Concert Hall Acoustics and Piano Lid Height

A Study of Five Arizona Concert Halls

by

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ABSTRACT

Traditional consensus in duos with grand piano has been that issues of balance between piano and the other instrument can be corrected through lowering the lid on the piano, particularly when the other instrument has been thought of as less forceful. The perceived result of lowering the lid on the piano is to quiet the piano enough so as not to overwhelm the other instrument, though the physics of the piano and acoustics suggest that it is incorrect to expect this result. Due to the physics of the piano and natural laws such as the conservation of energy, as well as the intricacies of sound propagation, the author hypothesizes that lowering the lid on the piano does not have a significant effect on its sound output for the audience of a musical performance. Experimentation to determine empirically whether the lid has any significant effect on the piano's volume and tone for the audience seating area was undertaken, with equipment to objectively measure volume and tone quality produced by a mechanical set of arms that reproduces an F-major chord with consistent power. The chord was produced with a wooden frame that input consistent energy into the piano, with measurements taken from the audience seating area using a sound pressure level meter and recorded with a Zoom H4N digital recorder for analysis. The results suggested that lowering the lid has a small effect on sound pressure level, but not significant enough to overcome issues of overtone balance or individual pianists' touch.

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CHAPTER 1

INTRODUCTION AND BACKGROUND

Though its beginnings can be found in the work of Pythagoras in Ancient Greece, the scientific study of acoustics began in the eighteenth century with the work of French mathematician Joseph Sauveur and Swiss mathematician Leonhard Euler. Hermann von Helmholtz's work in the later part of the nineteenth century laid the foundation for research and further discovery in acoustics and the application of the scientific method to the design and construction of halls for the performing arts.[1] In the early twentieth century, Wallace Clement Sabine began using applied acoustic knowledge and principals for building design and construction.[2] Advances in technology and computing power have resulted in the ability to digitally design halls and model the acoustic response on a seat-by-seat basis to optimize the auditory experience for the entire hall.

There are five general parameters for the function of a music hall: liveness or reverberance, warmth, brilliance, clarity, and presence.[3] Reverberation time is defined as the time elapsed for a sound to decay by 60 dB from its original level and has several variables that influence its duration, such as room shape, the overall volume of the room, and the reflectivity of room surfaces.[4] General guidelines on the ideal reverberation times vary with the type of activity in the halls: the spoken word requires a shorter reverberation time for clarity's sake (0.6-1.3 seconds), whereas opera houses may have

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[1] Ronald Lewcock, et al. "Acoustics." *Grove Music Online*. *Oxford Music Online*. Oxford University Press, accessed July 22, 2017, http://www.oxfordmusiconline.com/subscriber/article/grove/music/00134pg1.

[2] Ibid.

[3] Charles K. Boner, et. al., *Acoustics for Performance, Rehearsal, and Practice Facilities: A Prime for Administrators and Faculties* (Reston, VA: National Association of Schools of Music, 2000), 2.

[4] Ibid., 3.

reverberation times between 1.1 and 1.6 seconds, while concert halls designed for symphonic music may approach 2 seconds of reverberation.[5] In contrast, the reverberation times for the great cathedrals when empty can be as long as 12 seconds, as in St. Paul's Cathedral in London.[6]

Warmth and brilliance are more difficult to define than reverberation time, but nevertheless have foundations in observable science. Warmth and brilliance are functions of the proportions of overtones present in a sound: sounds characterized as brilliant have higher overtones contributing significantly to the makeup of the sound, whereas a warm sound is characterized by a sound dominated by the fundamental frequency and lower overtones, with rapidly decreasing power in the sound's overtones.[7]

Presence and clarity are closely related to the architectural design of a space. A hall is described as having excellent presence when the sound waves are diffusive enough throughout the hall that the listener feels enveloped from all sides by the sound, instead of experiencing the sound radially from the source. To this end, halls are designed with myriad surfaces of varying reflectivity and absorption of sound to create a rich sonic environment. Clarity is determined primarily by the overall dimensions of a hall and the paths of sound reflection as opposed to the direct path from source to listener.[8] Experiments have shown that listeners perceive a time difference delay between a direct-path signal and a reflection of up to 35 milliseconds as one sound, and generally will

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[5] Harvey White and Donald White, *Physics and Music: The Science of Musical Sound* (Philadelphia: Saunders College, 1980), 364, 375.

[6] Lewcock, "Acoustics." Accessed July 22, 2017.

[7] White and White, *Physics and Music*, 260.

[8] Boner, *Acoustics for Performance Rehearsal, and Practice Facilities,* 4.

recognize an initial time delay of up to 50 milliseconds as one sound before perceiving the second sound as an echo.[9]

In addition to the parameters described above, designers and acousticians also have to consider the purpose of a hall: in a space designed solely as a concert hall, the stage enclosure can be permanently enclosed so as to project the greatest possible sound into the audience, as in Katzin Concert Hall at Arizona State University. In contrast are multi-purpose auditoria, where orchestral concerts, opera events, lectures, and chamber music may all use the same space: these multi-purpose auditoria present their own design challenge, as reverberation time, clarity, presence, warmth, and brilliance change considerably based on the performing forces in the hall.

The preceding paragraphs give an indication of the complexities of concert hall and auditorium design, but the focus of this document is not the large concert halls suitable for full orchestra and their acoustics; however, the more intimate venues that are more suited for recital and chamber music performances. In music for smaller ensembles and solo performance, the piano has a greater presence than any other instrument. It is present for almost every performance involving vocalists, and much instrumental music includes the piano. While practice rooms and studios may have a mix of upright pianos and small grands, larger grand pianos are generally used in concert halls. Sizes of grand piano range from the smallest acoustic grands measuring about 5 feet long (1.5 meters) to over 10 feet (3 meters) for the largest concert grand pianos. Smaller recitals usually use at minimum seven-foot pianos (2.1 meters, also called music-room grands), with nine-foot concert grands used in larger spaces. The concert grand piano transmits a considerable

[9] White and White, *Physics and Music*, 359.

amount of power through the interactions of string and soundboard, which leads to its ability to be heard over full orchestra in a large concert hall. When collaborating with a single instrument (or small combination of instruments such as in the piano trio), the same piano with sufficient power to be heard over a symphony can lead to conflict between players about its power relative to the other instruments. For example, while the piano's single-note output can range from 37 to 85 dB at 10 meters, the oboe's maximum power output is about 80 dB at 9 meters (the least powerful instrument according to Meyer's observations), while the trombone may reach 100 dB at 16 meters. [10] This difference in power output capabilities illustrates that there exists a difference in power output to be overcome between instruments.

In most grand pianos, the lid can be propped open on two heights or left completely closed: the most open position, colloquially referred to as "full stick", raises the lid about 37 degrees from the horizontal; the shorter position, referred to as "short stick", raises the lid about 10 degrees.[11] The balance between the outputs of solo instruments[12] and the piano, as well as the placement of musicians around the piano, can give the appearance of the piano overpowering the other musicians, and oftentimes the pianist is asked to lower the piano's volume by lowering the lid from the 37-degree full stick position to short stick or closing the lid entirely. Due to the physics of the piano and natural laws such as the conservation of energy, as well as the intricacies of sound

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[10] Jürgen Meyer, *Acoustics and the Performance of Music*, trans. John Bowsher and Sibylle Westphal (Frankfurt: Verlag Das Musikinstrument, 1978), 38-73.

[11] Ibid., 100.

[12] "Instruments" throughout this document refer to non-piano musical instruments.

propagation, the author hypothesizes that lowering the lid on the piano does not have a significant effect on its dynamic output for the audience of a musical performance.

CHAPTER 2

LITERATURE REVIEW

The literature on musical acoustics falls into three broad categories: works dealing primarily with the musical instruments' physics, works on the design and construction of spaces for musical performance, and works on psychoacoustics (the study of the interaction between psychology and music). While useful to develop a more well-rounded knowledge of acoustics, the works on acoustic design and psychoacoustics have little relevance to this document aside from noting that hall design and materials in concert halls have very large effects on the acoustics and suitability of halls to different types of music.

The most thorough of the physics-dominated works is Neville H. Fletcher and Thomas D. Rossing's *The Physics of Musical Instruments* (2nd edition, New York: Springer Science+Business Media, 2010). This work is written as a physics textbook to thoroughly explain the science of sound production from a mathematical perspective and requires an excellent background in mathematics to master the concepts in it, particularly in Part 1, which presents the mathematical models of the transmission of sound.

Part II (Chapters 6 through 8) of *The Physics of Musical Instruments* is about the transmission, reflection, diffraction, and absorption of sound waves, as well as mathematical models of pipes, horns, and cavities (Chapter 8). Chapter 8 also introduces time-domain equations instead of frequency domain, which begins to more closely approximate the real-world responses of horns, pipes, and cavities to an impetus.

Parts III through V are concerned with specific musical instruments, grouped by family. Within Chapter 12 on the piano, Fletcher and Rossing derive and detail many of the governing equations of the piano that are found in Chapter 3 of this document, but also include directional characteristics of the piano. This subsection, 12.9.2, has radiation pattern maps for the piano taken from J. Meyer's "Acoustics and the Performance of Music" (1978, Verlag das Musikinstrument, Frankfurt am Main) that show changes in radiated power in certain registers and directions when the lid is open and closed. The maps, however, do not include the distance from the piano at which the maps were made. The patterns show the relative strength of 250-, 500-, 1000-, 2000-, and 4000-Hz tones from the piano, but without indication of signal strength, or how strong the input force was. The previous subsection, 12.9.1, concerned with dynamics, includes the only direct reference to changing the volume of the piano by lowering the lid: "Raising or lowering the lid causes surprisingly little change in the overall sound level, although it causes rather marked changes in the strength of the high-frequency sound in certain directions."[13] As with the radiated power maps in subsection 12.9.2, there is no elaboration about distance from the piano for the observation of effects in *The Physics of Musical Instruments*.

Jürgen Meyer's *Acoustics and the Performance of Music* (translated by John Bowsher and Sibylle Westphal) has a more cursory examination of the mathematical background of sound and acoustics, but more depth on the practical applications and observations of sound. In the section on the piano, he includes discussion on the importance of higher overtones in creating a more brilliant sound from the piano, as well as measurements of the sound pressure level at 10 meters' distance from the piano.[14] The

[13] Fletcher and Rossing, 392.

[14] Meyer, *Acoustics and the Performance of Music*, 72-73.

following section, "Directional Characteristics of Musical Instruments," has short sections on the string, brass, and woodwind instruments before examining the special case of the piano more closely. He notes that the response of the piano differs for its range (low, middle and high), and that radiation patterns are partially dependent both on range and lid height.[15] For the case of the lid fully open and using the middle range of the piano, Meyer notes the strongest area of sonic directivity as an angle of about 25 degrees in the vertical plane facing the piano (i.e., looking at the piano from the perspective of the pianist, where the lid is about 37.5 degrees when fully opened) with a secondary strong lobe at approximately 130-150 degrees to the left.[16] For the case of the closed lid, Meyer notes that there is essentially no change in the part of the radiation pattern that corresponds to the long, straight face of the piano, though there is a decrease in the radiation from the downstage side. The principal change in the quality of sound with the lid closed is that the intensity of the higher-frequency components of the sound is rather attenuated, making the timbre less brilliant; there is no mention of an overall sound pressure level decrease (a quieter sound) with a closed lid. With the lid on short stick, Meyer states that the overall sound is only "slightly duller" than with the piano on full stick, but with less clarity and brilliance than the piano on full stick.[17]

In *Five Lectures on the Acoustics of the Piano*, Harold A. Conklin notes that the piano case is constructed of heavy hardwoods such as rock maple, which have an additional benefit to the piano's tonal quality. While containing the entirety of the piano,

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[15] Ibid., 99.

[16] Meyer, *Acoustics and the Performance of Music*, 99.

[17] Ibid., 101.

the case also serves as an immovable termination point for the soundboard, keeping the vibrational energy within the soundboard and keeping the piano as resonant as possible, instead of transmitting vibrational energy into the case.[18] This benefit supports the hypothesis that the sound pressure level remains relatively steady across differing piano lid heights due to the relative non-involvement of the case and lid in the transmission of sound.

In the realm of journals, there has been considerable research published on the soundboard, as evidenced by articles such as "Dynamical properties of soundboards," by Antoine Chaigne, Benjamin Cotté, and Roberto Viggiano, published in the July 2013 edition of *The Journal of the Acoustical Society of America*. However, these articles generally are finite-element analyses of soundboards, mathematically recreating the physical responses to input motions. Similarly, *The Journal of the Acoustical Society of America* has articles detailing the modeling of a piano ("Modeling and simulation of a grand piano," by Juliette Chabassier, Antoine Chaigne, and Patrick Joly, 2013), hammer and string interactions (Stephen Birkett, April 2013), and similar computational-based studies of string and action behavior.

In 1953, Daniel W. Martin presented a paper for *The Journal of the Acoustical Society of America* that examined the response of Music Hall in Cincinnati in various parts of the auditorium to a single struck note from a concert grand piano; his findings included that room reverberation has a large effect on the overtone makeup of the sound,

[18] Harold A. Conklin, Jr., "Piano design factors—their influence on tone and acoustical performance" in *Five Lectures on the Acoustics of the Piano*, ed. Anders Askenfel (Stockholm: Royal Swedish Academy of Music, 1990), 30-31.

with a lesser, limited influence from directional characteristics of the piano.[19] Similarly, several articles in journals such as the *Journal of Architectural Education*, *American Scientist*, and *The Musical Quarterly* discuss at length the interaction between acoustics and architecture, but never involving the specificity of piano lid heights. From this lack of relevant journal articles and books, it would seem that there is little research on the specific effects that the piano lid has on sound quality in a hall.

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[19] Daniel W. Martin "The Effects of Music Hall Acoustics Upon Grand Piano Tone," *The Journal of the Acoustical Society of America*, 25, no. 1 (January 1953), doi: 10.1121/1.1917566, http://dx.doi.org/10.1121/1.1917566).

CHAPTER 3

MATHEMATICAL BACKGROUND

At its most basic, sound is the transference of energy from one air particle to the adjoining particle. This chapter is not meant to serve as an exhaustive analysis of the nature of sound from a physicist's perspective, but rather to provide the basis for understanding the production of sound and how it behaves. To aid in this discussion, table 1 lists the terminology for scientific terms used in this chapter. Unless otherwise stated, all equations in this chapter are from Neville H. Fletcher and Thomas D. Rossing's *The Physics of Musical Instruments, 2nd ed.* (New York: Springer), 2010. Additionally, all units are in SI, or metric units. For piano terminology, notes for the piano are denoted using a combination of note name and octave: the lowest note on most pianos is A0, the usual tuning pitch of 440 Hz is A4, and the highest note is C8; black-key notes are always noted as sharp (A$^{\#}$5 rather than B$^{\flat}$5).

