4.2 Acoustics

4.2: (1 Credit: Implement 4 of 7)

- Acoustical features are compatible with the requirements of the space. This includes meeting all acoustical privacy and speech intelligibility requirements.
- Acoustic design incorporates assistive listening systems.
- Noise and vibration from building systems are minimized.
- The volume of background music and other entertainment systems are controllable.
- Doors and windows are designed to the appropriate sound transmission class (STC).
- Walls are designed to the appropriate sound transmission class (STC)
- Sound flanking paths are controlled.
- Acoustic design is commissioned as per ASHRAE guide.

1. Overview

The acoustical environment is determined by the sounds introduced into the space and is directly affected by the surfaces of materials chosen to enclose the space. Successful acoustical conditions can greatly increase the comfort of a space, while poor acoustics can result in uncomfortable and unhealthy environments due to undesirable stress. The acoustical demands of a space should be considered at the earliest stages of the design phase to avoid unfavorable aural conditions.

Figure 1: Auditorium of the Central Intelligence Building illustrating acoustic design features such as sound absorbent cloth seats, large plaster disks which enhance the acoustics of the space. Image courtesy of [U.S. CIA Image Library]

While the semicircular outdoor amphitheaters designed by the Ancient Greeks illustrated an empirical understanding of sound propagation, generation and perception, by providing good sight lines and reduced grazing attenuation, it wouldn't be until the early 20th century that the American National Standards Institute (ANSI), appointed the Acoustical Society of America (ASA) to sponsor a committee that would standardize acoustical terminology and measurements [1,2]. It was at this time that practices implemented by the Greeks over two millennia ago, were formally included in modern acoustical standards, regulations and recommendations. The study of acoustics had expanded so much throughout the 20th century that the ASA eventually created four specialized standards committees: S1 on *Acoustics*, S2 on *Mechanical Shock and Vibration*, S3 on *Bioacoustics* and finally, S12 on *Noise* [2]. These committees are responsible for producing, developing and adopting standards in accordance with ANSI approved procedures [2].

In general, the acoustic performance of a space is determined by background noise present, noise isolation from adjacent spaces, and the reverberation time and speech intelligibility within the space [3]. Commonly, the way in which these factors are controlled are through the selection of appropriate site locations (in relation to both outdoor and indoor environmental noise sources); through the design of effective acoustical room boundaries; by providing sufficient attenuation to the HVAC systems; and by selecting appropriate room finishes and materials [4].

When these strategies are not sufficient, e.g. open offices, cubicle farms or spaces utilizing flexible wall partitions that do not penetrate hung ceiling planes, sound masking systems should be implemented. Architectural acoustic design typically aims to optimize the signal to noise ratio of the acoustic environment by controlling unwanted noise while enhancing desired sounds (the signal), such as desired verbal communication between individuals [5].

2. Issues to Consider

Human Hearing and Hearing Loss: Sound is the sensation of pressure variations occurring in the air around us [6]. These variations enter the outer ear in the form of vibrations, where they impact the eardrum and are transmitted towards the middle and inner ear [7]. Once the vibration reaches the middle ear three small bones (malleus, incus and stapes) amplify and transmit the vibration to the inner ear [7]. The sound energy then travels to the fluid filled cochlea where microscopic hairs known as cilia, convert the sound waves into nerve impulses and deliver the impulse to the brain, which interprets the signals as sounds [7]. Noise is unwanted sound, particularly that which is annoying to building occupants. Exposure to loud, excessive or chronic noise can damage and/or destroy the cilia, leading to hearing loss [3].

