space and were able to identify areas that were quieter and areas where speech intelligibility was higher within the large assembly space. Future work can capitalize on this workflow and test more design options in non-rectilinear rooms. New construction rather than acoustic retrofit will provide opportunities to develop acoustic microclimates from the start of a project. I will explore the influence of room geometry beyond room volume and location of added absorption beyond just the quantity of panels needed. I will also investigate non-rectilinear rooms with angled walls and sloped ceilings and adding elements like bleachers and other furniture to improve the mixing of sound and avoiding echoes. Acoustics is complex, and there is lots to learn. I am looking forward to being a fully participating member of the team.

Epilogue

Imagine leaning against the porch railing listening to the sounds of the woods – the tweet tweet and CAW CAW of the birds, the rustling leaves of the trees as the squirrel scrambles through the branches, the gentle whoosh of the breeze and the leaves rustle some more. A cloud moves and you feel the sun's warmth on your face and on your legs through your jeans. You grip the rail more tightly and close your eyes to hear the sounds around you more intensely. Even the sun on your face feels warmer. You hear click-thump as the door behind you opens and closes, and a classmate's footsteps thumping on the decking let you know she is passing right behind you. The thump, thump, thumps get quieter then turn into ting, ting, tings as she descends the metal stairs. Crunch crackle as she steps onto the gravel path, then a giggle in the distance as she runs on the grass toward the soccer field.

You open your eyes and see two other children at the other end of the railing observing the world as you are. Thump, thump, thump, ting, ting, ting, crunch crackle, and you step off the gravel path onto the soft springy mulch and smell its damp tang up close. You notice that the pumpkin on the vine in the planter box has grown since you checked on it Friday afternoon. This is the peaceful patio and quiet recess experience at Norman Rockwell Elementary's newest campus addition.

List of Figures

List of Recordings

Listen 1.	L1_BB_Entering_Covered_Area.wav	(basketball)
Listen 2.	L2_BB_2Outside_2Inside.wav	(basketball)
Listen 3.	L3_Voice_Echo_Rockwell.wav	(voice)

Listen 1.1.	L1-1_Gould_Court_91.wav	(relatively quiet)
Listen 1.2.	L1-2_Gould_Court_98.wav	(active)
Listen 1.3.	L1-3_Shorewood_Commons.wav	(moderate)

Appendix A. Reverberation time results for six ceiling types (24 rooms)

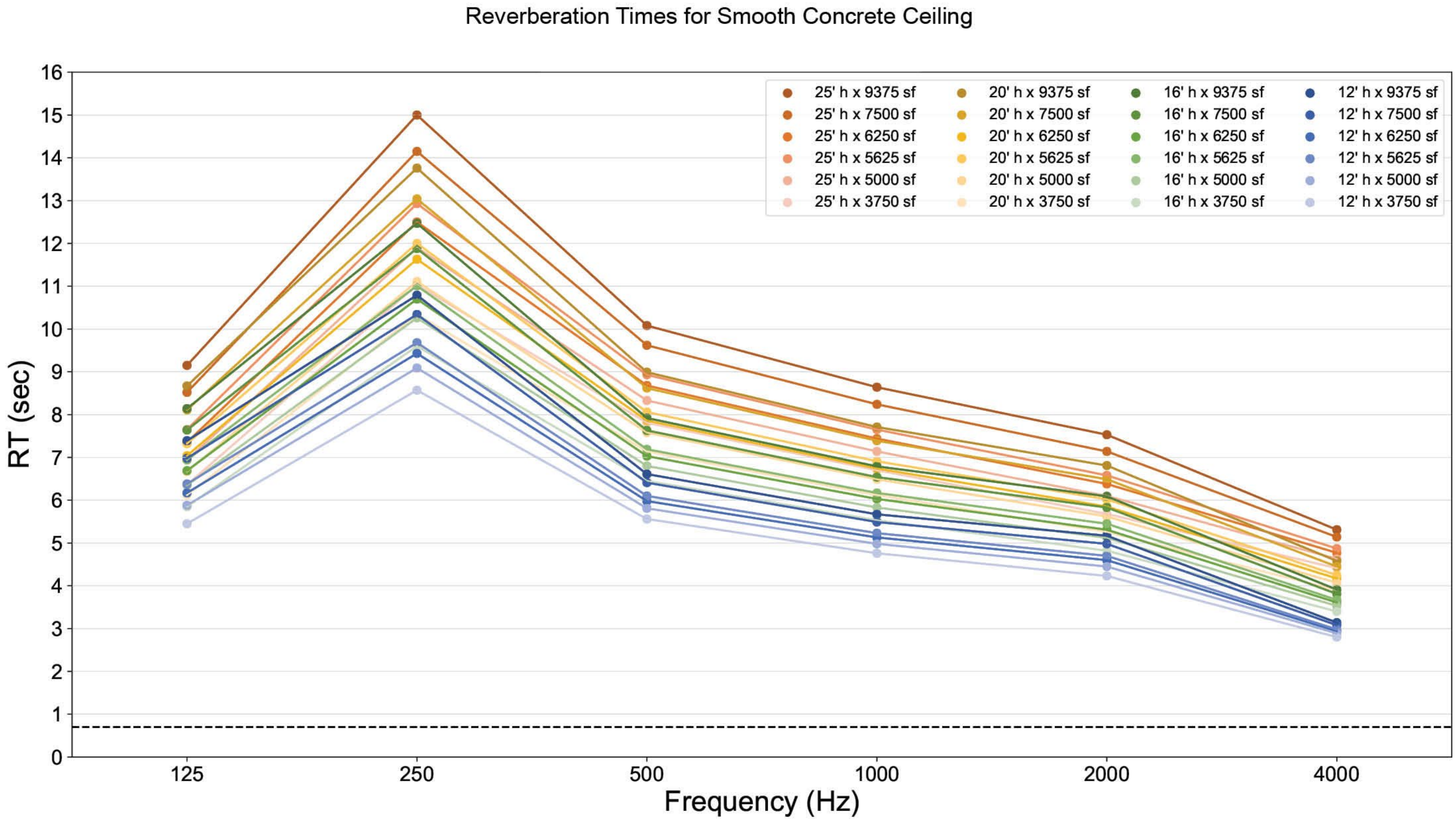


Figure A.1. Reverberation times for smooth concrete ceiling, 24 room volumes. CMU walls, vinyl on concrete floor.