Table 1. Scientific terminology in acoustics

Term	Abbreviation	Units	Description
Watt	W	1 Joule/second	A unit of power
Frequency	f	Hertz	Number of cycles per second
Displacement	X	m	Measurement of movement
Joule	J	$\frac{\mathrm{kg} \cdot \mathrm{m}^2}{\mathrm{s}^2}$	The base unit of energy; 1 kilowatt-hour = 3,600,000 Joules
Pascal	Pa	$\frac{\mathrm{N}}{\mathrm{m}^2}$	Pressure; atmospheric pressure is 101 kPa
Wavelength	λ	m	Distance between consecutive peaks or valleys in a sinusoidal wave
Speed of sound	c	m/s	345 m/s

The ear is an incredibly sensitive organ, able to detect sounds over a huge range of pressure levels (10^{-5} to 100 Pa). Due to this vast range, sound levels are measured using a logarithmic scale, in which the equidistant divisions on a scale increase geometrically (1, 10, 100, 1000, etc. The decibel (dB) represents the ratio of a given pressure to a reference pressure and is referred to as the sound pressure level (SPL), defined as

$$SPL = 20 \log \frac{p}{p_0} \tag{3.1}$$

with p_0 the reference pressure 2×10^{-5} Pa. Using this scale, 1 Pa of pressure results in 94 dB, with the threshold of pain at about 120 dB.[20] One of the interesting results of using a logarithmic scale is that a doubling of intensity only adds 3 dB.[21]

The ear hears sounds ranging from about 20 Hz to 20 kHz, and does not recognize sounds with the same SPL as equivalent across a wide spectrum of frequency. Since the ear does not hear equivalent SPLs at different frequencies as the same loudness, weighted scales were created to more accurately reflect how the ear perceives loudness in different frequency ranges. The most common is A-weighting, though B-, C-, D-, and Z-weightings also exist. A-weighted scales deemphasize lower and higher frequencies to allow for the ear's decreased sensitivity at the extremes of its range, as shown in Figure 1, reproduced from *The Physics of Musical Instruments*.[22] B-weighting attenuates the lowest

[20] Neville H. Fletcher and Thomas D. Rossing, *The Physics of Musical Instruments, 2nd ed.* (New York: Springer, 2010), 161.

[21] Juan G. Roederer, *Introduction to the Physics and Psychophysics of Music, 2nd ed.* (New York: Springer-Verlag, 1975), 81.

[22] Fletcher and Rossing, 162.

frequencies by about 5 dB, while C-weighting has almost no attenuation and is designed for very loud sounds (greater than 100 dB).[23] D-weighting is used in the measurement of aircraft engine noise, and Z-weighting has no adjustment at all, measuring the sound intensity equally across all frequencies.

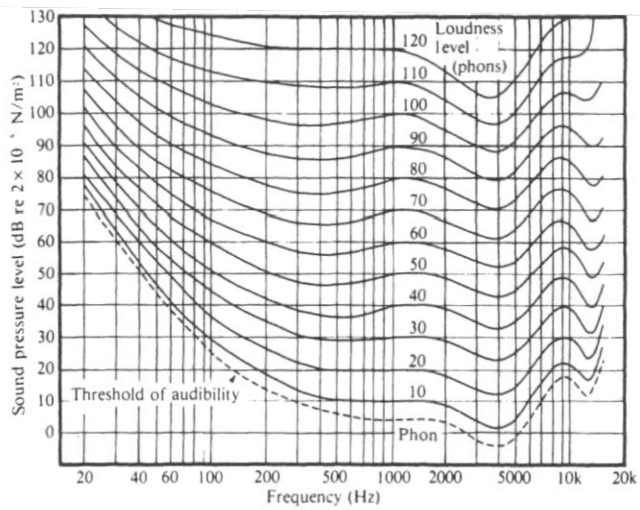

Figure 1. Equal loudness curves for human hearing. Loudness levels in phons correspond to unweighted decibels, with the 120-phon level as the threshold of pain.

Generally, the source of a sound is simplified to be a point source, in which it is assumed that the source of the sound has no volume or displacement of its own, which greatly reduces the complexity of any mathematical modeling of an environment. Due to the size of the soundboard in a grand piano, one cannot assume a point source simplification until reaching a distance away from the piano of at least one wavelength of the lowest fundamental frequency present. Given the frequencies of 27.5Hz for A0 and

[23] Arthur H. Benade, *Fundamentals of Musical Acoustics* (New York: Oxford University Press, 1976), 248.

87.3Hz for F2 the equation

$$\lambda = \frac{c}{f} \tag{3.2}$$

results in wavelengths of 12.5m for the lowest note A0 and 3.95m for F2.

Due to the three-dimensional nature of sound, determining the power radiated at a given radius *r* is found by integrating using the pressure level and radius from the source, given with the equation

$$P = \frac{4\pi r^2 p(r)^2}{\rho c} \tag{3.3}$$

where *r* is the radius from the source, $p(r)$ represents the pressure level at a distance *r*, ρ is atmospheric density, and *c* the speed of sound. Equation (3.3) shows that for a power of 1 milliwatt at a distance of one meter, the resulting sound pressure level would be about 79 dB; Equation (3.3) also shows that as the distance from a sound source increases, the pressure level goes down much faster.[24] A corollary is to examine the ratios of the intensities of the waves (*I*) at varying points in a spherical condition (that is, the surface of a sphere with the center as the point source): if one assumes that no energy is lost in transit between two radii r_1 and r_2, the intensities of the waves are related by the equation

$$\frac{I_1}{I_2} = \left(\frac{r_2}{r_1}\right)^2 \tag{3.4}$$

which corresponds to Equation (3.3) in showing that intensity (and thus loudness) is inversely proportional to the square of distance.[25] Integrating over the sphere surrounding

[24] Fletcher and Rossing, 163.

[25] Roederer, 74.

a source would give the acoustic power output, which ranges from about 0.01 watt in a clarinet's pianissimo to 6.4 watts in a trombone's forte.[26]

The caveat in the previous paragraphs' equations has been the assumption of conservation of energy, wherein no energy is lost in the transmission of sound from one particle to the next. In reality, losses occur, but energy is never created nor destroyed: from thermodynamics, energy dissipates, becomes vibrational energy, heat energy, or is otherwise transformed. In acoustics, the energy that is imparted from the musician's body into the instrument is transformed mostly into sound energy, which then propagates through all three dimensions in a given space. As mentioned earlier, as energy is transferred from particle to particle, a discrete amount is lost, resulting in the gradual decay of sound from a single input.

The mathematical background concerning the piano is well-documented and gives excellent insight into the results found later in this document. According to physicists, the only input that directly impacts the loudness or tonal quality in the piano is key touch point velocity, or how fast the key is depressed. Key touch point velocity and hammer velocity are related in Steinway pianos by the ratio

$$\frac{v_h}{v_p} = 5.5, \tag{3.5}$$

though the equation is valid for approximately the first 70% of hammer motion, as the hammer then disengages from the action and is in free travel for the remainder of the path to the strings.[27]

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[26] Roederer, 74.

[27] Fletcher and Rossing, 357

The general equation of motion for a given piano key according to Fletcher and Rossing is

$$F - F_s = m_k(0.018a_p) + m_a(0.72a_p) + m_h(5.5a_p), \tag{3.6}$$

where F_s is the static force necessary to depress the key, a_p is the acceleration at the touch point on the key, m_k is the key equivalent mass, m_a the action equivalent mass, and m_h the hammer equivalent mass.[28] Using values from Steinway pianos, the equation can be rewritten as

$$a_p = 3.3(F - 0.44). \tag{3.7}$$

Through a series of intermediary equations, the hammer velocity when the key strikes the key stop in the action is found to be

$$V_0 = 5.5a_pT_s = 1.34\sqrt{F - 0.44} \tag{3.8}$$

where T_s is the time required for the key to travel the distance s to the key stop.[29] Experimentation by Dijksterhuis in 1965 found that T_s ranges from 140 milliseconds (ms) for a soft touch to 12 ms for a strong touch, giving a dynamic range of about 21 dB. This result contradicts the dynamic range of the piano indicated in Meyer's *Acoustics and the Performance of Music*, where a dynamic range of 48 dB is indicated, as well as ranges of 33-35 dB in Fletcher and Rossing's *The Physics of Musical Instruments*. A possibility for this discrepancy could be the variance in key weight and force required, as the hammer mass grows considerably larger in the bass regions of the piano (10 grams in the bass to

[28] Fletcher and Rossing, 359.

[29] Ibid.

3.8 grams in the treble, with the ratio of hammer mass to string mass varying more, 8—0.08).[30]

The interactions between hammer and string are complex and vary considerably over the range of the piano. The hammer strike on the string induces a wave that initially is broken into two parts, as the hammer acts as a node (a point of no displacement) on the string. Experimentation by early piano builders determined that the ideal placement for a hammer strike is approximately 1/7 to 1/9 the length of the speaking length of the string in the bass and 1/12 to 1/17 the speaking length of the string in the treble. This placement minimizes the formation of standing waves of partials that are greatly out of tune with the fundamental pitch of the string.[31] The placement of hammers is a compromise between less fundamental pitch and the best tone, as placing the hammer closer to the pin reduces the strength of the fundamental pitch, but a placement further from the pin makes the sound considerably less clear due to increased contact time between hammer and string.[32] Given the speed of waves in piano strings immediately after being struck by the hammer and the compressibility of the hammer, it is inevitable that the reflection of the wave from the far end of the piano returns before the hammer has lost contact with the string; in the bass of the piano, the magnitude of the reflected wave is enough to throw the hammer off the string, while in the treble, the string and hammer maintain contact for more than one full cycle of wave movement. Applying greater force to the key decreases hammer contact time with the string and is one of the contributing factors to the greater brilliance

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[30] Fletcher and Rossing, 366.

[31] Ibid., 373.

[32] Ibid.

(defined as louder upper overtones compared to the fundamental) of louder dynamics on the piano.[33]

Once the hammer is free of the string, the string vibrates in a multitude of segments, producing the overtones of the fundamental that give the piano its distinct tone. This vibration initially is normal (at a 90-degree angle) to the soundboard, which transmits energy quickly from the string to the soundboard via the bridge for approximately the first 7 seconds of vibration; following this time period, the vibrational plane of the strings shifts to be parallel with the soundboard, greatly reducing the transmission of energy through the bridge.[34] An additional reason for this two-phase decay in power is that the initial hammer strike sets all three strings into motion in phase, though due to small differences in tuning, the three strings quickly fall out of phase with each other.[35] An interesting effect of wave motion is that when the *una corda* pedal is depressed on grand pianos, the action shifts slightly to the right, striking two strings instead of three. In addition to having less vibrational energy from impacting two strings rather than three, the unstruck string begins to vibrate exactly out of phase to the struck strings, further diminishing the energy and sound power.[36]

The soundboard of the piano is generally made from a light, responsive wood, such as Sitka spruce, which transforms the mechanical energy of the strings into acoustic energy with minimal losses. Without the soundboard, the piano would have almost no

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33 Fletcher and Rossing, 372.

34 Gabriel Weinreich, "The coupled motion of piano strings," in *Five Lectures on the Acoustics of the Piano*, ed. Anders Askenfelt (Stockholm: Royal Swedish Academy of Music, 1990), 74-75.

35 Fletcher and Rossing, 385.

36 Ibid., 386.

tone, as the excitation of air would happen solely via the strings, whose diameter is not sufficient to excite enough air to be easily audible.[37] The soundboard's response in the lowest frequencies is of particular interest, as the radiation efficiency drops considerably at frequencies of less than 200 Hz (G3 and lower), leading to a spectrum in the lower range of the piano dominated much more by the overtones rather than the fundamental.[38] At the very lowest frequencies, the wavelength of the fundamental exceeds the length of the soundboard, resulting in almost no transmission of the fundamental.[39]

The information in this section, while by no means an exhaustive examination of the mathematical background and modeling of the piano, serves to illustrate its complexity. Additionally, the author strove to show that the conservation of energy leads to predictable SPL responses in an anechoic space (free of surface reflections).

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[37] Fletcher and Rossing., 374-375.

[38] W. V. McFerrin, *The Piano: Its Acoustics* (Boston, Tuners Supply Co., 1971), 69.

[39] Fletcher and Rossing, 380, 381.

CHAPTER 4

METHODOLOGY

Sampling of the halls was accomplished through use of an audio recorder, a sound pressure level meter, and a wooden bracket that depressed the same six keys of an F-major chord with the same force for every repetition. In an ideal experiment, there would be enough recorders and sound pressure level meters to simultaneously record data for every seat needed in the experiment, but due to constraints of money and equipment availability, there was one set of equipment and the chord was repeated for each new sample.

The striking mechanism for the keyboard was comprised of 2x4 pieces of white pine and assembled according to the following plans shown in figures 2, 3, 4, and 5 (all measurements in inches). The part of the mechanism that comprised the striking surface of the keys was comprised of a horizontal 2x4 piece of wood with ½-inch dowel segments one inch in length attached with wood screws. The dowel ends that contacted the keys were covered with two layers of thick felt so as to minimize the percussive impact of uncovered wood and to more closely approximate the flexibility and "give" present in a pianist's fingers. Calibration resulted in a total force of 11.3 N (kg-m/s^2) across the six dowels, or an average of 1.88 N per dowel. From *The Physics of Musical Instruments*, a *pianissimo* key strike is about 0.3 N, ranging to 35 N for *fortissimo*, resulting in a *piano* dynamic for each sample.[40]

[40] Fletcher and Rossing, 360.

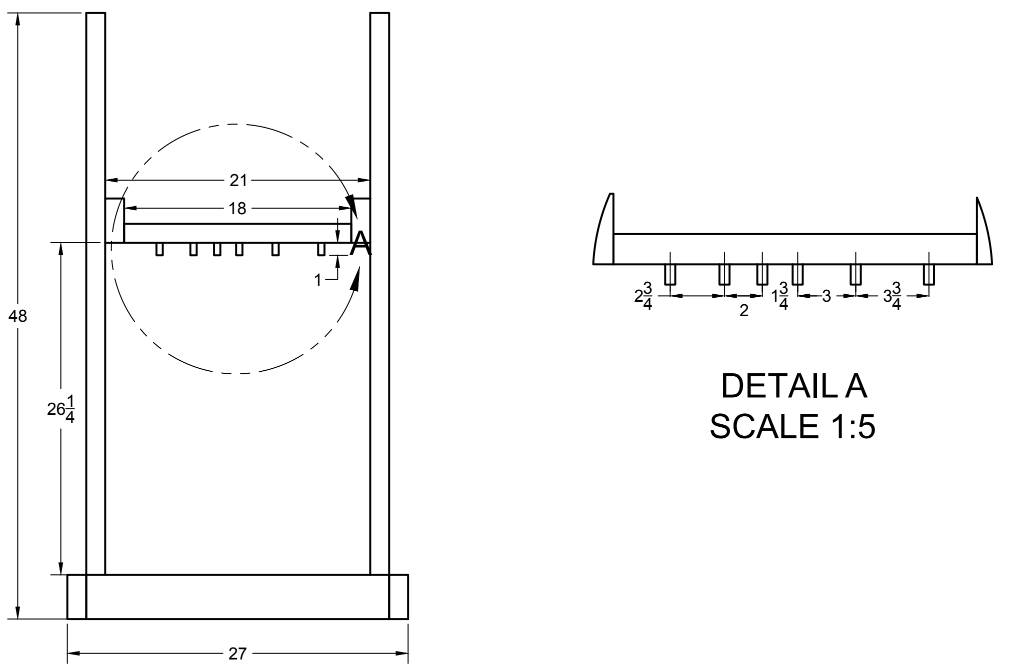


Figure 2. Front view drawing of the key striker. Specific dimensions between the "fingers" are noted in Detail A of the figure. All measurements are in inches.