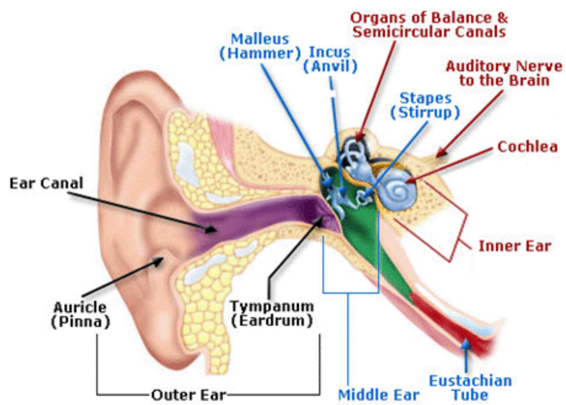


Figure 2: Anatomy of the human ear. Image courtesy of the [U.S. Department of Labor Image Library](#).

According to the World Health Organization (WHO), hearing loss is the most prevalent, preventable disability in the world and can be generally categorized as either sensorineural (SNHL) or conductive [8,9]. SNHL, the most common type of permanent hearing loss, occurs when there is damage to the cochlea or to nerve pathways from the inner ear to the brain, and isn't typically correctable through medical or surgical interventions [8]. Whereas conductive hearing loss is usually a result of illness or genetic defect and can often be corrected through medical intervention [8].

For individuals suffering from hearing loss, volume increases of about 15 – 25 dB are required to achieve the same level of understanding as persons with normal hearing [9]. Personal assistive devices such as hearing aids and cochlear implants can benefit individuals with hearing loss. Assistive listening systems (ALS) provide selective assistance to people who need higher volumes to hear voice or other sounds distinctly. ALS provided in occupied spaces increases volume without increasing the loudness for all occupants [9]. There are several different types of ALSs, most of which require deployment of special transmitters and receivers to individual users, click here for additional information on ALSs provided by the National Association of the Deaf (NAD) [10]. New technologies, similar to the Williams Sound® Hearing Hotspot featured here, are coming on line to provide personal control of digital systems produced through PA systems through wifi networks to smart phones. These systems do not require specialized receivers.

Location: When designing a successful acoustical environment, the outdoor noise levels need to be considered. For example, if a site is predetermined to be adjacent to increased highway or industrial noise, the designer can employ appropriate sound control measures (i.e. selection of windows and exterior materials with a high sound transmission classification) into the construction or orient/locate "noise sensitive" indoor spaces away from the sources of background noise[5]. Similarly, the acoustic requirements within each area of a building should also be considered vis a vis their adjacent spaces so that the indoor noise pollution can more easily be controlled. For example, noise pollution can adversely effect learning and concentration, therefore an educational facility should orient noisy areas such as hallways and gymnasiums away from rooms with more stringent acoustical requirements, such as libraries, performing arts spaces, and study areas [5] (for additional guidance on designing for educational environments see ANSI/ASA S12.60: Parts 1 & 2). Controlling construction costs is easier if these approaches are employed at the earliest stages of the design phase because changes after the completion of construction can often be significantly more difficult to implement and result in higher overall costs [5].

Sound Reflection, Transmission and Absorption: When sound waves hit a wall or surface, they will be distributed in different ways. The waves that bounce off of the material are said be *reflected*, the waves that pass through the material do so through *transmission*, and the waves that remain inside the material, are said to be *absorbed* [11]. These behaviors are dictated by the material composition of the wall or surface and by the frequency of the sound itself [12]. Surfaces that are most successful at reflecting sounds are dense, smooth, flat and large, i.e. block concrete, wood, glass or metal [11]. While reverberation of unwanted noise caused from high levels of reflection can lead to distraction and annoyance from noise pollution, appropriately utilizing reflective materials through directional orientation and wavelength calculations can also help to amplify desired sounds and increase speech intelligibility [13]. For example hanging reflecting panels from a ceiling can improve sound distribution and correct for directional sound focusing caused by concave ceiling surfaces [3].