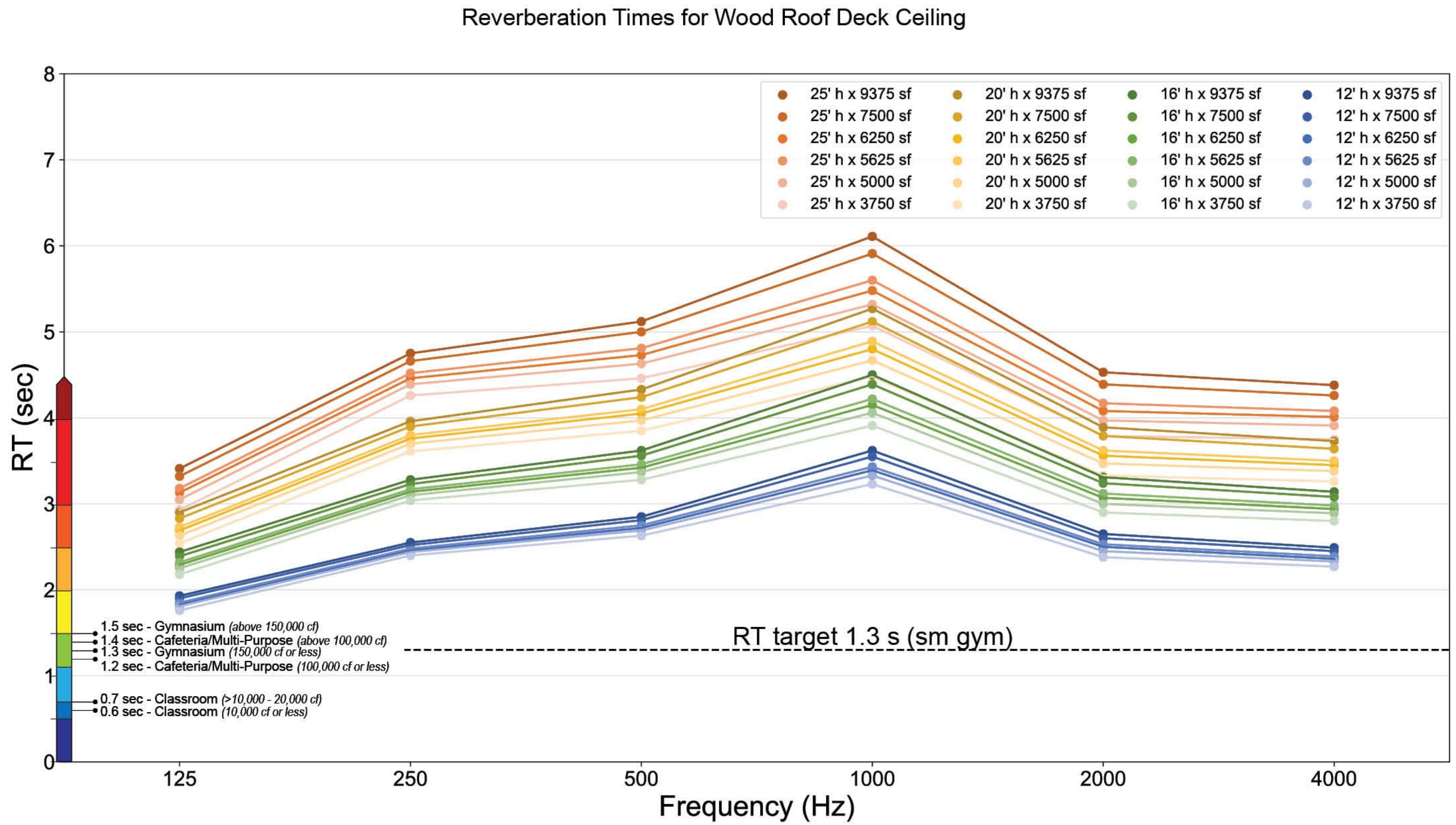


Figure A.2. Reverberation times for wood roof deck ceiling, 24 room volumes. CMU walls, vinyl on concrete floor.