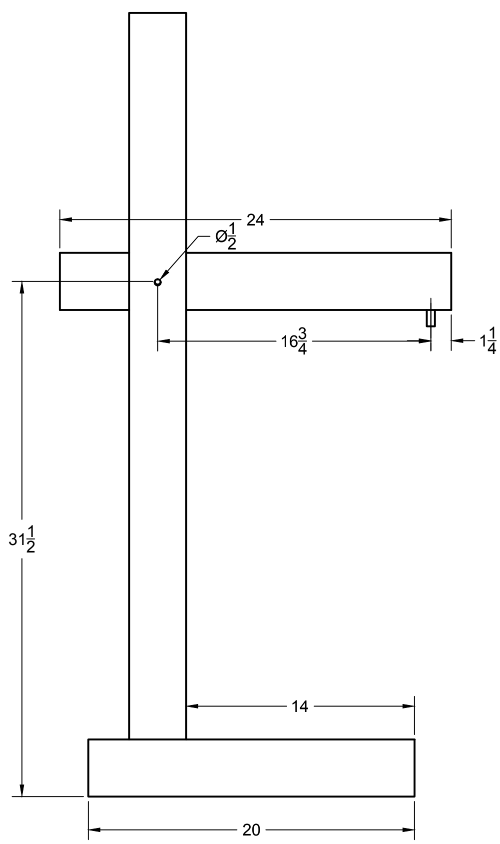


Figure 3. Side profile drawing of the key striker.

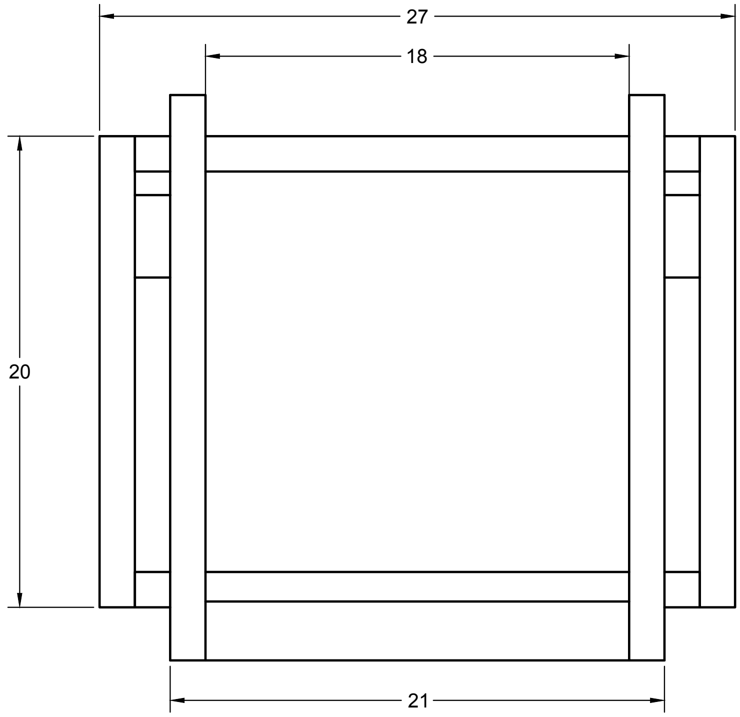


Figure 4. Top view drawing of the striker. In this view, the 21-inch dimension is at the keyboard.

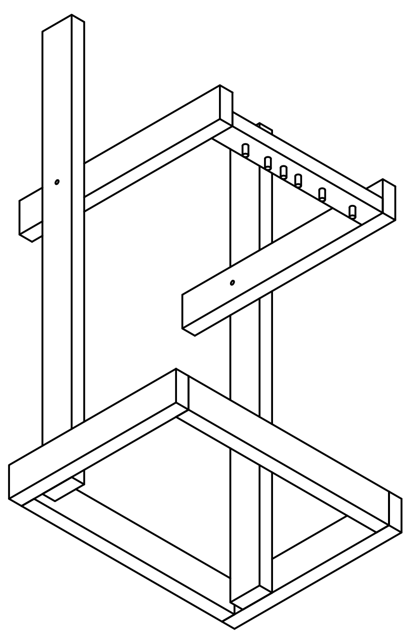


Figure 5. The isometric view shows the placement of the dowels that strike the keys as well as the positioning of the bolts used as hinges between the vertical components and the free-swinging "arms" of the striker.

The sound recorder used was a Zoom H4N, used in stereo mode with the included microphones on its stamina setting. The microphones were not used with any wind socks attached, as conditions inside the individual halls did not have air currents from the HVAC system that impacted the sound quality and sensitivity of the microphones. An SD card was used to transfer WAV files of the halls from the H4N to the computer for further analysis. For each hall, the microphone gain was set before collecting data by using the REC LEVEL adjustment rocker on the right side of the H4N's body while using the chord-playing frame to ensure that the H4N was sensitive enough to clearly record each chord repetition without reaching the maximum capabilities of the microphones (commonly referred to as 'clipping'). The microphones were used in the 90-degree placement, which has more detailed and sensitive sound pickup in the 90-degree field directly forward of the recorder, as opposed to 120-degree configuration, more suitable for recording an ensemble using an entire stage.

Decibel levels were recorded using a Quest NoisePro DLX Dosimeter loaned from Northern Arizona University's Office of Regulatory Compliance within the Environmental and Industrial Hygiene Programs office. Calibration prior to each hall's experiments was accomplished through the calibration menu and using the supplied calibration speaker. Within the calibration menu, choosing the pre-test calibration and adjusting the microphone's gain when used with the calibration speaker allowed the user to calibrate the sensitivity of the microphone against the known constant 1000-Hz sine wave at 114 dB from the speaker. Once the gain was set to the correct level, the calibration was saved, and the dosimeter was ready for measurement to begin.

The dosimeter is more commonly used to calculate aggregate noise exposure for compliance with Occupational Safety and Health Administration guidelines (for example, 8 hours of exposure to 90-dbA sounds is allowed, whereas only 2 hours of exposure is allowed for 100-dbA sounds) and return it in equivalent units for average sound across a collection time. For this document, the dosimeter was used as a sound pressure level meter with maximum-level reporting enabled. A dosimeter program was selected, with the following parameters used: Fast Response, to have a 0.125-second response to a sudden change in sound pressure level (for example, when the hammer strikes the strings of the piano); Exchange Rate, Criterion Level, and Criterion Time were left at default levels, as they are related to the aggregate dosimeter dosing measurements; Threshold was set for 40 dB to ensure that even a quiet strike of the keys would result in a valid measurement; Upper Limit was set to 114 dB, as literature suggested that the maximum SPL output of the piano is approximately 85 dB in the bass and 70 dB in the treble at a distance of 10 meters.[41] Weighting was set to use A-weight standards, as they more closely reflect the ear's response curve to varying frequencies of the same intensity and more closely reflect the ear's perception of sound.

Once the dosimeter was calibrated, the microphone was attached to an assistant's shirt collar as high as possible and oriented to pick up sound more clearly from directly in front of the assistant. Each seat was recorded as its own session, with the unit display showing the maximum SPL recorded in the session. The dosimeter and H4N recorder were both held by the assistant in the audience seating area. To minimize the effect of the

[41] Fletcher and Rossing, 392.

seats one row in front of the assistant, which can create acoustic ‘shadows’, the recorder was held at shoulder height.

The frame was positioned at the keyboard as shown in figures 6 and 7, with each felt-covered dowel centered over the key in the position a pianist would usually use to play an all-white key chord (center of the key width and key depth). To play the chord, which consisted of F2, C3, F3, A3, C4, and F4, the tester at the piano lifted the arm of the frame to the point where the keys were at rest with the felt touching the keys, then released to free-fall to the key bottom; this configuration allowed a reasonably loud chord to be produced while also minimizing extraneous sound from the frame (such as the dowels striking the keys from a higher position) and minimizing wear and tear on the piano.

Figure 6. In this picture from Northern Arizona University’s Ashurst Hall, the striking frame’s relationship to the piano is shown in profile.

Figure 7. The keys depressed by the frame are shown, with no other keys depressed, resulting in only six dampers raised off the strings in addition to the upper register of the piano with no dampers.

Upon a signal from the assistant that the dosimeter and recorder were ready, the tester released the frame to strike the keys; after at least two seconds of response, the assistant reported the peak decibel level to the tester, who recorded it in a Microsoft Excel spreadsheet. After confirmation of a successful test, the assistant changed seats to the next seat to be tested, and the entire hall was tested in similar progression.

In each hall, testing was first conducted on the piano with full stick, opening the lid to approximately 37 degrees, with on-stage standing and sitting testing following seating area testing. After the completion of full stick testing, the lid was lowered to the 'short stick' position, and the testing protocol repeated, followed by testing with the lid closed. Once each round of testing was completed, recording was stopped on the H4N recorder and filenames noted for later transfer to computer.

In the interests of expediency in testing locations with other restrictions on time and piano wear and tear, it was decided to not collect data from every seat in the hall; rather, using methods similar to election pollsters to extrapolate trends from smaller datasets with margins of error and confidence intervals, seats were selected to provide a selection to allow strong confidence in the validity of the results without testing 100% of a hall's seats. Using calculators from the University of California—San Francisco's Clinical and Translational Science Institute, the number of seats per hall was calculated to have a 95% confidence level with 5% margin of error. Confidence level is defined as the percentage of an infinite number of experiments that would fall within the observed results, while margin of error refers to the probability that a result is outside of the boundaries of the experiment. The number of seats chosen for each hall is summarized in table 2.

Table 2. Total number of seats in the five halls tested compared to the seats tested to obtain a 95% confidence level and 5% margin of error.

Hall	Seats Tested	Total Seats	Piano Tested
Ashurst (Northern Arizona University)	100	100	Steinway B
Katzin Concert Hall (Arizona State University)	183	347	Steinway D
Recital Hall (Arizona State University)	94	125	Steinway B
Crowder Hall (University of Arizona)	225	544	Steinway D
Holsclaw Hall (University of Arizona)	133	204	Steinway B

The distribution of seats was chosen to sample as much of the hall as possible, with hall diagrams, seating charts, and seats selected for testing shown in figures 8-12 and Appendix A. In addition to the seats selected within the audience area, a control of ten samples were taken from on-stage: five samples were taken with the assistant standing in front of the piano in the area of the curved 'crook' where vocalists tend to stand, and five samples seated in front of the piano where cellists and tubists tend to sit. These on-stage samples were taken to provide a baseline for what a pianist's partner encounters to compare to the data taken from the seating area and so determine the fidelity of sound in the seating area compared to the stage. Figures 8, 9, 10, 11, and 12 show the diagrams of each hall, specific seats tested may be found in the data tables in Appendix A (all 100 seats in Ashurst Hall were tested for this document).

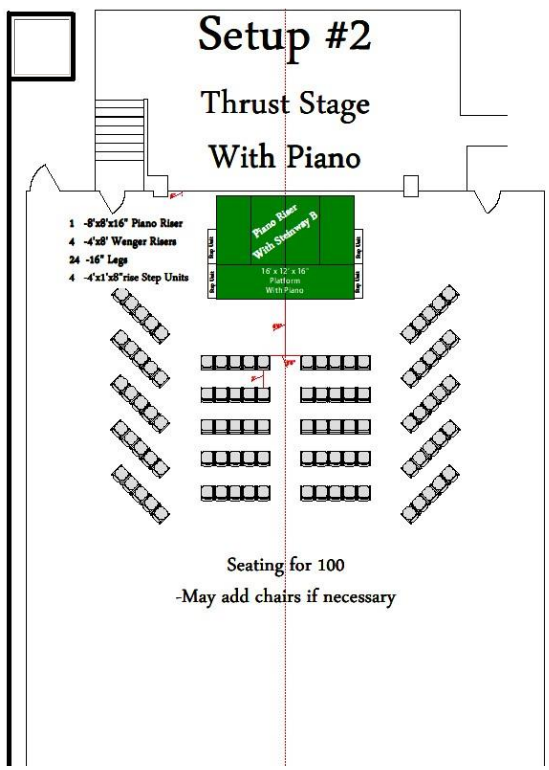


Figure 8. Ashurst Hall's standard recital layout when using the Steinway B on risers instead of the Steinway D on the thrust stage (piano in the green area). For this experiment, the seat stage right closest to the stairs is designated A1. The diagram is courtesy of Calvin Legassie, Auditorium Manager at Northern Arizona University.

Figure 9. The University of Arizona's Holsclaw Hall, with views from the rear of the hall and from the stage. For this experiment, seat numbering begins with A1 in the stage right seat closest to the stage. Both photographs are from the Fred Fox School of Music's website, www.music.arizona.edu.

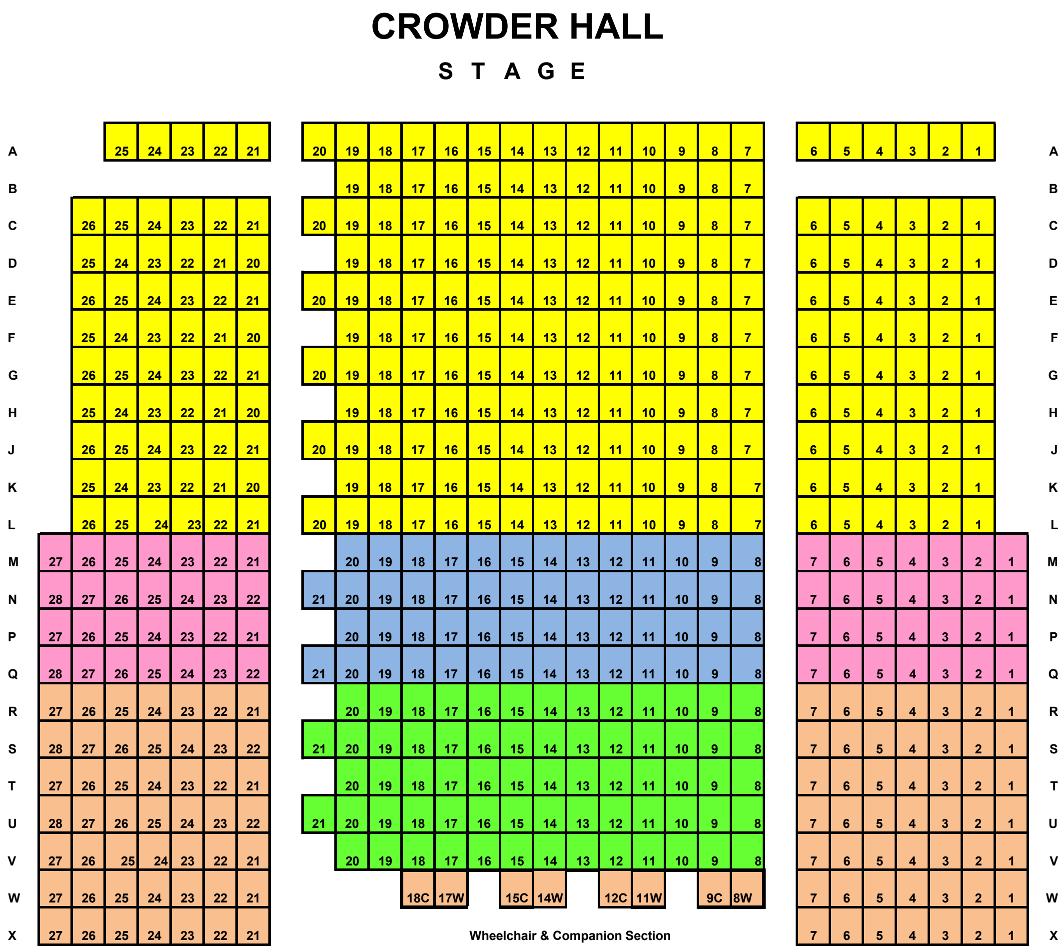


Figure 10. The University of Arizona's Crowder Hall seating chart. This chart is slightly out-of-date, as Rows W and X in the rear of the hall have been removed and is from the Fred Fox School of Music website, www.music.arizona.edu.