Noise transmission, as it relates to architectural acoustics, is typically discussed in terms of a material's sound transmission class (STC); an STC rating is often provided by the manufacturer of the material[12]. All the materials in an element assembled from several materials have to be considered together (e.g. the STC of a wall or ceiling assembly). Often times, acoustic dissatisfaction is caused from sound that is transmitted from internal and external sources, i.e. noise pollution from highway traffic, airplanes or adjacent indoor spaces. Knowing the STC value for construction materials and assemblies, such as flooring, walls, ceilings, doors, and windows helps designers make selections that will meet the acoustical demands of a space. The higher the STC value of a material or assembly, the better the material is at noise attenuation [12].

Figure 3: Installed sound absorption paneling. Image courtesy of U.S. Department of Labor Image Library.

Good STC ratings can be significantly compromised by *sound flanking paths*, which are essentially sound conductive paths in the construction or holes or joints. These paths often do not identify themselves until after construction and need to be eliminated to maintain desired sound levels. The International Code Council recommends *field verification* to successfully limit these pathways following the completion of construction. (For guidance on field verification, see ICC G2-2010: Guideline for Acoustics)

When spaces require low reverberation times, absorptive materials are introduced. Common absorptive materials in architecture fall into three main categories, the first are *porous absorbers*, these materials are typically good at absorbing sounds with a wide range of frequencies and include, mineral fiber ceilings, carpets, curtains or open-cell foam panels (i.e. baffles) [11]. The second category, *panel absorbers*, are thin panels that are set off of the surface of walls or ceilings, creating a cavity between the panel and installation surface [11]. The cavity along with the overall mass of the panel, determines the frequency at which most sound is absorbed [11]. The third are *composite panel/porous absorbers*, which are a combination of the above categories and function by introducing absorptive materials into the cavity created between a wall and a panel absorber [11]. Additionally, Helmholtz resonators made by slitting concrete block can be used where a hard surface material is desired to meet other design goals.

Sound Masking Technology: Recent workplace design strategies favor open floor plans and flexible workspaces to better serve collaboration and innovation, these conditions can however create noise disturbances and a general lack of acoustic privacy. Disturbances or annoyances increase with speech intelligibility, that is to say, when a conversation is not only audible but can also be easily understood, it will create more of a disturbance for those nearby. Speech intelligibility is commonly measured by using the Speech Intelligibility Index or SII (for guidance on measuring SII see the *Referenced Standards* section). For spaces where acoustical privacy is preferred or even required i.e. government, financial or healthcare facilities, sound masking systems can be implemented and specially "tuned" to meet the demands of the space. Sound masking systems, typically consisting of electronic components and loudspeakers located above a suspended ceiling, operate by introducing specialized ambient sound that interferes with the human voice [14]. Implementing a well-designed and professionally tuned, sound masking system results in a decreased SII and increased level of acoustic privacy (for additional information on sound masking tuning, see the *Measurement and Verification* section).

Sustainability: The adoption of green building and energy efficiency strategies can inadvertently lead to poor indoor acoustics. Green building practices such as daylight optimization, natural ventilation and use of low mass, recycled building materials can introduce large open spaces, highly reflective surfaces, outdoor noise pollution, and reduced use of suspended sound absorbent ceilings. Employing other sound absorbent materials into the space such as carpeting, absorbent panels, acoustic baffles or drapes can help to increase sound absorption and decrease noise pollution, flutter and echoing [5]. Conversely, the addition of a sustainable green roof to a structure often provides acoustical benefits. The increase in roof mass improves sound insulation through the roof, increases the damping of the roof and reduces panel resonance [4].

Aesthetics: Trends in architectural and interior design aesthetics also can contribute to poor acoustics. Most notably, the "industrial aesthetic" characterized by exposed masonry, polished concrete floors, exposed mechanical systems, exposed hard ceiling surfaces and loft style spaces, leads to high background noise levels. In such spaces, speech intelligibility can be very poor where it is needed (e.g. dining areas) and cause distractions where it is not desirable (e.g. open office workstations). Older people and those with hearing impairments find such spaces very challenging. To mitigate these negative acoustical effects, see the above section, "*Sustainability"* for material recommendations.