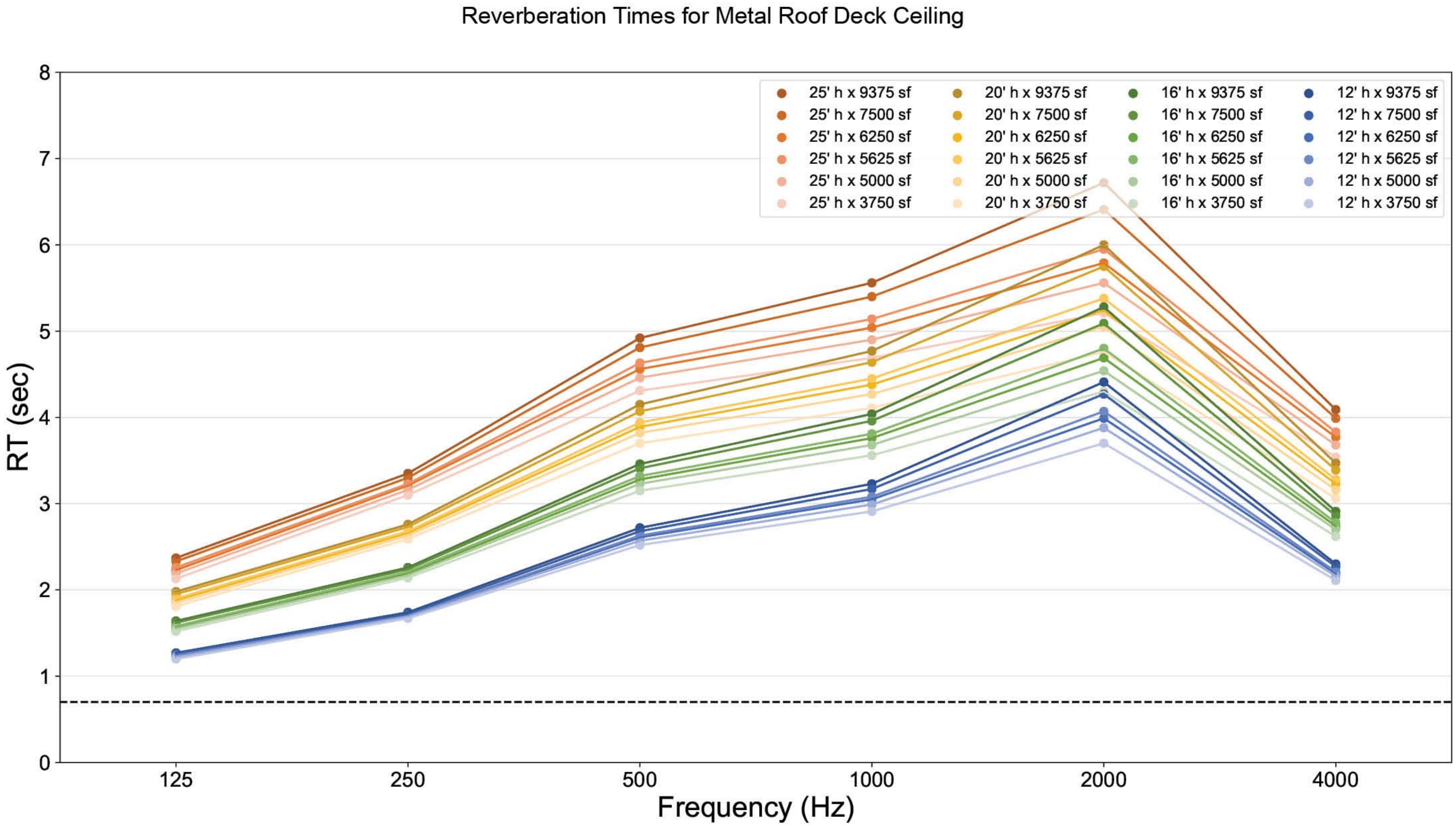


Figure A.3. Reverberation times for metal roof deck ceiling, 24 room volumes. CMU walls, vinyl on concrete floor.