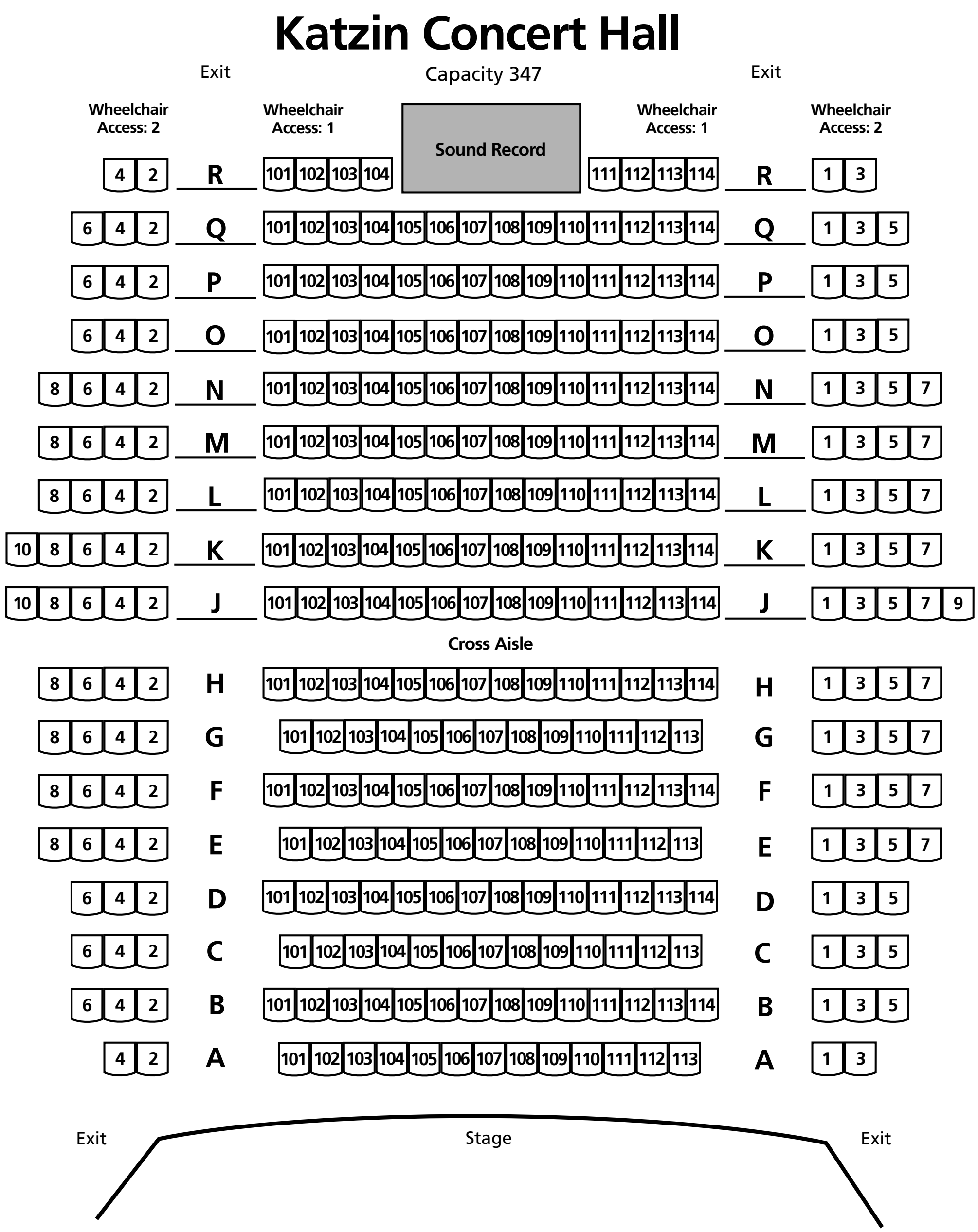


Figure 11. Arizona State University's Katzin Concert Hall seating chart, from the ASU School of Music website, www.music.asu.edu.

Figure 12. Arizona State University's Recital Hall is the most intimate of the five venues of this experiment. From this view, seat A17 is furthest stage right, proceeding down by odd numbers, with seats A1 and A2 in the center of the first row, with A18 on the stage left end. The photograph is courtesy of Nathan Arch.

Heat maps of the sound pressure level data for each iteration of the experiment were created with Tableau Desktop 10.3, a data-analysis and visualization program. Data was input from the original Microsoft Excel files of SPL data, then set to be presented as heat maps, with color schemes manually changed from Red-Green to Blue-Red. Additionally, for Katzin Concert Hall and Recital Hall at Arizona State University, the data columns were manually adjusted to more closely resemble the seat numbering systems used.

For the analysis of each sample, each WAV file was opened in Amadeus Pro, a music editing and sound analysis program. In Amadeus Pro, the sound file is shown as a time-and-intensity display, zoomed in to precisely select durations of the signal for analysis, as shown in Figure 13. Included in Amadeus Pro is a display that shows the duration of a signal selection, accurate to thousandths of a second, which was used to select the first two seconds of each test, plus-or-minus 0.005 seconds. Each selection was then analyzed using the spectrum analyzer function of Amadeus Pro, set to use a spectrum size of 32,768 points, the Blackman windowing function, and averaging the spectrum over the selection. The Blackman windowing function uses the principle of a Fourier transform, which breaks a complex signal down into a series of simple sine waves, to determine the relative strengths of signals that comprise a complex signal, such as the series of overtones present in a six-note chord played on the piano. The output of the spectrum analysis is a graph with the relative strengths of the signals shown in negative decibels on the y-axis, where 0 dB represents the threshold of the microphone 'clipping' and the lowest signal approaching negative infinity (-∞), with frequency in Hertz on the x-axis, as shown in Figure 14**.** The graphical output includes a feature of being able to select each peak with the computer mouse and receive the peak level in negative decibels, the frequency of that peak, the closest note to the peak, and that note's frequency. The peak levels for the first 15 overtones (including the six fundamental tones) were recorded in Microsoft Excel for later analysis in three spreadsheets with multiple pages in each (one spreadsheet per university, with pages for decibel data from the dosimeter, along with full-, short-, and no-stick spectrum analysis data for each hall).

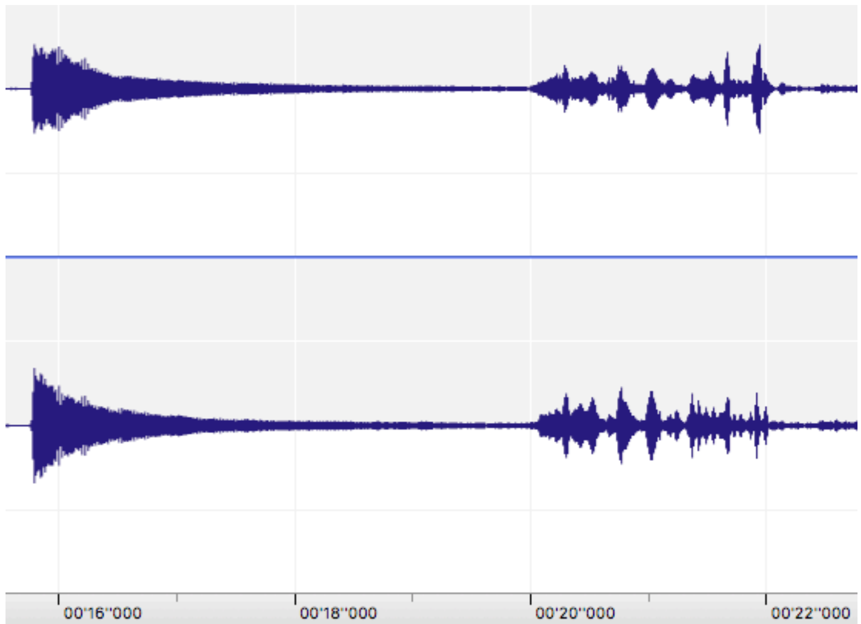


Figure 13. The WAV file from Recital Hall, No Stick is shown zoomed-in to see the chord strike (just less than 16 seconds) and its duration before the assistant announces the decibel level (20 seconds).

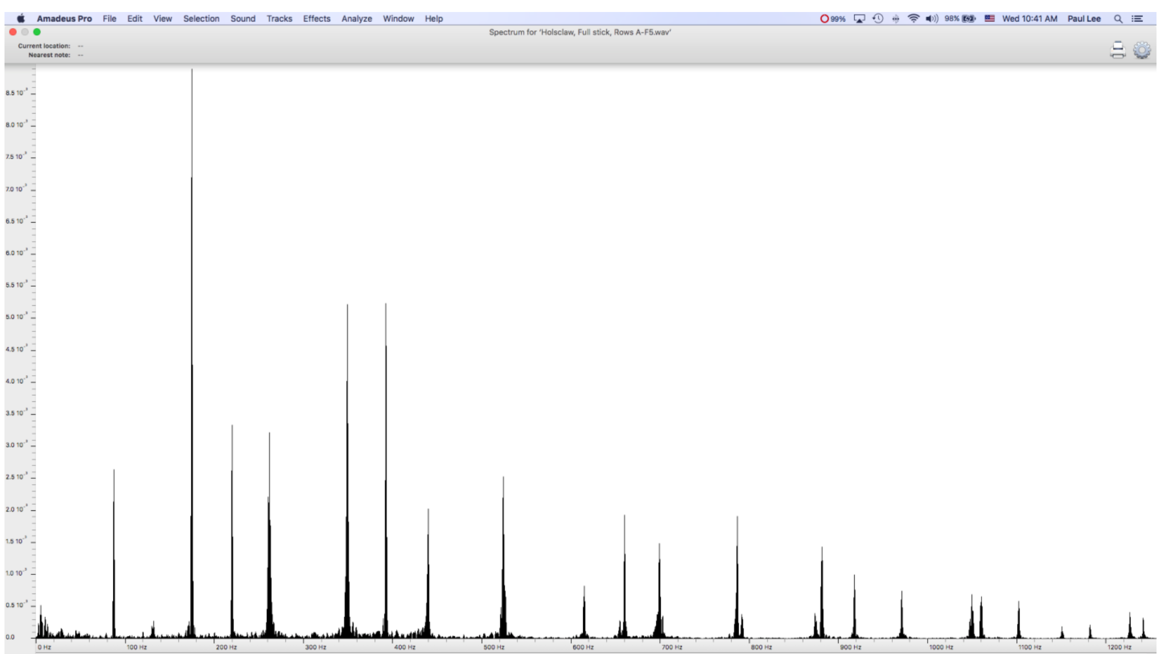


Figure 14. The relative strengths of the overtones present in a chord in the full-stick portion of Holsclaw Hall testing. Note the clear delineation of overtones (peaks) against background noise (gaps between peaks).

CHAPTER 5

RESULTS AND ANALYSIS

ASHURST HALL

Ashurst Hall is the sole small performing space for music at Northern Arizona University and is built as a multi-purpose hall. Among its unique features are no permanent seating, a flat floor with no rake (inclined seating for clear stage views), an upper (permanent) stage with a Steinway Model D piano, a lower (moveable) stage with a Steinway Model B piano, and a large hole in the hall's ceiling that opens into the rafters for lighting access, as shown in figures 15 and 16. Additionally, some measure of acoustic control can be affected by opening and closing the heavy drapes over the windows down both lengths of the hall.

Figure 15. As set up for a small recital using the floor piano, Ashurst Hall has 100 (out of 300 possible) chairs placed.

Figure 16. The large hole in the ceiling has a significant contribution to the acoustics of Ashurst Hall.

Ashurst Hall was tested on June 16, 2017, with the assistance of two undergraduate music majors at Northern Arizona University. At the time, only the Model B (6 feet, 10.5 inches) Steinway was available for use, so data was collected only using the setup seen in figure 15. Without permanent seating, no preexisting naming convention existed for the seating area, so rows were lettered A through E, seats numbered 1 through 20, beginning on the stage right side of the hall. In the interests of gaining a more complete understanding of this hall, all 100 seats were tested and used in the results of this experiment.

The average sound pressure level in Ashurst Hall for the standard 11-Newton blow was 72.5 dB-A, with the average levels for each stick height shown in table 3.

Table 3. Average sound pressure level for the seating area of Ashurst Hall.

	Full Stick	Short Stick	No Stick
Sound Pressure Level (dB-A)	73.4	72.1	71.9
Percentage difference from full stick		-1.8	-2.0
Standard Deviation	1.81	1.71	1.60
Range (dB-A)	9.1	7.8	7.3

From a general perspective, a one-decibel difference in sound pressure level is considered the smallest difference in sound that is discernible by the ear; the average results show a difference of 1.3 and 1.5 decibels difference from the full stick average in Ashurst Hall. The standard deviation is a measure of how closely related the data is to the average—larger deviations indicate that there are more outliers to the data than in a smaller deviation. Similarly, the range represents the difference between the largest and smallest observations in each experiment. With these fairly small standard deviations, the data can be presumed to be rather accurate. Figure 17 shows the heat-map distributions of peak sound pressure level in Ashurst Hall.