Acoustic Ambiance: There is more to the aural environment than the physical properties of sound waves. *Psychoacoustics* is a branch of science that deals with the perception of sound and the sensations produced by sound. By acknowledging common responses to particular sounds, designers have the opportunity to implement soundscapes in a design scheme that will create a desired acoustic ambiance for occupants. E.g. Natural sounds, particularly water, evoke positive feelings towards the landscape [15], while background sounds of blended speech can encourage social cohesion [16]. Soundscapes also serve as a tool for designers to more effectively communicate design concepts to clients and end users.

3. Related Standards

ANSI/ASA S12.2 provides three primary methods for evaluating room noise: a survey method, an engineering method, and a method for evaluating low-frequency fluctuating noise. Two methods for evaluating room noise—RC (room criterion) and NCB (balanced noise criterion) curves—were the basis of the previous ANSI S12.2-1995 standard, and RC is included briefly for informational purposes in Annex D. All of the methods assume that the measured noise is free of tones.

The three methods include:

1. The survey method that employs the A-weighted sound level (*note: simplest method*)
2. The engineering method that employs noise criteria (NC) curves
3. The method for evaluating low-frequency fluctuating noise using room noise criteria (RNC) curves

ANSI/ASA S12.60: Parts 1 & 2 provides a minimum set of requirements for school planners and designers to create classrooms and other learning spaces with acoustical characteristics that are necessary for good speech communication between students and teachers.

ANSI/ASA S3.5 defines a method for computing a measure, called Speech Intelligibility Index (SII) that is highly correlated with the intelligibility of speech under a variety of adverse listening conditions as evaluated by speech perception tests. The SII is calculated from acoustical measurements of speech and noise. Although not part of the standard, there are three programs available online and free of charge here. Each program calculates the SII value in accordance with the ANSI S3.5 standard and has been verified by members of the ASA working Group S3.5.

ASHRAE Guideline 0-2013: Commissioning Process presents best practices for applying whole-building commissioning to facilities. These practices apply to all phases of new construction and renovation projects. To assist in further understanding of the commissioning process, this guideline outlines the roles and responsibilities of the owner and the commissioning authority.

2016 International Building Code: Section 1207 Sound Transmission applies to common interior walls, partitions and floor/ceiling assemblies between adjacent dwelling units and sleeping units or between dwelling units and sleeping units and adjacent public areas such as halls, corridors, stairways or service areas. Standards are specified for Air-borne sound, Masonry, and Structure-borne sound.

ICC G2-2010: Guideline for Acoustics provides suitable sound isolation recommendations for construction systems that separate occupied spaces in multiple-family and commercial buildings. The International Code Council developed these guidelines that exceed code requirements in an effort to better match occupant expectations for the acoustical comfort [17].

ISO 1996-1:2016 Acoustics defines the basic quantities to be used for the description of noise in community environments and describes basic assessment procedures. It also specifies methods to assess environmental noise and gives guidance on predicting the potential annoyance response of a community to long-term exposure from various types of environmental noises.

The Occupational Safety and Health Administration (OSHA) sets the legal limits of noise exposure in the workplace in units of decibels (dB) based on a workers time weighted average over an eight-hour day.