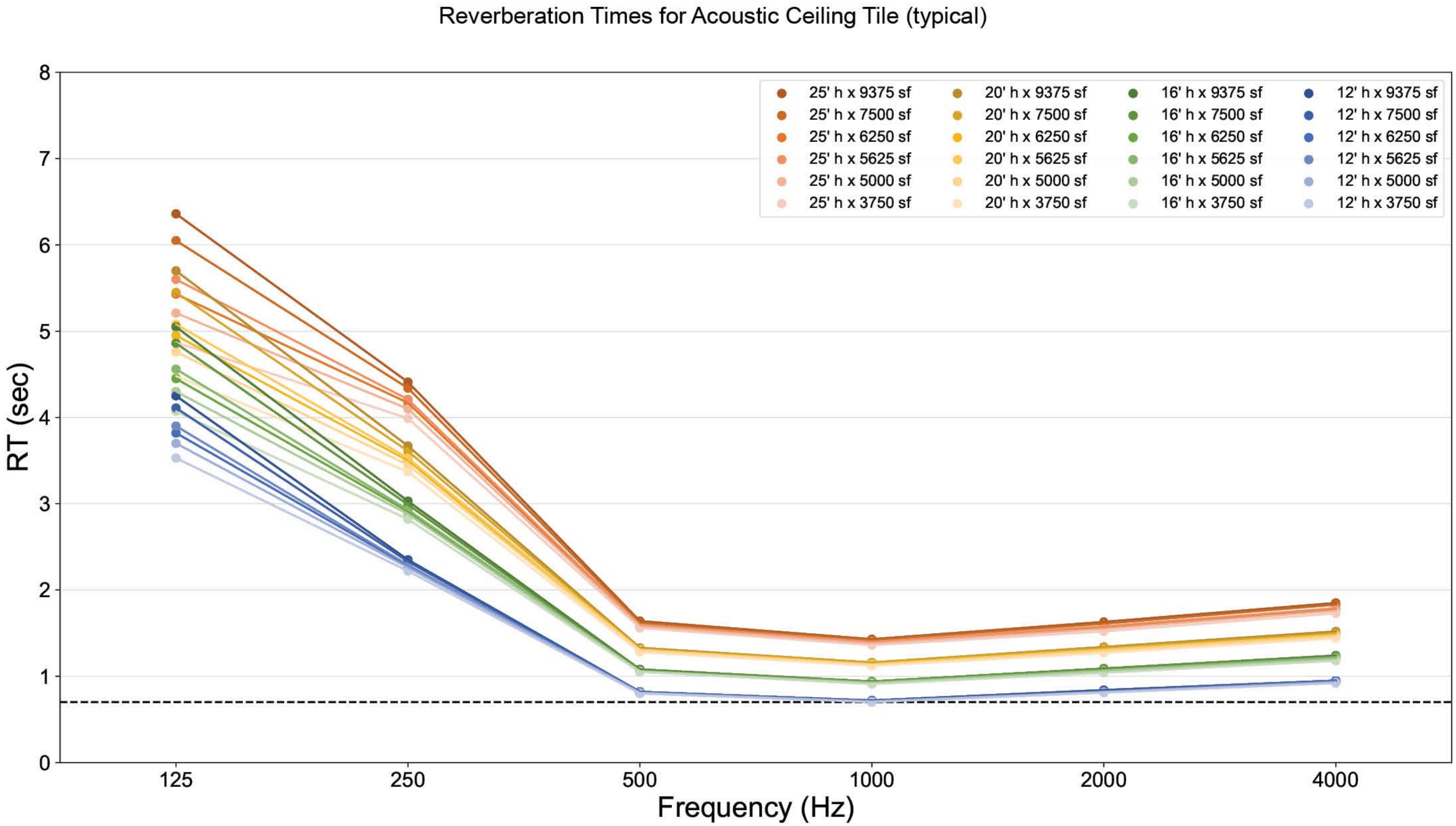


Figure A.4. Reverberation times for acoustic ceiling tile (typical), 24 room volumes. CMU walls, vinyl on concrete floor.

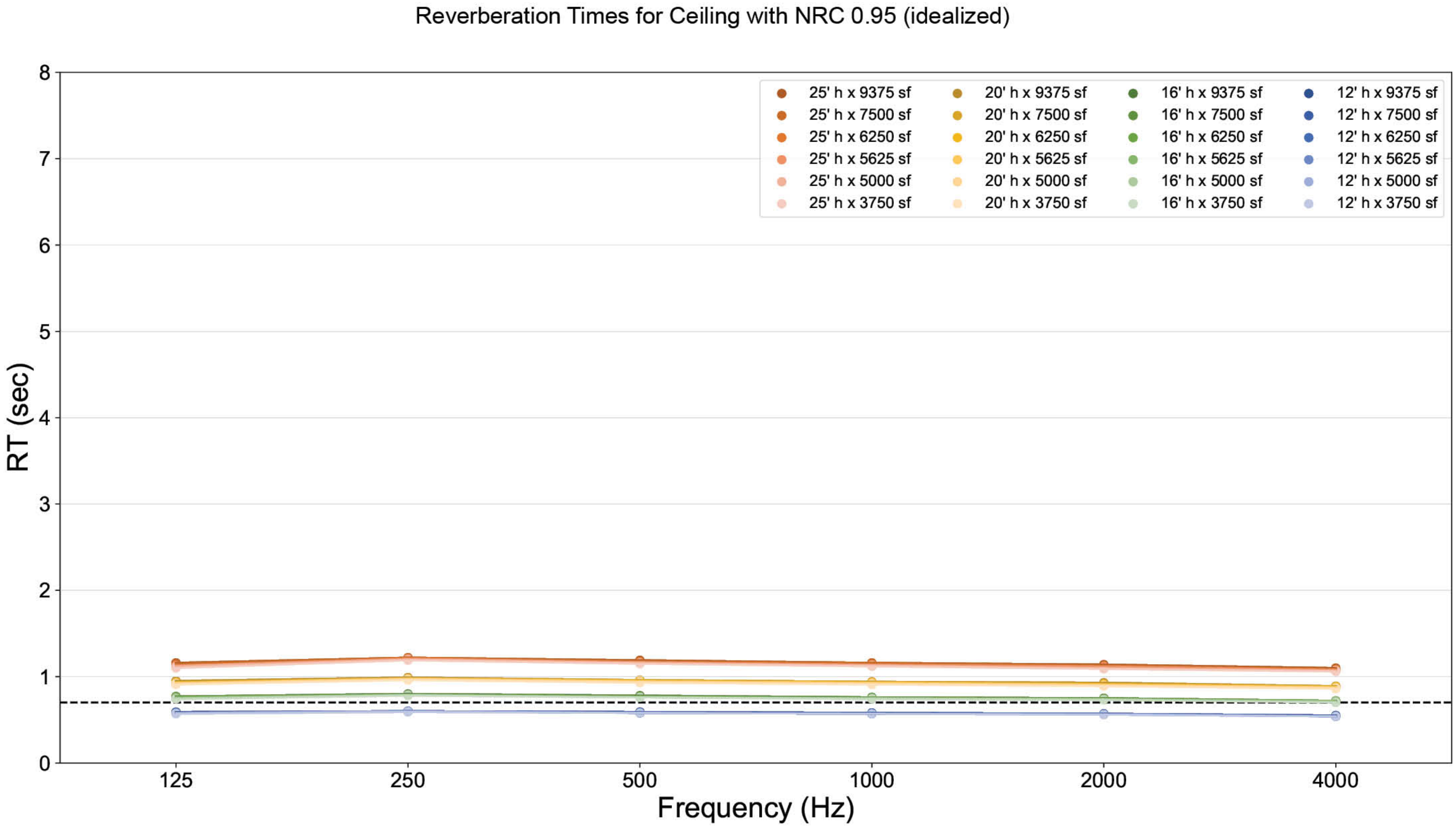


Figure A.5. Reverberation times for NRC 0.95 ceiling (idealized), 24 room volumes. CMU walls, vinyl on concrete floor.