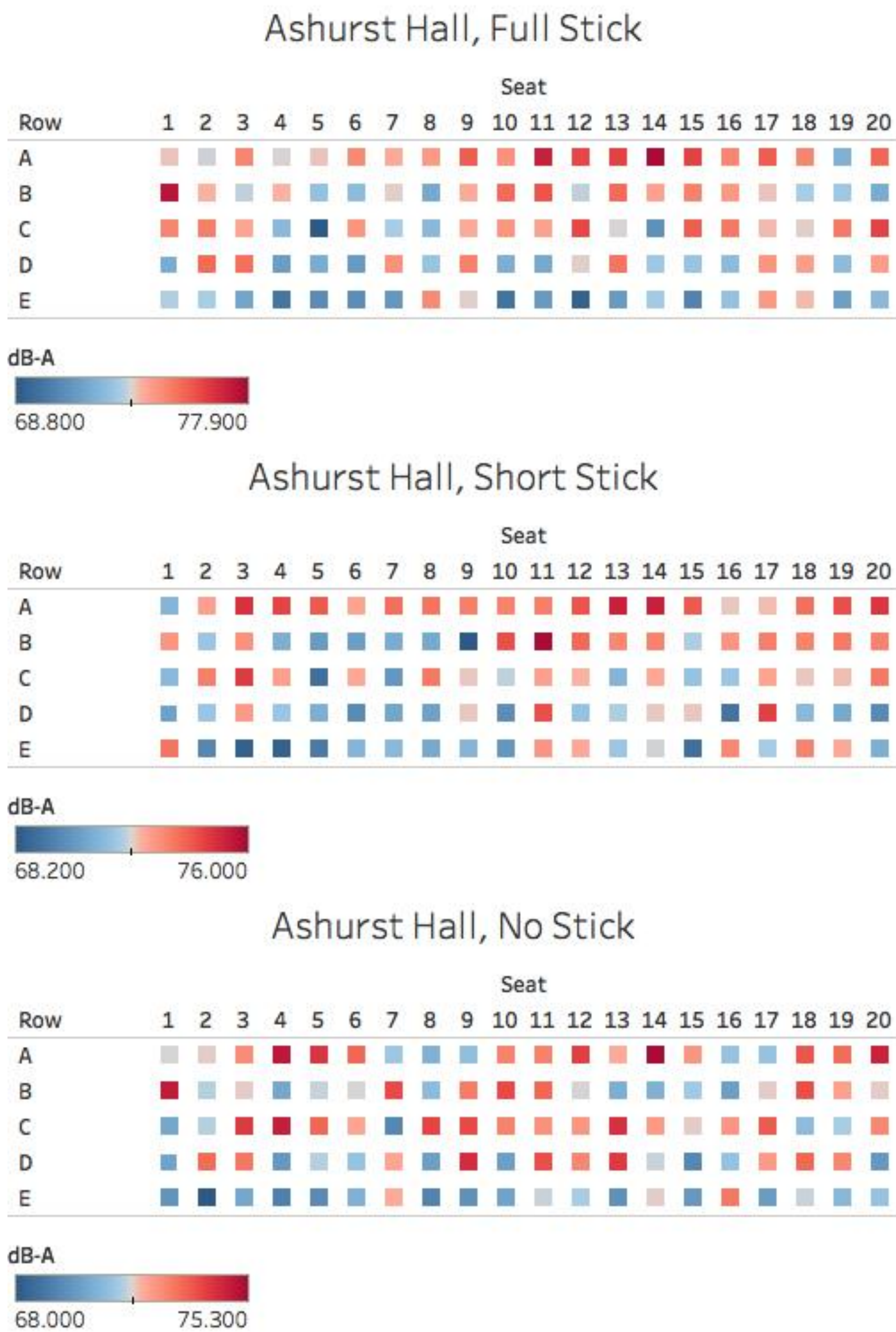


Figure 17. Heat maps showing the distribution of peak sound pressure level readings. Note a consistent strength in readings in all three lid heights in the area around seats A10 to A15.

The data on this experiment suggest that there is a small difference in volume for the audience seating area between stick heights, but one of the goals of the experiment is to attempt to determine which stick height results in a sonic environment for the audience which most closely matches what the performer onstage experiences. Table 4 shows the average results for the on-stage data collection with both sitting and standing measurements included.

Table 4. Data from Ashurst Hall on-stage with the standard piano dynamic as used across all experiments.

	Standing			**Sitting**		
	Full Stick	Short Stick	No Stick	Full Stick	Short Stick	No Stick
Sound Pressure Level (dB-A)	83.0	78.7	77.4	80.6	79.7	79.1
Percent difference from full stick		-5.18	-6.75		-1.12	-1.86
Standard Deviation	2.04	0.904	0.187	1.11	0.991	0.336
Range (dB-A)	5.6	2.5	0.5	2.7	2.3	0.8
Percent difference from audience area	11.6	8.39	6.85	8.93	9.54	9.10

The data collected from standing in front of the piano shows a considerable difference in performer's perception of piano loudness between full stick and the lower lid heights, but a very small difference in loudness if the performer is sitting in front of the piano. Of interest is the rather large difference in piano loudness between standing on stage with the lid fully open and what the data show from the audience seating area; more conclusions will be drawn later in this document, but the large hole in the ceiling of Ashurst Hall (see Figure 16, page 34) may have a considerable effect on the distribution of sound.

In addition to the testing protocol used at all five halls, testing at Ashurst Hall included experiments at all three stick heights using a 1.5-inch height for the striker, resulting in a *forte*-level dynamic. The justification for the extra experiments included the piano being due for extensive maintenance later in the summer, a relatively small number of strikes to collect data, and that the piano in question was the older of the two in Ashurst Hall. Table 5 shows the average sound pressure level data from the *forte*-level experiments in Ashurst Hall.

Table 5. The *forte*-level experiment in Ashurst Hall shows an average increase of 11 decibels over the standard force input experiment.

	Full Stick	Short Stick	No Stick
Sound Pressure Level (dB-A)	84.3	84.3	82.9
Percent difference from full stick		0	-1.66
Standard Deviation	1.53	1.61	1.34
Range (dB-A)	8.9	7.4	6.1

Similar to the standard force input experiments, the heat map distributions for the stronger strikes, shown in Figure 18, show an area of louder response in the A10-A15 region, with an area of louder response extending into Rows B, C, and D for the short stick response. This data suggests that for Ashurst Hall, the area with the loudest response is closer to the stage on the stage-left side of center.

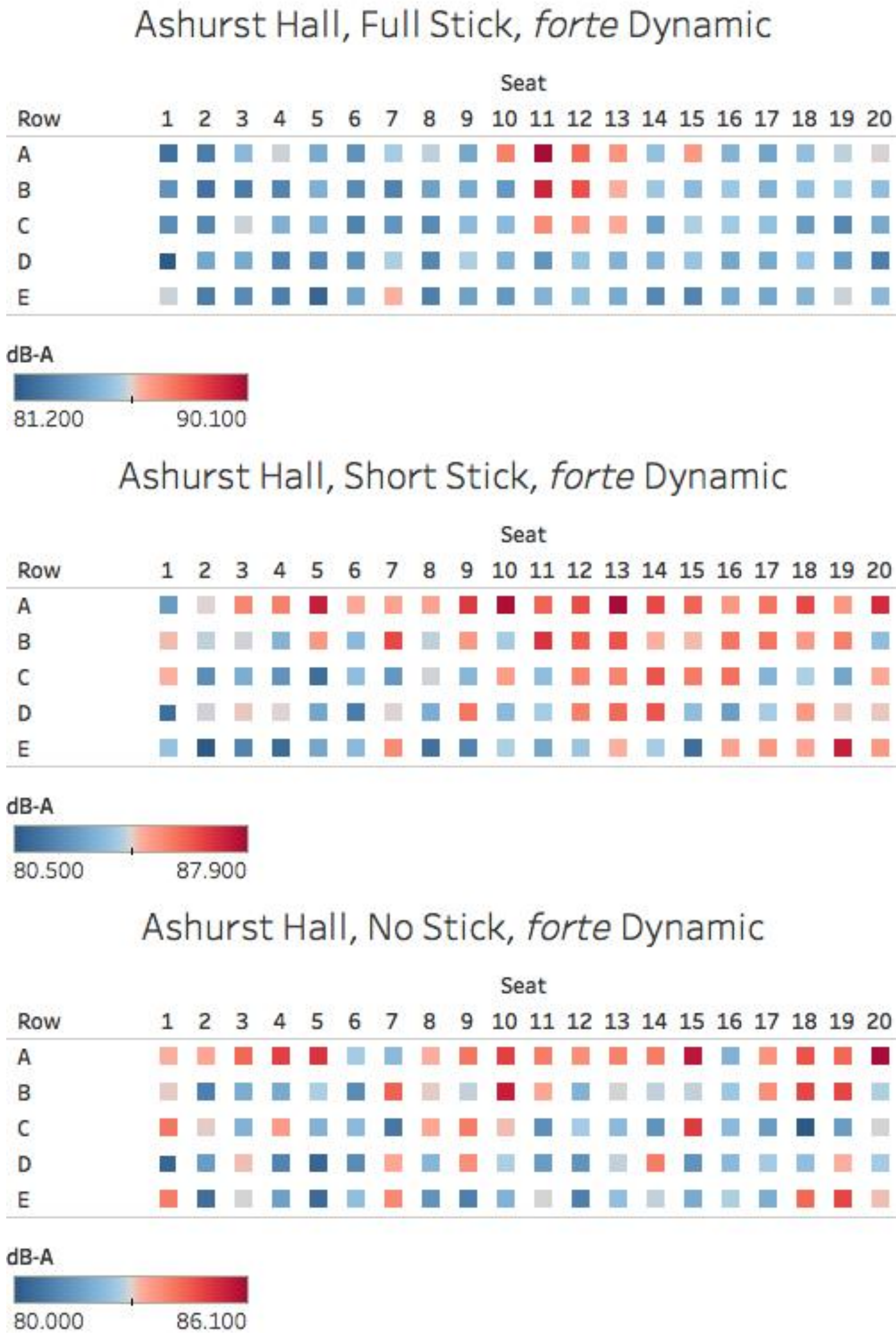


Figure 18. Heat maps from the *forte*-level experiment show that there appears to be an area stage-left of center that has a louder response across all three stick heights. On average, the *forte* strike results in an average sound pressure level 11 decibels greater than the standard energy experiments.

Figure 19 shows the six heat maps of Ashurst Hall's sound pressure level measurements, but with equal weighting for the three iterations of standard and *forte* dynamic. Arranged in this manner, it is clear that lowering the lid for the piano on the floor at Ashurst Hall has an effect on the piano's loudness for the audience seating area. The data also suggest that particularly for the standard-energy test, the most equitable distribution of sound from the piano comes when it is at full stick, with the least equitable distribution coming in the case of short stick.

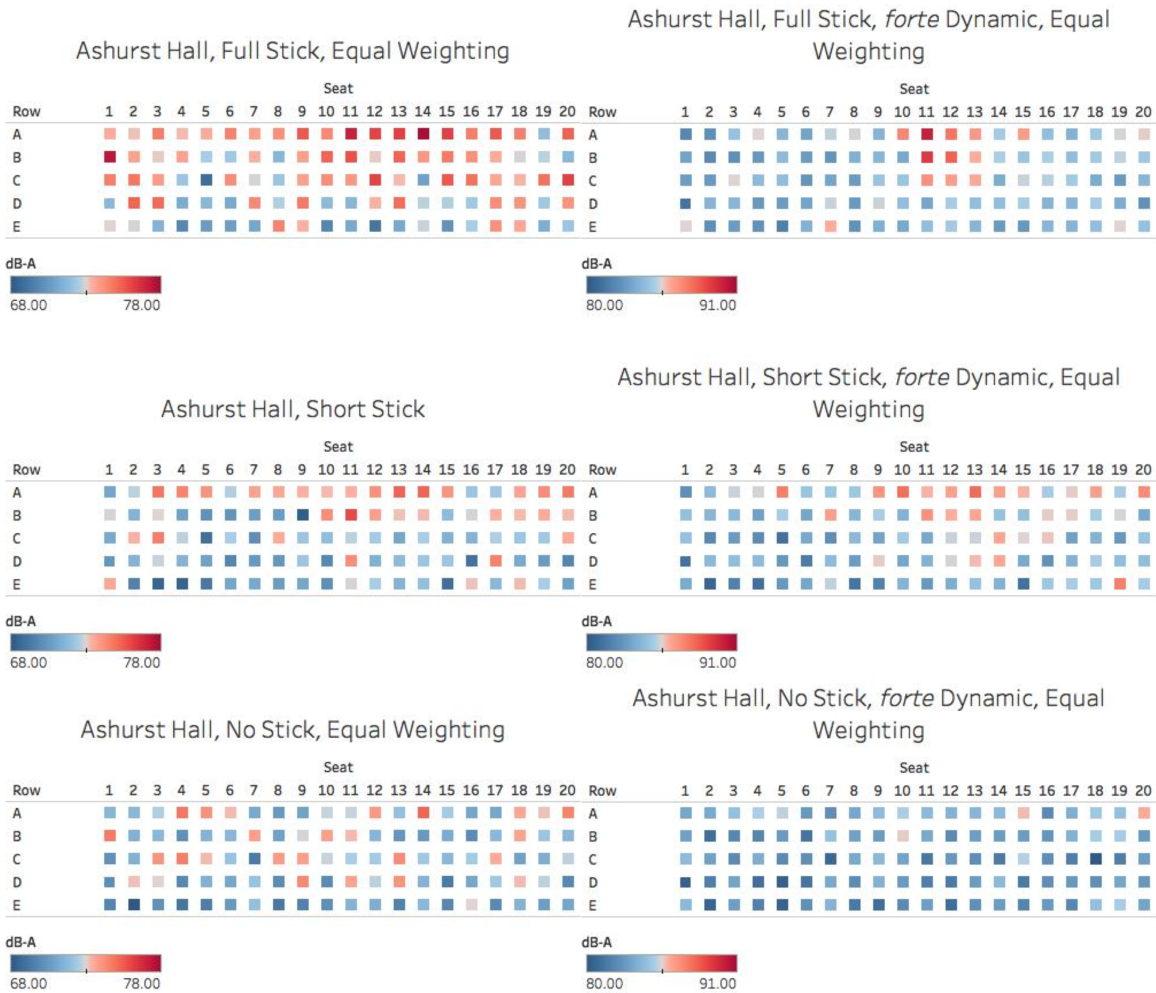


Figure 19. When adjusted for equal weight of the heat map function across the three variations of stick height for an experiment, it is more readily apparent that the full stick and standard dynamic level for the experiment result in a more equitable distribution of sound. Conversely, full stick with *forte* dynamic results in a more concentrated area of higher sound pressure level.

An additional consideration in the evaluation of stick height in the halls is the tonal makeup of the sound and the presence, absence, or proportion of overtones in the data. Given a chord of F2, C3, F3, A3, C4, and F4, the expected overtone series for the range F2 to C6 is comprised of the notes F3, C4, F4, G4, A4, C5, $D^{\#}5$ E5, F5, G5, A5, $A^{\#}5$, B5, and C6 (keeping in line with standard piano note naming conventions, black notes are always listed as sharp). As seen in table 6, the overtone series as generated by the Blackman windowing function in Amadeus Pro differs slightly, with the statistical data from the standard strike for the piano included.