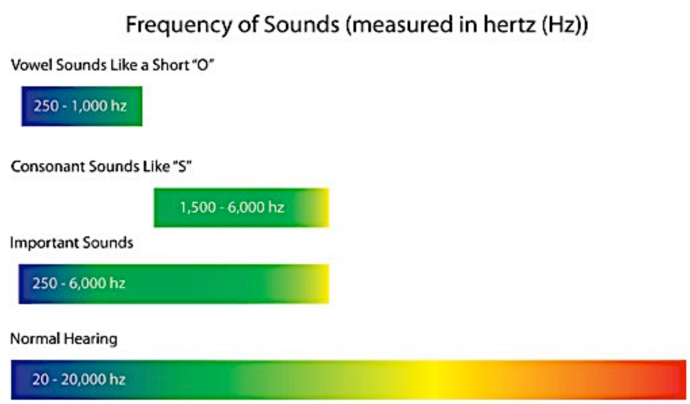
Subpart B of 24 CFR Part 51 - Environmental Criteria and Standards outlines the U.S. Department of Housing and Urban Development's (HUD) Noise Abatement and Control standards for federally funded housing projects. HUD's policy provides minimum national standards applicable to HUD programs to protect citizens against excessive noise in their communities and places of residence.

4. Measurement and Verification

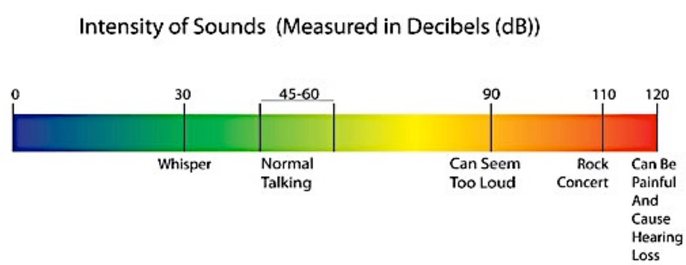
Three main measureable properties of sound

1. *Frequency* or "pitch"
2. *Wavelength*
3. *Amplitude* or "loudness"

Commonly known as "pitch", *frequency* is a value measured in units of Hertz (Hz) and represents the number of complete cycles per second of vibration [3]. The human hearing range is approximately 16 – 20,000 Hz [18], with sensitivity dropping off sharply at lower frequencies. While a pure sound is composed of one frequency, most sounds we hear throughout the day are composed of multiple tones, and are usually grouped for analysis and measurement, these groups are called frequency bands[11].



A wavelength represents the distance between the start and end of a sound-wave cycle and is measured in distance (meters, feet, inches, etc.) [11], with shorter distances representing higher frequencies and longer distances representing lower frequencies [12]. Knowing wavelength values is important for acoustical design, as these distances are comparable in size to architectural elements and can help to control the way in which sound behaves in a room [18].



Wavelength Equation:

λ=C/f
λ = wavelength of sound
C = velocity of sound
f = frequency of sound

Figures 4 & 5: Commonly accepted values for sound frequency and intensity. Image courtesy of the Centers for Disease Control and Prevention.

Sound amplitude is often equated with loudness. While there are several metrics for measuring the pressure of a sound wave, loudness is commonly measured in terms of decibels (dB), referring to the relative amplitude of a sound wave [12]. Values of 50 dB – 80 dB represent most indoor activities, i.e. conversation, where 20 dB is the approximate sound level of a whisper and 120 dB is the threshold for pain [18]. Decibel levels are not additive, but logarithmic; an increase of 10 dB is the equivalent of a sound being twice as loud.

Measuring Devices
Two commonly used measuring devices are the sound level meter, which is used for area sampling, and the noise dosimeter, or sound exposure meter, which is used for personal sampling [19]. The sound level meter works best in areas with constant noise levels, as it measures instantaneous noise, whereas the noise dosimeter gives a better indication of noise exposure in environments with fluctuating noise levels because it is typically worn by the tester and gives a noise level average for an extended period of time.
See ANSI/ASA S12.2 Standard above for three primary methods of evaluating room noise

Tuning Sound Masking Systems
All sound masking systems require tuning and adjustments by acousticians or trained technicians in order to meet desired acoustical conditions. To tune a sound masking system, technicians must first identify specific acoustical zones, assign Speech Intelligibility Indexes (SIIs) desired for each zone and define allowable tolerances within the SII values. In each identified zone, sound measurements will be taken at ear height such that the system's volume and frequency settings can be adjusted accordingly to meet the acoustical requirements of the space [14]. Tuning should be completed after the furnishings and ceilings are in place, prior to occupation of the facility, and with mechanical systems operating at daytime levels [14]. Although tuning can be a time consuming process, it is vital to implementing an effective sound masking system.