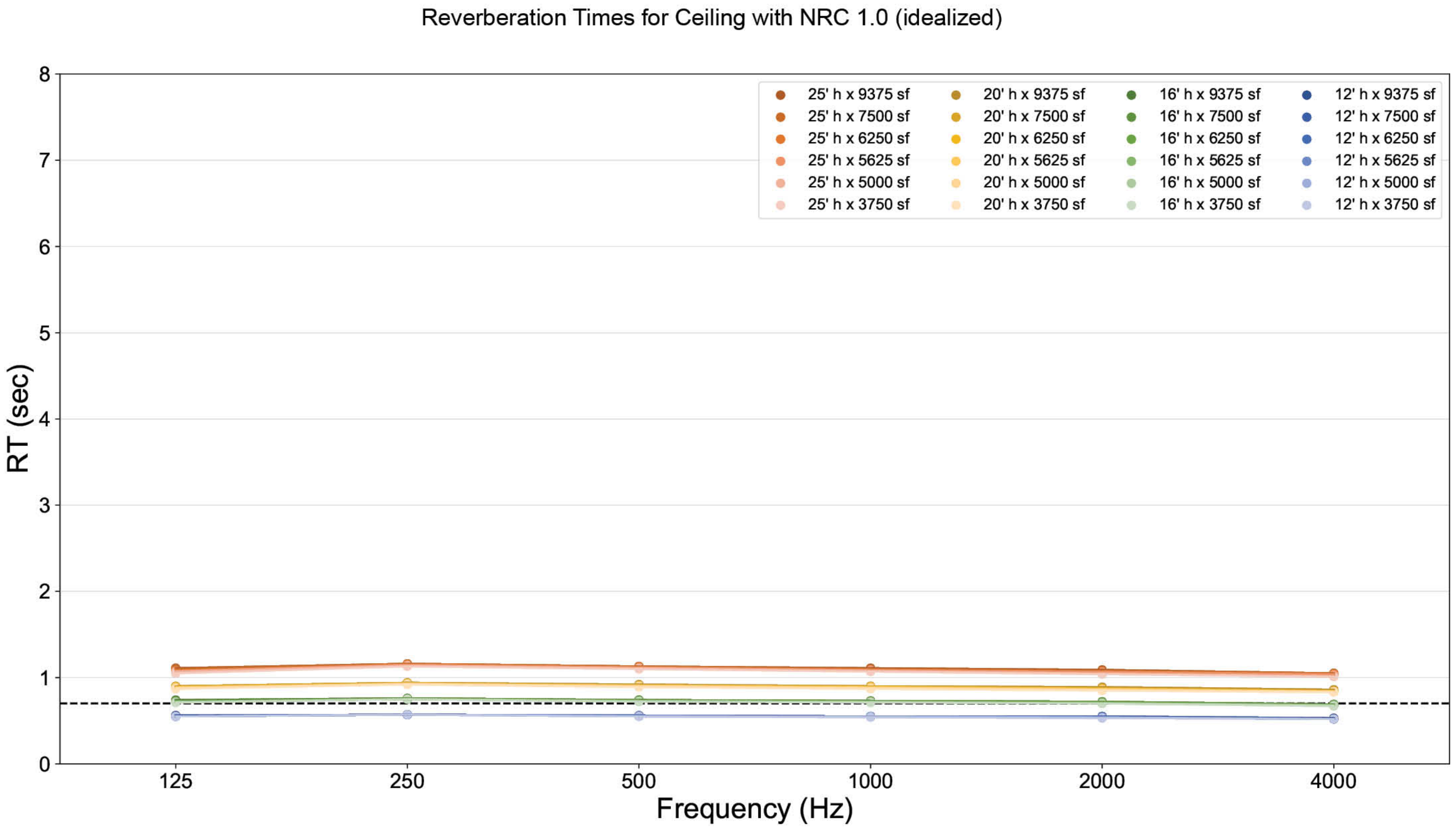
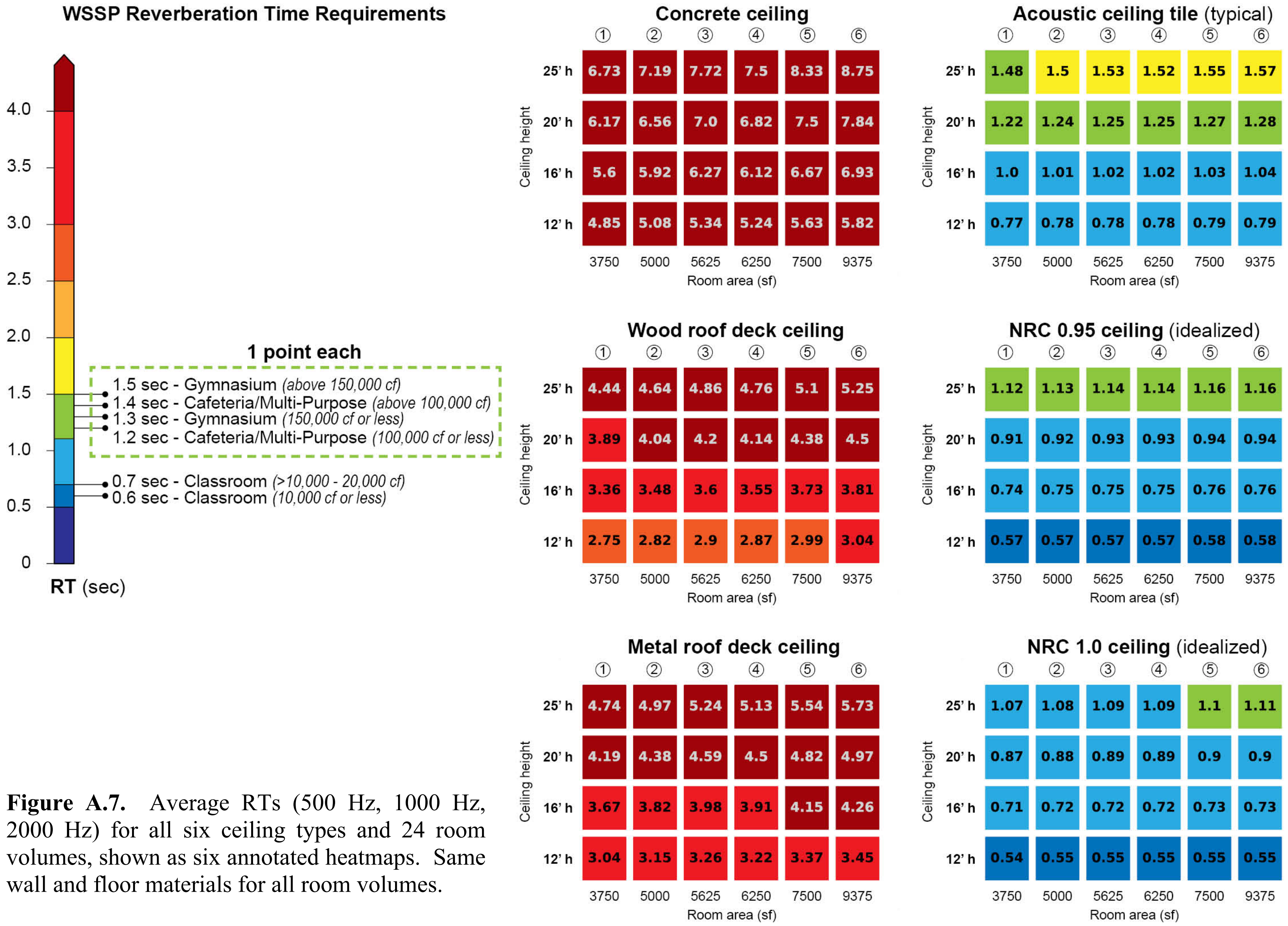