Table 6. Fourier analysis of the WAV files for the seating area of Ashurst Hall show a much wider standard deviation and range than the sound pressure level data as recorded with the NoisePro dosimeter.

Stick Height		F3	A3	C4	F4	G4	A4	C5
Full	Avg.	-47.8	-46.6	-43.0	-41.7	-49.3	-54.8	-51.8
	Std. Dev.	5.39	6.79	5.00	6.01	6.01	6.20	5.60
	Range	28.2	33.1	24.8	32.1	32.9	30.1	29.6
Short	Avg.	-45.1	-47.1	-39.7	-44.7	-51.4	-54.8	-51.9
	Std. Dev.	4.42	5.35	4.73	4.52	5.18	3.48	5.19
	Range	21.8	27.0	217.	26.6	24.9	16.5	28.6
No	Avg.	-44.6	-44.4	-41.6	-43.1	-52.1	-54.5	-53.3
	Std. Dev.	4.36	6.51	5.20	4.72	5.57	3.54	5.22
	Range	19.9	56.3	26.0	22.3	33.8	15.8	24.9

Stick Height		D$^{\#}$5	E5	F5	G5	A5	A$^{\#}$5	B5	C6
Full	Avg.	-58.9	-58.4	-55.2	-57.5	-59.1	-61.1	-64.3	-59.4
	Std. Dev.	6.40	5.04	5.57	4.26	4.57	5.28	7.10	4.64
	Range	36.2	26.5	25.8	22.9	33.4	29.3	47.2	21.8
Short	Avg.	-59.7	-58.0	-56.1	-57.6	-59.3	-62.7	-66.5	-59.7
	Std. Dev.	7.27	4.29	4.41	4.25	3.00	5.30	5.79	5.34
	Range	45.2	21.4	23.4	24.1	137.	26.8	33.5	31.7
No	Avg.	-62.5	-59.8	-57.6	-59.3	-61.0	-63.8	-58.5	-61.4
	Std. Dev.	5.12	4.36	5.19	3.70	4.19	4.97	5.85	4.55
	Range	24.2	19.0	25.2	16.4	19.1	27.2	29.6	23.8

When compared to the on-stage standing and sitting data for the piano on short stick, the variance in the seating-area data is very pronounced, as shown in table 7, with standard deviations of two to three times that of the on-stage data; ranges are even more varied, up to a factor of twenty separating on-stage from audience seating areas for some overtones. With such a wide variance in range and the concurrent large standard deviation, the validity of overtone data is of some concern.

Table 7. When compared to the data taken onstage for Ashurst Hall's short-stick iteration, the difference in deviation and range is remarkable compared to the data taken from the audience seating area.

		F3	A3	C4	F4	G4	A4	C5
Audience	Avg.	-45.1	-47.1	-39.7	-44.7	-51.4	-54.8	-51.9
	Std. Dev.	4.42	5.35	4.73	4.52	5.18	3.48	5.19
	Range	21.8	27.0	21.7	26.6	24.9	16.5	28.6
Standing	Avg.	-41.0	-36.4	-29.4	-39.9	-49.5	-48.8	-44.3
	Std. Dev.	1.22	0.277	2.10	6.17	0.745	0.678	1.16
	Range	2.9	0.7	5.7	15.4	1.9	1.7	6.8
Sitting	Avg.	-39.2	-38.7	-28.8	-42.2	-66.7	-47.6	-46.3
	Std. Dev.	0.550	0.973	0.876	2.64	2.96	0.682	2.68
	Range	1.3	2.5	2.1	6.2	7.9	1.8	6.6

		$D^{\#}5$	E5	F5	G5	A5	$A^{\#}5$	B5	C6
Audience	Avg.	-59.7	-58.0	-56.1	-57.6	-59.3	-62.7	-66.5	-59.7
	Std. Dev.	7.27	4.29	4.41	4.25	3.00	5.30	5.79	5.34
	Range	45.2	21.4	23.4	24.1	137.	26.8	33.5	31.7
Standing	Avg.	-58.3	-55.0	-51.0	-50.4	-69.6	-56.9	-66.1	-49.7
	Std. Dev.	2.05	0.780	2.79	1.41	3.73	0.775	4.26	4.03
	Range	4.6	2.1	7.2	3.4	9.0	1.9	11.6	10.4
Sitting	Avg.	-53.8	-54.9	-56.4	-53.7	-57.1	-56.2	-70.4	-54.7
	Std. Dev.	1.13	1.95	4.70	2.84	1.35	1.66	1.90	5.70
	Range	3.1	5.2	12.5	7.0	3.6	4.3	5.3	14.8

HOLSCLAW HALL

Data was collected at Holsclaw and Crowder Halls at the University of Arizona on July 10, 2017. Holsclaw Hall was the smallest traditionally-designed hall tested for this document and is also unique in that it is the only hall that has a pipe organ in the space. The presence of the organ creates a false upstage wall in Holsclaw, which may affect the volume and quality of sound, particularly on no-stick testing. Additionally, Holsclaw has remote-controlled adjustable acoustic curtains running the entire length of the hall on both sides, allowing the performers to dampen the acoustic environment as desired.

The average sound pressure level data for the standard test is summarized in table 8. While the full-stick average sound pressure level is close to that of Ashurst Hall, the short- and no-stick experiments show a greater difference than in Ashurst. A possible explanation is the difference in stage height between Ashurst and Holsclaw: being much lower to the audience, the direct path may be more robust from Ashurst Hall.

Table 8. Average sound pressure level for the seating area of Holsclaw Hall. There is a greater percentage difference between stick heights in Holsclaw as opposed to Ashurst Hall.

	Audience Seating Area			Standing On Stage			Sitting On Stage		
	Full Stick	Short Stick	No Stick	Full Stick	Short Stick	No Stick	Full Stick	Short Stick	No Stick
Sound Pressure Level (dB-A)	73.1	70.6	70.0	77.0	75.5	74.2	73.8	76.9	70.8
Percent difference from full stick		-3.4	-4.2		-1.9	-3.6		+4.2	-4.1
Standard Deviation	1.72	1.29	1.27	0.295	0.268	1.29	0.378	0.683	1.31
Range (dB-A)	11.5	6.1	7.5	0.7	0.6	0.6	0.9	1.7	3.0

Heat maps for Holsclaw Hall show that the distribution of energy from the piano is much more uniform than that of Ashurst Hall, though there is a marked increase in energy in the first row for full stick. Figure 20 shows the equally-weighted heat maps for full-, short-, and no-stick iterations of the experiment.

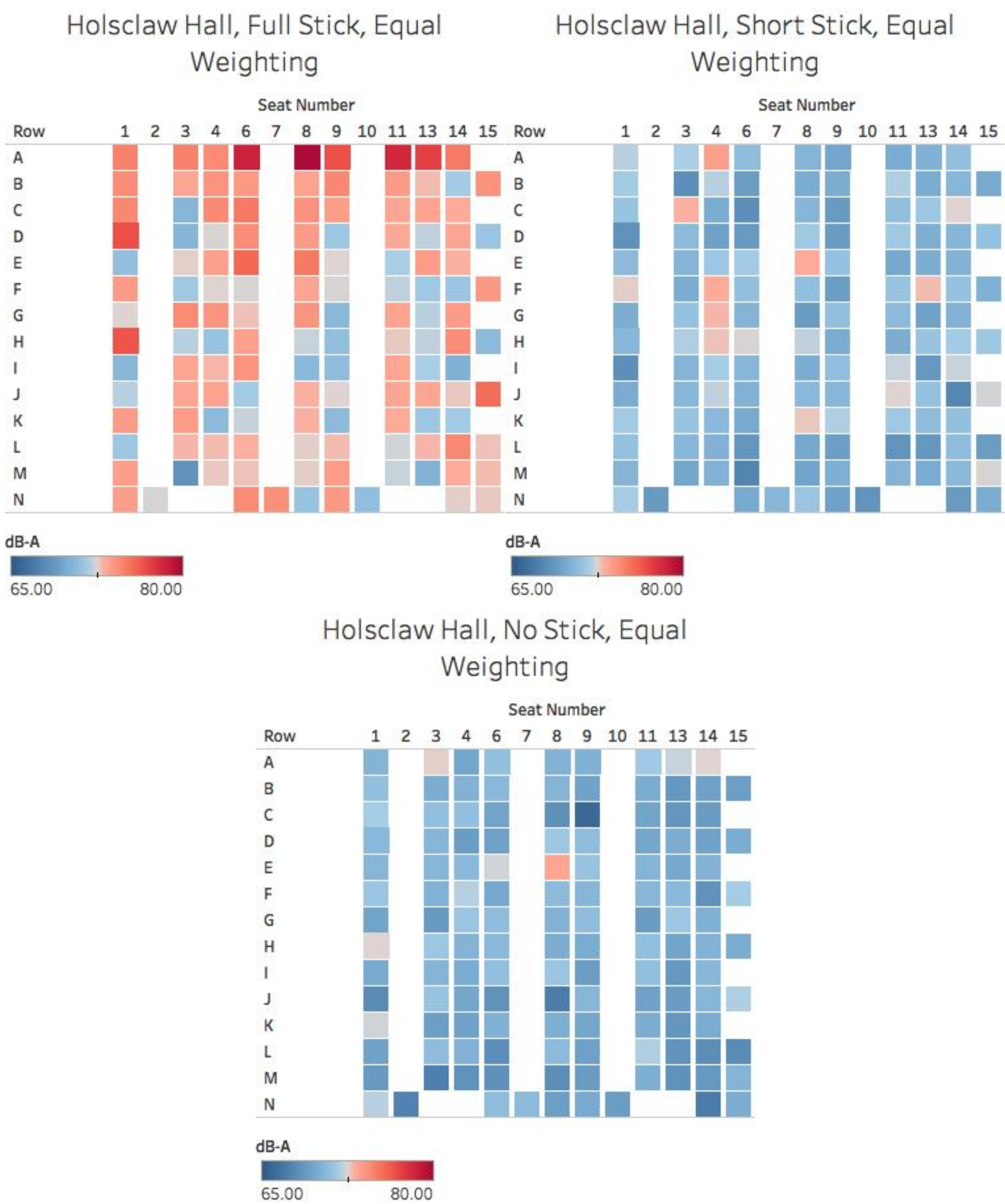


Figure 20. When equally-weighted, it is more readily-apparent that there appears to be a difference in volume in the audience seating area between stick heights for Holsclaw Hall.

For the full-stick experiment, the lower overtones in the series are less pronounced in the audience seating area than the upper overtones, which may suggest a thinner, more brilliant tone: louder overtones higher in the harmonic series result in a tone that is judged by audiences to be more brilliant than one that is predominantly based on the fundamental and lower overtones. Table 9 summarizes the mean, standard deviation, and range of overtones analyzed from both the audience seating area and on stage.

Table 9. Overtone analysis of the Holsclaw full stick experiment using the Blackman windowing function combined with statistical analysis from Microsoft Excel shows that deviations and ranges for the audience seating area are roughly consistent across the first 15 overtones.

		F3	A3	C4	F4	G4	A4	C5
Audience	Avg.	-46.1	-49.4	-47.3	-47.5	-50.7	-52.7	-52.7
	Std. Dev.	5.14	5.14	3.48	4.05	5.33	3.63	3.14
	Range	25.3	22.1	19.9	22.8	23.0	18.4	20.4
Standing	Avg.	-54.0	-40.7	-39.7	-46.1	-40.3	-54.0	-51.8
	Std. Dev.	4.43	0.255	0.672	0.622	0.442	1.06	3.23
	Range	11.0	0.6	1.7	1.4	1.0	2.9	6.5
Sitting	Avg.	-46.6	-45.2	-40.1	-40.5	-47.2	-45.7	-54.2
	Std. Dev.	1.71	0.224	0.773	1.65	0.241	0.336	1.47
	Range	3.8	0.6	1.7	3.7	0.6	0.9	3.5

		$D^{\#}5$	E5	F5	G5	A5	$A^{\#}5$	B5	C6
Audience	Avg.	-57.8	-57.2	-57.4	-60.1	-60.4	-61.1	-65.9	-63.1
	Std. Dev.	4.68	3.48	3.30	3.55	3.25	4.27	3.55	2.70
	Range	25.6	15.6	17.5	14.8	16.0	22.2	17.2	15.4
Standing	Avg.	-52.5	-52.0	-55.0	-56.9	-57.3	-65.8	-62.3	-63.8
	Std. Dev.	0.811	0.873	0.952	0.988	4.06	2.18	0.522	2.11
	Range	1.9	2.2	2.6	2.4	9.3	5.7	1.3	4.7
Sitting	Avg.	-60.1	-59.1	-58.5	-56.3	-56.7	-65.9	-62.2	-65.3
	Std. Dev.	0.767	0.762	2.80	0.522	1.36	1.14	1.42	2.61
	Range	1.8	2.0	7.0	1.2	2.9	2.8	3.3	6.4

When the lid is lowered to the short-stick position, some interesting and unexpected results follow regarding the strength of overtones onstage versus those in the audience seating area, summarized in table 10. When standing in front of the piano, the lower overtones on stage are less present than in the audience seating area, though the higher overtones (E5 and above) more closely match the strength found in the audience seating area. When sitting, however, the data suggest three distinct groups of results: the lowest overtones (F3 to F4) are generally stronger on stage than in the audience seating area; the next two overtones (G4 and A4) are only 3.2 and 1.6 percent different than their strength between stage and audience; the higher overtones (C5 to C6) are again consistently stronger on stage than in the audience seating area, which would give the impression of greater brilliance to a performer than the audience may hear.

Table 10. Aggregate tonal analysis of the short stick experiment in Holsclaw Hall suggests that the overtone makeup of the sound in the audience seating area is more closely aligned with the on-stage makeup than on full stick.