See ANSI/ASA S3.5 Standard above for methods of SII measurement

5. Design Considerations

- *Acoustical features are compatible with the requirements of the space. This includes meeting all acoustical privacy and speech intelligibility requirements.* Understanding function and acoustical requirements early in the design process helps to determine the appropriate location, size, shape, materiality and sound masking technology for a space. Unwanted noise can have adverse effects on productivity, concentration, sleep and overall health. Additionally, failure to accommodate adequate acoustical privacy can result in occupant dissatisfaction, or even be cause for liability risks. The acoustical features selected will determine the acoustic conditions that users experience. Material and technology selection is critical for insuring optimal conditions. Appendix A of ANSI/ASA S12.2 provides guidance on acceptable noise levels for the following indoor space types: broadcast studios, concert halls, auditoriums, private residences, schools, hotels, office buildings hospitals, movie theatres, churches, courtrooms, libraries, restaurants, industrial spaces, laundries and garages. These values are summarized here.

- *Acoustic design incorporates assistive listening systems*. Assistive listening systems (ALS) amplify sound and brings it directly to the ear [10]. ALSs increase the volume of the desired sound, typically speech or music, by about 15 to 25 dB, and separate those sounds from background noise, which improves the "speech to noise ratio" [10]. Each system has at minimum, three components: a microphone, a transmission technology, and a receiving device to deliver the sound to the ear [10]. Systems operate utilizing one of four technologies: FM or radiobroadcast, infrared, inductive loop technology and sound over Wi-Fi. Radiobroadcast technologies are used most often in educational settings because they allow for flexibility and mobility[20]. Where as infrared systems offer privacy, because of their inability to travel through walls and are often utilized in areas where confidentiality is a concern, i.e. courthouses [10]. Inductive loop technology is recommended for users that regularly wear hearing aids as the amplified sound will be delivered through their device and additional headphones are not required [10]. Sound over Wi-Fi is a recent innovation. It provides audio without the need for special transmitters and receivers and can be utilized by any person who has a Wi-Fi connected device, on site or not.
- *Noise and vibration from building systems is minimized*. Building systems i.e. HVAC equipment, pipes and electrical conduit often come in direct contact with the building structure and can cause structure borne noise transmission from mechanical vibrations throughout the building. To avoid this, strategies such as lining ceilings with robust absorbent materials, isolating mechanical equipment, using flexible connectors that isolate duct noise installing acoustically insulated ceiling tiles, and installing sound masking devices can be employed [11]. For guidance on the aforementioned methods and for additional noise control strategies, designers should refer to the ASHRAE Handbook – HVAC Applications, Chapter 48 Noise and Vibration Control
- *Volume of background music and other entertainment systems are controllable*. Background music and entertainment systems like televisions are used in a variety of different applications. Some facility managers encourage high volumes because it helps to create a "lively" atmosphere, while others seek to minimize volumes to create a calmer atmosphere. Building occupants also vary in their subjective response to noise generated from these sources. Variability in management goals and occupant desires suggests that where needs and responses may vary over time, maximum control over background volume levels is desirable. This flexibility will help to create specific background conditions to match the goals of management and responses of occupants at any particular time. New technology is available to create and vary "soundscapes" using software. Such systems do not replace good acoustic design but provide more control than simply adjusting volume or changing the source material.
- *Doors and windows are designed to the appropriate sound transmission class (STC).* The STC value for a material represents the amount of airborne sound blocked from transmitting through it [3]. The higher the STC rating integer, the better the material is at attenuating airborne sound. Generally speaking, materials that are high in mass, resilience and stiffness have a higher STC rating [11]. When installing doors and windows it is important to select materials that satisfy STC recommendations for a specific space type, however the design must also account for flanking sound paths that often exist through gaps and undercuts on doors and windows [11]. STC values for various space types can be found in *UFC 3-450-01, Design: Noise and Vibration Control and Architectural Graphic Standards.*
- *Walls are designed to the appropriate sound transmission class (STC).* See the above

recommendations.