Figure A.6. Reverberation times for NRC 1.0 ceiling (idealized), 24 room volumes. CMU walls, vinyl on concrete floor.



1 point each

- 1.5 sec - Gymnasium *(above 150,000 cf)*
- 1.4 sec - Cafeteria/Multi-Purpose *(above 100,000 cf)*
- 1.3 sec - Gymnasium *(150,000 cf or less)*
- 1.2 sec - Cafeteria/Multi-Purpose *(100,000 cf or less)*

- 0.7 sec - Classroom *(>10,000 - 20,000 cf)*
- 0.6 sec - Classroom *(10,000 cf or less)*

Concrete ceiling

Ceiling height	① 3750	② 5000	③ 5625	④ 6250	⑤ 7500	⑥ 9375
25’ h	6.73	7.19	7.72	7.5	8.33	8.75
20’ h	6.17	6.56	7.0	6.82	7.5	7.84
16’ h	5.6	5.92	6.27	6.12	6.67	6.93
12’ h	4.85	5.08	5.34	5.24	5.63	5.82

Room area (sf)

Acoustic ceiling tile (typical)

Ceiling height	① 3750	② 5000	③ 5625	④ 6250	⑤ 7500	⑥ 9375
25’ h	1.48	1.5	1.53	1.52	1.55	1.57
20’ h	1.22	1.24	1.25	1.25	1.27	1.28
16’ h	1.0	1.01	1.02	1.02	1.03	1.04
12’ h	0.77	0.78	0.78	0.78	0.79	0.79

Room area (sf)

Wood roof deck ceiling

Ceiling height	① 3750	② 5000	③ 5625	④ 6250	⑤ 7500	⑥ 9375
25’ h	4.44	4.64	4.86	4.76	5.1	5.25
20’ h	3.89	4.04	4.2	4.14	4.38	4.5
16’ h	3.36	3.48	3.6	3.55	3.73	3.81
12’ h	2.75	2.82	2.9	2.87	2.99	3.04

Room area (sf)

NRC 0.95 ceiling (idealized)

Ceiling height	① 3750	② 5000	③ 5625	④ 6250	⑤ 7500	⑥ 9375
25’ h	1.12	1.13	1.14	1.14	1.16	1.16
20’ h	0.91	0.92	0.93	0.93	0.94	0.94
16’ h	0.74	0.75	0.75	0.75	0.76	0.76
12’ h	0.57	0.57	0.57	0.57	0.58	0.58

Room area (sf)

Metal roof deck ceiling

Ceiling height	① 3750	② 5000	③ 5625	④ 6250	⑤ 7500	⑥ 9375
25’ h	4.74	4.97	5.24	5.13	5.54	5.73
20’ h	4.19	4.38	4.59	4.5	4.82	4.97
16’ h	3.67	3.82	3.98	3.91	4.15	4.26
12’ h	3.04	3.15	3.26	3.22	3.37	3.45

Room area (sf)

NRC 1.0 ceiling (idealized)

Ceiling height	① 3750	② 5000	③ 5625	④ 6250	⑤ 7500	⑥ 9375
25’ h	1.07	1.08	1.09	1.09	1.1	1.11
20’ h	0.87	0.88	0.89	0.89	0.9	0.9
16’ h	0.71	0.72	0.72	0.72	0.73	0.73
12’ h	0.54	0.55	0.55	0.55	0.55	0.55

Room area (sf)

Figure A.7. Average RTs (500 Hz, 1000 Hz, 2000 Hz) for all six ceiling types and 24 room volumes, shown as six annotated heatmaps. Same wall and floor materials for all room volumes.