		F3	A3	C4	F4	G4	A4	C5
Audience	Avg.	-47.7	-50.9	-46.3	-47.5	-52.7	-55.2	-56.0
	Std. Dev.	5.42	6.26	4.08	4.25	5.44	3.30	3.49
	Range	29.9	30.3	23.2	22.2	24.8	18.6	17.2
Standing	Avg.	-51.7	-43.5	-48.8	-40.7	-54.5	-54.8	-50.2
	Std. Dev.	4.89	0.658	1.40	1.38	1.55	0.862	2.83
	Range	10.1	1.8	3.8	3.4	3.8	2.3	5
Sitting	Avg.	-53.5	-46.1	-41.4	-40.3	-51.0	-56.1	-50.1
	Std. Dev.	2.88	0.192	0.820	0.152	0.630	1.63	1.89
	Range	7.5	0.5	1.9	4.1	1.5	3.7	3.0

		D#5	E5	F5	G5	A5	A#5	B5	C6
Audience	Avg.	-62.9	-59.5	-59.9	-63.9	-63.0	-65.0	-70.0	-64.5
	Std. Dev.	5.05	3.46	3.61	3.20	3.78	4.67	4.98	2.82
	Range	26.6	16.7	18.7	17.4	19.9	22.6	21.6	13.9
Standing	Avg.	-68.3	-60.4	-60.8	-62.1	-62.9	-61.5	-66.7	-61.6
	Std. Dev.	5.09	1.72	3.03	1.53	3.74	1.39	1.87	1.35
	Range	11.3	3.8	8.2	4.1	9.2	3.2	4.2	3.4
Sitting	Avg.	-55.9	-54.3	-56.7	-56.2	-63.2	-69.9	-65.8	-60.7
	Std. Dev.	0.781	0.618	1.12	0.782	2.66	1.38	1.83	1.68
	Range	2.0	1.3	2.5	1.8	6.4	3.5	4.2	3.9

CROWDER HALL

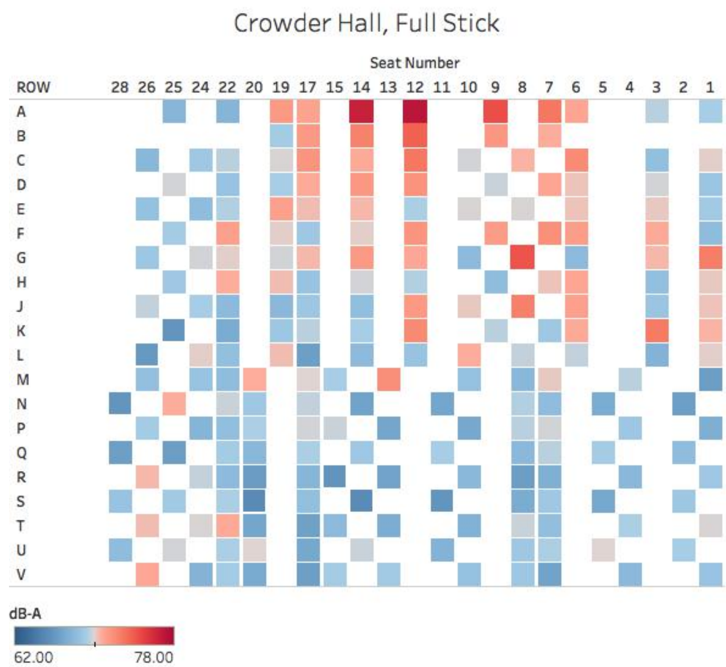
Crowder Hall is a multipurpose hall with a large backstage area and fly system; orchestra shells would normally be used to direct more sound from the stage to the audience seating area. For the purposes of this document, the shells were unable to be used during data collection, so there may be a greater sound loss to the backstage and overhead areas than would be expected during a normal performance. However, as the objective in this document is to examine the effects of the piano lid when keeping other factors constant, the shells' absence is immaterial.

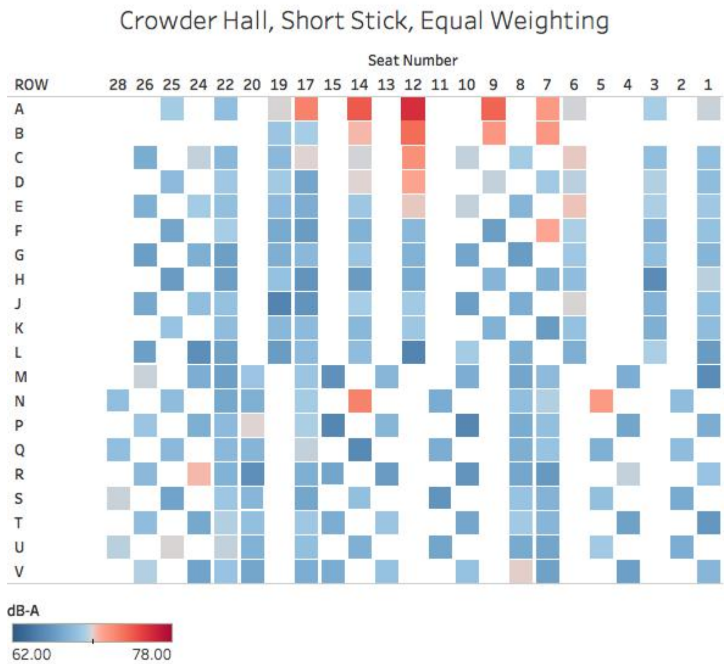
A summary of the sound pressure level data obtained in Crowder Hall is presented in table 11. Though the total range of each iteration of the experiment is larger than Holsclaw Hall, the small standard deviation suggests that the acoustic response across the audience seating area is quite uniform. As hypothesized from the absence of acoustic shells in the previous paragraph, the overall sound pressure levels are two to three decibels softer than the equivalent iterations in Holsclaw and three to four decibels softer than Northern Arizona University's Ashurst Hall.

Table 11. With small differences in the standard deviation, the acoustic response of Crowder Hall can be surmised to be quite uniform across the space.

	Audience Seating Area			Standing On Stage			Sitting On Stage		
	Full Stick	Short Stick	No Stick	Full Stick	Short Stick	No Stick	Full Stick	Short Stick	No Stick
Sound Pressure Level (dB-A)	69.3	68.1	66.6	80.6	76.1	74.2	75.4	76.5	75.3
Percent difference from full stick		-1.73	-3.90		-5.6	-7.9		+1.5	-0.1
Standard Deviation	1.84	1.69	1.82	0.639	1.74	1.55	0.335	0.404	1.01
Range (dB-A)	12.1	11.2	9.9	1.6	3.9	3.1	0.8	1.1	2.2

Figure 21 shows the equally-weighted heat maps of the three iterations of the Crowder Hall experiment. As would be expected, the area of greatest sonic intensity is in rows A through C in the stage center area; somewhat unexpectedly, the data from the front-and-center area of Crowder does not indicate a louder area on the no stick iteration of the experiment as is seen on both full and short stick iterations. Additionally, once one is removed from the area directly in front of the piano in the first three rows of the audience seating area, the response is quite uniform, reinforced mathematically by the small standard deviations seen in table 11.





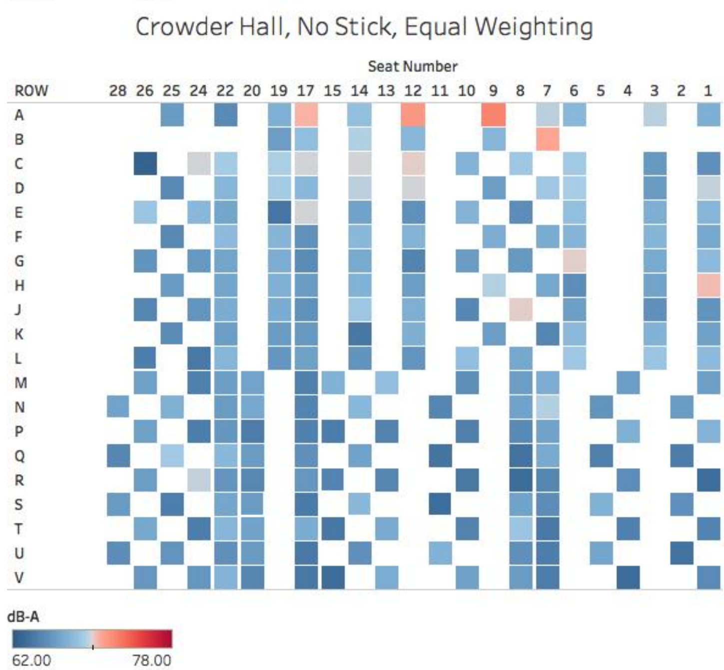


Figure 21. When weighted equally, the three iterations of stick height in Crowder Hall show a diminishing area in the center area in the first rows of particularly loud responses. Apart from this area of relatively loud responses, the rest of the hall shows rather uniform responses.

Overtone analysis of the samples collected in Crowder Hall show more uniform results than Holsclaw Hall, shown in table 12. Comparison between the audience seating area and the data collected on stage standing in front of the piano suggest that the overtone makeup is more closely correlated than that between audience seating area and sitting in front of the piano. The large range and considerable standard deviation suggest that there is a large variance in the overtone makeup of the sound across the hall. Generally, however, the standard deviation decreases with higher overtones, indicating that for higher overtones, the variance of the hall becomes less noticeable.

Table 12. Overtone analysis of the experiment's full-stick iteration in Crowder Hall. Similar to Holsclaw Hall, the audience and standing data are more similar than the audience and sitting data.

		F3	A3	C4	F4	G4	A4	C5
Audience	Avg.	-51.2	-56.0	-46.3	-51.2	-56.6	-56.8	-56.2
	Std. Dev.	4.55	5.52	4.58	5.28	5.90	4.59	3.47
	Range	25.8	28.1	24.3	60.9	40.5	27.2	21.0
Standing	Avg.	-51.7	-43.5	-48.8	-40.7	-54.5	-54.8	-50.2
	Std. Dev.	4.89	0.658	1.40	1.38	1.55	0.862	2.83
	Range	10.1	1.8	3.8	3.4	3.8	2.3	5
Sitting	Avg.	-42.8	-49.1	-39.5	-44.9	-47.2	-47.5	-47.6
	Std. Dev.	0.702	1.00	0.783	1.86	0.606	2.35	0.915
	Range	1.6	2.2	2.1	4.7	1.3	6.2	2.0

		$D^\#5$	E5	F5	G5	A5	$A^\#5$	B5	C6
Audience	Avg.	-63.3	-65.7	-64.8	-65.6	-63.1	-68.4	-68.1	-66.9
	Std. Dev.	6.00	3.76	3.54	3.67	3.85	4.85	5.89	3.03
	Range	34.6	21.7	22.3	21.4	20.4	29.4	30.1	16.8
Standing	Avg.	-62.0	-60.0	-58.9	-60.8	-57.1	-67.0	-65.1	-63.1
	Std. Dev.	5.02	2.00	1.63	2.19	1.79	3.46	1.95	1.27
	Range	14.0	5.0	4.1	5.0	4.7	9.3	5.0	7.2
Sitting	Avg.	-52.4	-63.8	-61.5	-61.9	-54.4	-67.4	-65.7	-59.8
	Std. Dev.	0.908	0.945	1.18	1.11	1.30	0.526	1.69	1.05
	Range	2.4	2.4	2.8	2.9	3.2	1.3	4.0	2.4

Interestingly, analysis of the short stick iteration of the Crowder Hall test suggests that there is a considerable difference between the on-stage overtone makeup of the sound and the overtone makeup in the audience seating area. Generally, the standing and sitting overtone analysis in table 13 shows averages that are much closer to each other than to the averages from the audience seating area. Conversely, overtones such as G4 show a close correlation between the audience seating area average and the onstage sitting average while varying considerably between the onstage sitting and standing averages. Similar to the full-stick overtone analysis, standard deviations are large, with correspondingly large ranges.

Table 13. Overtone analysis of the short-stick iteration of Crowder Hall suggests that there is less correlation between the audience seating area and the onstage, full-stick test than between the two versions of the onstage test.

		F3	A3	C4	F4	G4	A4	C5
Audience	Avg.	-50.9	-57.0	-47.1	-53.5	-59.0	-59.6	-56.4
	Std. Dev.	4.23	5.24	4.22	4.02	6.59	4.66	3.86
	Range	21.8	31.1	24.9	22.1	71.9	29.9	19.1
Standing	Avg.	-42.8	-45.8	-45.3	-40.7	-41.2	-50.9	-47.4
	Std. Dev.	1.13	0.130	8.79	1.41	0.239	0.646	1.18
	Range	3.0	0.3	20.5	3.6	0.6	1.5	2.9
Sitting	Avg.	-38.4	-63.4	-39.2	-47.6	-61.5	-49.3	-45.9
	Std. Dev.	0.520	0.814	1.60	1.47	0.228	1.56	0.597
	Range	1.2	2.0	4.1	3.6	0.6	4.2	1.5

		D#5	E5	F5	G5	A5	A#5	B5	C6
Audience	Avg.	-63.9	-68.1	-66.8	-67.2	-65.3	-71.8	-69.9	-70.5
	Std. Dev.	5.92	3.91	3.10	3.44	3.83	4.03	4.93	3.53
	Range	31.9	22.1	15.1	18.4	21.5	21.4	29.1	19.2
Standing	Avg.	-57.5	-59.9	-60.7	-59.2	-56.5	-67.6	-61.8	-61.9
	Std. Dev.	0.526	0.313	1.67	2.75	0.490	0.850	0.696	1.07
	Range	1.4	0.8	4.1	6.3	1.2	1.8	1.5	2.4
Sitting	Avg.	-54.5	-58.9	-59.8	-60.1	-59.1	-63.0	-64.3	-66.2
	Std. Dev.	0.581	0.224	1.14	0.564	0.926	0.343	0.795	1.89
	Range	1.3	0.6	2.9	1.4	2.1	0.8	1.8	4.9

For the no-stick iteration of the experiment in Crowder Hall, overtone analysis presented in table 14 shows a nearly uniform 8-10 decibel difference between the audience seating area and the onstage iterations, though with notable exceptions. Decibel levels for the audience seating area, standing, and sitting iterations for overtones C4, $D^{\#}5$, and B5 are very close to each other, suggesting that these overtones have less distance losses than the other overtones. Standard deviations and ranges in the audience seating area are again indicative of a large variance in the quality and overtone makeup of the sound throughout the hall.

Table 14. Overtone analysis of the no-stick iteration at Crowder Hall shows that ranges and standard deviations for the audience seating area are quite large, suggesting a wide variance in the overtone makeup of the F-major chord. With the lid closed, differences between standing and sitting onstage are small.