- *Sound flanking paths are eliminated.* Sound flanking paths are created where construction has holes or joints. Common flanking paths include recessed electrical outlets, joints between partitions, mullions in window walls, and undercuts at doors. All of these need special seals or hardware to maintain desired STC levels.
- *Acoustic design is commissioned as per ASHRAE guide.* Buildings that are correctly commissioned have fewer change orders, tend to be more energy efficient, and have lower operation and maintenance costs. Commissioning of acoustical systems should be done in accordance with ASHRAE Standard 202-2013, The Commissioning Process for Buildings and Systems, and ASHRAE Guideline 0. In many cases, the commissioning process, which would include on-site performance testing and evaluation of a building systems, will help to identify any noise related acoustical problems prior to project completion and occupancy [21].

6. Definitions

Absorbing materials	Materials that dissipate acoustic energy within their structure as heat and/or mechanical energy of vibration. Usually building materials designed specifically for the purpose of absorbing acoustic energy on the boundary surfaces of rooms or in the cavities of structures [3].
Acoustical environment	The overall environment, interior to exterior, that affects the acoustic conditions of the space or structure under consideration [3].
Amplification	Usually the increase in intensity level of an audible signal produced by means of loudspeakers and associated electrical amplification apparatus [3].
Attenuation	Reducing the magnitude of a sound signal by separation of a sound source from a receptor, acoustical absorption, enclosure, active cancellation by electronic means, or a combination of these or other means [3].
Baffle or barrier, sound.	A shielding structure or partition used to increase the effective length of a sound transmission path between two locations [12]
Damping	Dissipation of structure-borne noise. This is usually accomplished by using a material with a high internal energy-absorbing capacity [12]
Decibel (dB)	A descriptive notation adopted for convenience in representing vastly different sound quantities [12].
Diffraction	The ability of sound waves to “flow” around an obstruction or through openings with little loss of energy [3]
Flanking sound path	The transmission of sound or noise from one room to another by indirect paths rather than directly through an intervening partition [12].
Focusing	Concentration of reflected acoustic energy within a limited location in a room as the result of reflections from concave surfaces [3].
Frequency	The number of complete cycles per second of vibration (or other periodic motion). The unit is hertz (Hz) [3].
Intensity	The amount of sound energy per second that is carried across a unit area [12].
Loudness	A subjective human definition of the intensity of sound.
Noise	Any undesired sounds, usually of different frequencies, resulting in an objectionable or irritating sensation [12].

Noise reduction coefficient	The arithmetic average of the sound absorption coefficients of a sound-absorbing material at 250, 500, 1000, and 2000 Hz [3].
Reflected sound	The resultant sound energy returned from a surfaces(s) that is not absorbed or otherwise dissipated upon contact with the surfaces(s) [3].
Reverberation	The persistence of sound within a space after the sound source has stopped [3]
Sound absorption coefficient	The ratio of sound-absorbing effectiveness of 1ft ^{2} of acoustical absorbent to 1 ft ^{2} of perfectly absorptive material; usually expressed as a decimal value between 1.0 (perfect absorption) and 0 (perfect reflection [3]
Sound transmission class	A rating of the laboratory-derived airborne sound transmission loss data for a structure determined in accordance with the procedures of ASTM E90 and E413 [3].
Speech Intelligibility Index (SII)	A measure between 0 and 1, that represents the intelligibility of speech under a variety of adverse listening conditions, such as noise masking, filtering, and reverberation [22].
Wavelength	The distance between adjacent regions of a sound wave where identical conditions of particle displacement or pressure occur [3].

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