Appendix B. Absorption coefficients used in calculations and simulations

Material references	A 125	A 250	A 500	A 1000	A 2000	A 4000	Source
Ceiling							
Smooth unpainted concrete	0.01	0.01	0.02	0.02	0.02	0.05	Cox & D'Antonio
Wood roof deck	0.24	0.19	0.14	0.08	0.13	0.1	Mehta p 407
Metal roof deck, plain	0.4	0.3	0.15	0.1	0.04	0.12	Mehta p 408
Acoustic tile, 1.27 cm thick (typical)	0.07	0.21	0.66	0.75	0.62	0.49	Cox & D'Antonio
NRC 0.95, idealized material (generic)	0.95	0.95	0.95	0.95	0.95	0.95	(NRC 0.95 = avg of 250, 500, 1000, 2000)
NRC 1.0, idealized material (generic)	1	1	1	1	1	1	(NRC 1= avg of 250, 500, 1000, 2000)
Floor							
Layer of vinyl & underlay, stuck to concrete	0.02	0.02	0.04	0.05	0.05	0.1	Cox & D'Antonio
Walls							
Concrete block, painted	0.1	0.05	0.06	0.07	0.09	0.08	Cox & D'Antonio
Acoustic wall panels (generic) NRC 0.95, idealized material	0.95	0.95	0.95	0.95	0.95	0.95	(NRC 0.95 = avg of 250, 500, 1000, 2000)
Glass							
Double glazing, 2-3 mm glass, 1 cm gap	0.1	0.07	0.05	0.03	0.02	0.02	Cox & D'Antonio p 478
Curtains							
Cotton curtains, 0.475 kg/m2, draped to 3/4 area (“fabric 133%”)	0.04	0.23	0.4	0.57	0.53	0.4	Cox & D'Antonio p 475
Cotton curtains, 0.475 kg/m2, draped to 1/2 area (“fabric 200%”)	0.07	0.37	0.49	0.81	0.65	0.54	Cox & D'Antonio p 475
Air							
Air attentunation coeff "m" (sabins/ft)				0	0.003	0.008	Mehta p 85

Appendix C. Source signals and background noise levels used in simulations (dB)

	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz	Source
Female Speaker									
L0 Soft Voice (65 dB)	60	52	59	63	55	52	49	49	Pachyderm Acoustic “Soft or whispered”
L1 Normal Voice (70 dB)	31	41	64	67	61	56	54	53	Pachyderm Acoustic “Conversation”
L2 Loud Voice (76 dB)	31	42	67	71	71	66	62	57	Pachyderm Acoustic “Competing Conversation”
L3 Louder Voice (81 dB)	31	46	67	74	76	75	73	63	Interpolated (between CC & “Shouting”)
Background Noise Level									
B0 Quiet (NC-35)	60	52	45	40	36	34	33	32	NC-35
B1 Low noise	60	52	59	63	55	52	49	49	NC-35 + L0
B2 Mid noise	60	52	64	67	61	56	54	53	NC-35 + L1
B3 High noise	60	52	67	71	71	66	62	57	NC-35 + L2

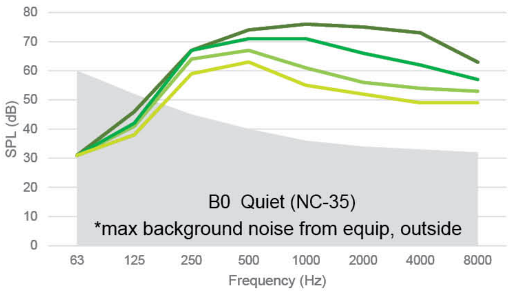
Appendix D. Speech Intelligibility: Background noise of other talkers in the room

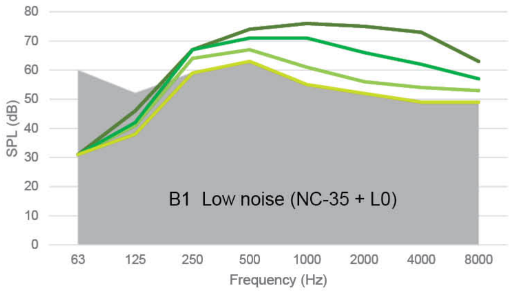
Speech Intelligibility: Background noise of other talkers in the room

SPL ***How loud is it?***

STI ***How well can people be understood?***

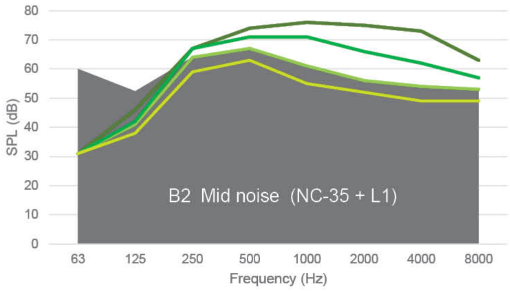
Source signals & background noise levels



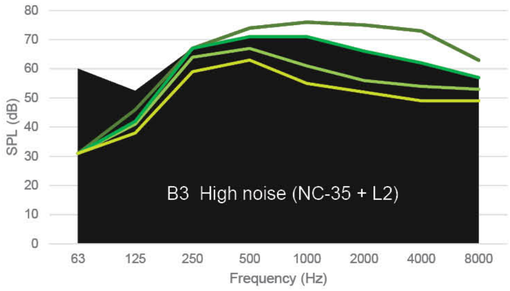


Source: Female Voice

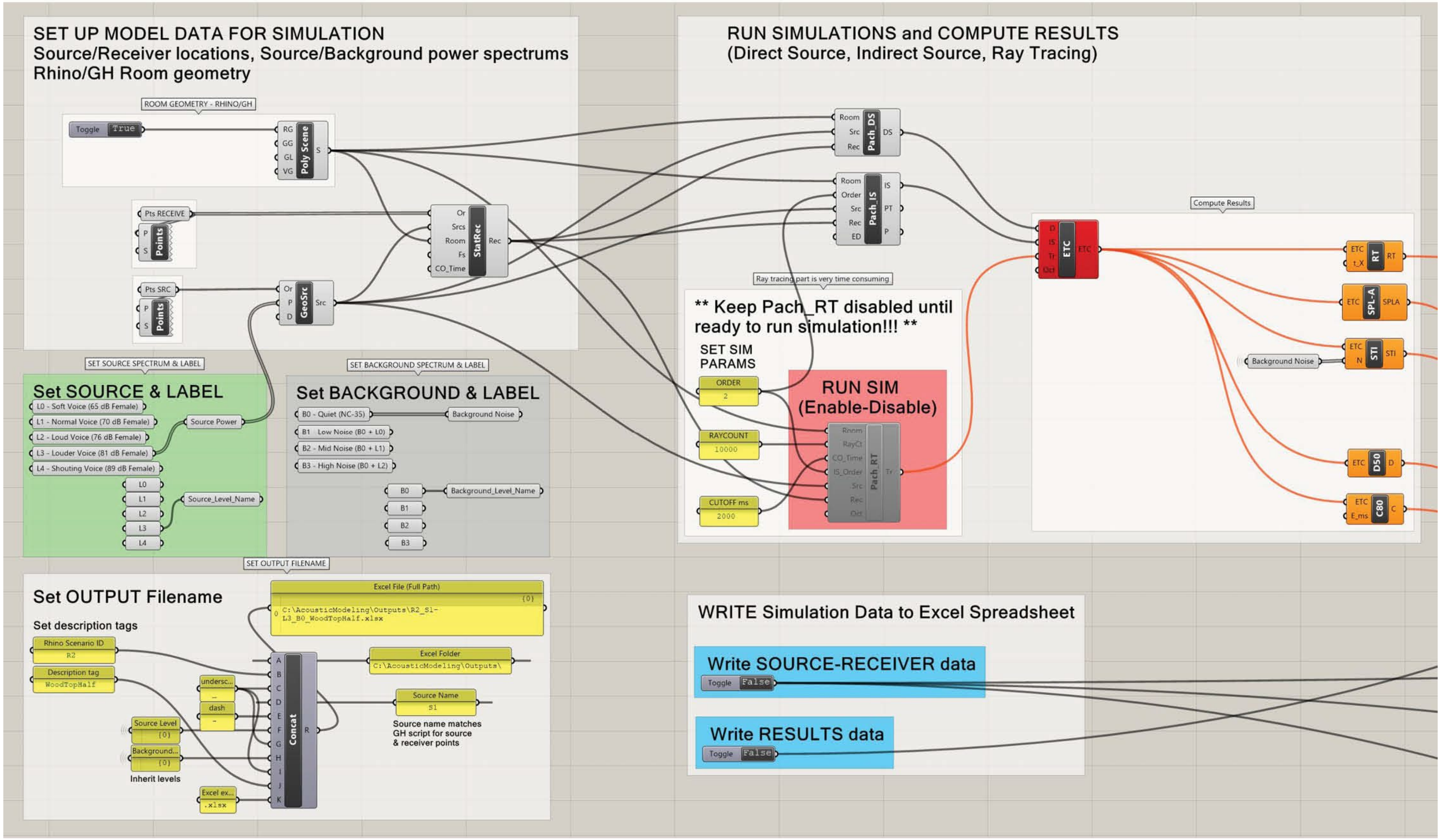
- L3 Louder Voice (81 dB)
- L2 Loud Voice (76 dB)
- L1 Normal Voice (70 dB)
- L0 Soft Voice (65 dB)



A signal-to-noise ratio of at least 15 dB
is required for good **speech intelligibility**.
Lower than 15 dB means lower speech intelligibility.



Appendix E. User interface control panel for acoustic simulations within Rhino (Grasshopper script)



SET UP MODEL DATA FOR SIMULATION
Source/Receiver locations, Source/Background power spectrums
Rhino/GH Room geometry

RUN SIMULATIONS and COMPUTE RESULTS
(Direct Source, Indirect Source, Ray Tracing)

Set SOURCE & LABEL

Set BACKGROUND & LABEL

Set OUTPUT Filename

Set description tags

Rhino Scenario ID: R2

Description tag: WoodTopHalf

Excel File (Full Path): C:\AcousticModeling\Outputs\R2_S1-L3_B0_WoodTopHalf.xlsx

Excel Folder: C:\AcousticModeling\Outputs\

Source Name: S1

Source name matches GH script for source & receiver points

Inherit levels

Ray tracing part is very time consuming

** Keep Pach_RT disabled until ready to run simulation!!! **

SET SIM PARAMS

ORDER: 2

RAYCOUNT: 10000

CUTOFF ms: 2000

RUN SIM (Enable-Disable)

WRITE Simulation Data to Excel Spreadsheet

Write SOURCE-RECEIVER data

Write RESULTS data

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