		F3	A3	C4	F4	G4	A4	C5
Audience	Avg.	-50.8	-56.2	-48.7	-54.2	-61.4	-61.2	-59.1
	Std. Dev.	4.25	5.17	4.10	5.18	6.88	4.70	3.52
	Range	21.8	33.2	30.3	59.0	78.8	24.9	23.4
Standing	Avg.	-42.1	-45.0	-48.8	-45.4	-47.7	-52.7	-53.3
	Std. Dev.	0.515	0.455	4.15	1.84	0.367	1.78	2.35
	Range	1.1	1.2	10.4	4.8	0.9	5.0	5.2
Sitting	Avg.	-38.4	-43.5	-45.2	-45.4	-63.4	-53.7	-45.3
	Std. Dev.	0.167	0.409	0.467	2.38	0.944	1.33	0.991
	Range	0.4	1.1	1.2	5.2	2.2	3.2	2.5

		$D^{\#}5$	E5	F5	G5	A5	$A^{\#}5$	B5	C6
Audience	Avg.	-66.0	-68.6	-68.0	-68.7	-67.1	-72.1	-72.4	-71.0
	Std. Dev.	5.89	3.53	3.20	3.22	3.41	4.55	5.21	3.58
	Range	31.0	19.1	17.1	16.9	22.2	24.2	32.2	18.5
Standing	Avg.	-67.8	-62.4	-59.9	-60.8	-61.9	-71.4	-66.9	-65.1
	Std. Dev.	1.95	0.691	3.15	2.42	0.687	1.60	0.567	1.26
	Range	4.8	1.6	7.3	6.5	1.6	3.7	1.5	3.0
Sitting	Avg.	-50.5	-57.2	-69.3	-60.7	-63.7	-70.4	-63.0	-65.9
	Std. Dev.	1.73	0.472	0.409	2.22	2.32	2.13	0.743	2.18
	Range	3.0	1.1	1.1	4.7	5.2	5.9	1.8	5.9

KATZIN CONCERT HALL

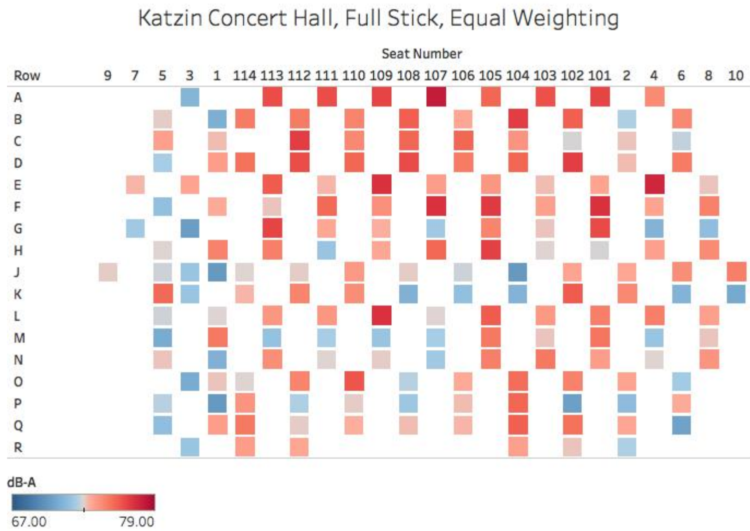
Arizona State University's Katzin Concert Hall was designed and built as a concert hall; as such, the stage is fully-enclosed, which reflects sound out into the audience seating area. Additionally, myriad reflective surfaces and three-dimensional wall effects serve to create an environment where sound waves should diffuse efficiently, creating a space with a more uniform auditory response. For this document, only one of the three concert grand pianos at Katzin was used, the New York-manufactured Steinway Model D piano; it may be that the different tonal qualities of the other pianos (a Hamburg-manufactured Steinway Model D and a Bösendorfer 290 "Imperial") result in differing spectra for the hall, but equipment restrictions prevented testing on multiple pianos.

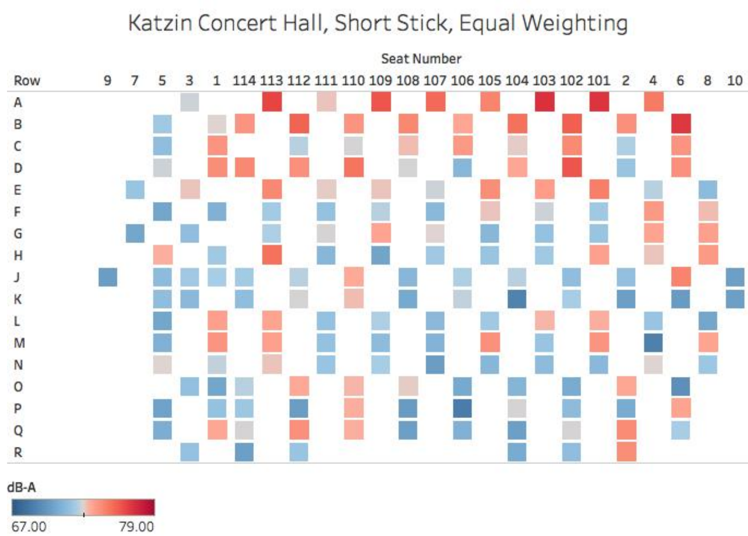
A summary of the sound pressure level data is shown below in table 15. With small ranges and small standard deviations, the data suggest that the sound pressure levels in Katzin Concert Hall are more uniform than in Holsclaw or Crowder Halls. Ashurst Hall, though similar in rough dimension to Katzin Concert Hall, has on the whole a louder response, which can be attributed to the piano on a low platform and the lack of depth in the seating area.

Table 15. Average sound pressure levels in the audience seating area for Katzin Concert Hall. Compared to both Crowder and Holsclaw Halls, the difference in sound pressure levels is less as a percentage of the full-stick levels.

	Audience Seating Area			Standing On Stage			Sitting On Stage		
	Full Stick	Short Stick	No Stick	Full Stick	Short Stick	No Stick	Full Stick	Short Stick	No Stick
Sound Pressure Level (dB-A)	73.9	72.7	71.6	80.1	76.0	76.4	78.3	79.2	75.8
Percent difference from full stick		-1.62	-3.11		-5.1	-4.6		+1.1	-3.2
Standard Deviation	1.75	1.64	1.50	0.427	1.21	1.36	1.36	2.01	1.20
Range (dB-A)	8.1	8.7	9.0	1.2	2.9	3.0	3.6	5.0	3.2

Figure 22 shows heat maps of the sound pressure level data from the audience seating area of Katzin Concert Hall. This data shows an interesting set of results: though the hall as a whole more evenly disperses sonic energy from the stage, there are regular areas of quieter response, such as along the stage-right wall of the hall (odd-numbered one-digit seats). As expected, the area closest to the stage and in the center part of the audience seating area shows the highest sound pressure levels for the hall, though this area of greatest intensity is not as intense compared to the rest of the hall. Short- and no-stick iterations of the experiment show again the expected area of highest sound pressure levels is in the center-stage area closest to the stage; as with the full-stick iteration, the difference between this loudest area and the rest of the hall is less prominent than in other halls tested.





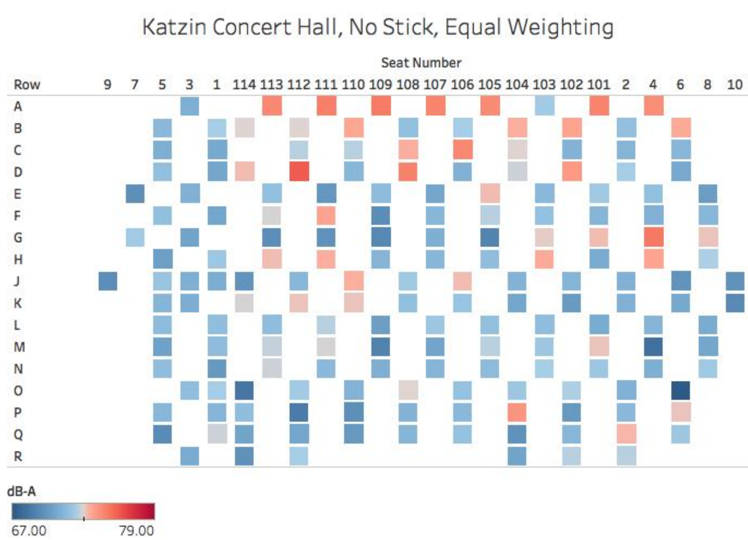


Figure 22. Heat maps of the audience seating area of Katzin Concert Hall suggest an overall excellent distribution of sonic energy from the stage.

Shown in table 16, overtone analysis of the full-stick iteration in Katzin Concert Hall suggests that the onstage sonic environment is much more reliably transmitted to the audience seating area than in previous halls examined. Particularly when comparing the standing iteration to the audience seating area, the individual overtones' strengths are generally closely aligned, though with some significant outliers (such as the 11-decibel difference between audience seating area and standing for C4). Standard deviations for the audience seating area are on average consistent with other halls, but the lower range indicates that while there is considerable variance in the overtone strength across the hall, there are fewer areas of overtone power extremes. As would be expected, sitting in front of the piano results in a more intense sonic environment when compared to the audience seating area, though again, the variance is not as extreme as it is in other halls. The sitting iteration is consistently 4 to 5 decibels louder across the overtone spectrum than the audience seating area, which is consistent with the full-stick, seated test sound pressure level average of 78.3 decibels.

Table 16. Overtone analysis for the full-stick iteration of the Katzin Concert Hall experiment suggests that the sonic environment in the audience seating area is more closely aligned with what the standing performer would hear rather than the sitting performer.

		F3	A3	C4	F4	G4	A4	C5
Audience	Avg.	-45.5	-52.2	-42.2	-45.9	-53.6	-51.5	-49.7
	Std. Dev.	4.71	5.45	4.95	4.24	6.34	4.61	4.35
	Range	26.3	25.4	30.9	28.8	32.6	22.4	22.7
Standing	Avg.	-43.8	-47.4	-31.2	-47.2	-53.0	-42.6	-46.9
	Std. Dev.	0.491	0.607	1.60	2.71	0.946	1.08	4.29
	Range	1.2	1.6	3.9	6.7	2.5	2.9	10.9
Sitting	Avg.	-40.4	-50.3	-39.8	-41.3	-44.6	-42.1	-42.4
	Std. Dev.	1.22	0.524	4.58	4.63	0.576	0.619	3.19
	Range	3.1	1.4	12.2	10.2	1.6	1.6	8.4

		$D^{\#}5$	E5	F5	G5	A5	$A^{\#}5$	B5	C6
Audience	Avg.	-58.6	-57.0	-55.4	-57.0	-58.6	-65.2	-68.2	-61.0
	Std. Dev.	5.11	3.85	3.66	4.22	3.51	5.93	5.81	3.85
	Range	29.9	26.7	26.0	23.6	17.6	31.9	27.2	20.0
Standing	Avg.	-58.7	-47.2	-48.8	-49.4	-56.1	-64.3	-71.7	-58.0
	Std. Dev.	0.563	0.512	1.82	1.39	0.559	0.796	2.04	2.78
	Range	1.4	1.3	4.9	3.4	1.4	1.9	5.1	7.4
Sitting	Avg.	-54.7	-53.0	-50.3	-50.9	-58.2	-54.3	-61.5	-59.3
	Std. Dev.	0.251	0.308	2.12	0.589	0.327	0.593	0.612	1.94
	Range	0.6	0.8	5.3	1.2	0.9	1.6	1.3	4.7

Overtone analysis for the short-stick iteration in Katzin Concert Hall is presented in table 17. As compared with the full-stick iteration, the data is considerably more muddled in the short-stick overtone response. Though on the whole, the overtones are louder in the sitting iterations, the difference between audience seating area and sitting in front of the piano are considerably varied: overtones F3 to G4 are all 6 to 7 decibels quieter in the audience seating area than onstage, but then A4 and the higher overtones have a smaller difference between the onstage and audience seating area values. When compared to standing in front of the piano, the same issues of variance occur: for some overtones, their presence in the audience seating area is essentially the same as onstage (for instance, F3 and G4), while A3 is more present in the audience seating area than onstage, and then others are considerably stronger onstage than in the audience seating area (F4, A4, and C5).

Table 17. Overtone analysis of Katzin Concert Hall in the short-stick iteration suggests that the sonic environment is less uniform from stage to audience seating area, with some overtones more present in the audience seating area than on stage and vice versa.

		F3	A3	C4	F4	G4	A4	C5
Audience	Avg.	-45.0	-54.3	-42.1	-47.1	-51.1	-52.5	-52.0
	Std. Dev.	4.65	4.28	5.40	4.60	5.25	4.50	4.27
	Range	24.5	23.9	28.8	27.9	30.4	22.9	24.4
Standing	Avg.	-44.5	-61.2	-39.5	-39.3	-51.7	-44.6	-45.5
	Std. Dev.	1.98	1.06	6.72	2.24	0.973	0.957	2.92
	Range	4.6	2.5	16.0	5.6	2.7	2.3	6.8
Sitting	Avg.	-38.8	-49.5	-35.6	-41.9	-45.1	-52.5	-41.2
	Std. Dev.	0.681	0.412	1.15	1.32	0.757	0.904	2.21
	Range	1.7	1.0	2.5	3.2	2.1	1.9	6.1

		D$^{\#}$5	E5	F5	G5	A5	A$^{\#}$5	B5	C6
Audience	Avg.	-60.4	-58.2	-56.4	-58.1	-60.4	-65.6	-69.5	-62.0
	Std. Dev.	5.63	3.41	3.79	4.00	3.76	5.67	5.27	3.92
	Range	26.4	16.1	20.0	18.8	17.5	41.0	33.1	22.0
Standing	Avg.	-49.8	-52.0	-54.7	-53.7	-55.7	-56.3	-66.3	-58.4
	Std. Dev.	0.891	115	1.21	1.22	1.28	1.10	0.881	3.49
	Range	2.0	2.8	3.0	2.7	3.1	2.6	2.3	8.7
Sitting	Avg.	-52.0	-54.8	-51.2	-56.7	-58.1	-53.8	-64.6	-59.1
	Std. Dev.	0.451	0.179	1.32	2.32	1.03	0.469	1.27	3.62
	Range	1.1	0.5	2.8	4.7	2.5	1.2	3.5	9.3

Table 18 summarizes the overtone analysis of the no-stick iteration in Katzin Concert Hall. Similar to the other iterations in Katzin and elsewhere, the upper overtones are much more equally present both on stage and in the audience seating area than the lower overtones. When compared to previous iterations, trends in overtone presence are nonexistent in the no-stick Katzin Concert Hall experiment: while previous iterations showed trends in both lower and upper overtones, the data in table 18 suggests that overtones are more present in some situations than in others. Even the higher overtones, which have been more equally present onstage and in the audience seating area, have no observable trend, as overtones such as B5 are much louder in the sitting iteration than in either the audience seating area or the standing iterations.

Table 18. Overtone analysis for the no-stick iteration at Katzin Concert Hall suggests that the lower overtones are less present in the audience than onstage, resulting in a shriller tone for the audience seating area.

		F3	A3	C4	F4	G4	A4	C5
Audience	Avg.	-44.9	-54.9	-43.1	-48.8	-52.7	-53.1	-51.9
	Std. Dev.	4.67	5.16	5.13	4.52	5.28	5.46	4.54
	Range	24.0	27.7	29.7	27.3	28.5	56.8	25.3
Standing	Avg.	-39.2	-56.5	-45.4	-38.7	-43.0	-43.0	-45.7
	Std. Dev.	0.900	0.671	7.72	3.29	1.22	1.78	5.32
	Range	2.2	1.8	18.2	6.4	2.7	4.0	12.5
Sitting	Avg.	-36.6	-67.3	-42.7	-42.5	-46.1	-44.3	-41.1
	Std. Dev.	3.99	0.780	3.42	0.634	0.299	0.645	3.39
	Range	8.5	1.7	8.1	1.5	0.7	1.5	8.0

		D#5	E5	F5	G5	A5	A#5	B5	C6
Audience	Avg.	-60.8	-57.8	-57.9	-59.0	-62.6	-66.3	-72.3	-44.9
	Std. Dev.	5.05	5.08	3.81	4.84	3.85	5.58	5.44	4.67
	Range	30.9	60.7	22.8	45.4	26.2	29.9	24.4	24.0
Standing	Avg.	-53.6	-56.3	-58.1	-61.2	-59.2	-62.5	-67.8	-65.9
	Std. Dev.	0.899	1.84	2.42	2.12	3.85	2.37	3.32	3.26
	Range	2.2	4.7	6.1	5.3	9.3	5.6	7.4	8.9
Sitting	Avg.	-54.0	-59.7	-54.6	-56.2	-64.2	-58.3	-37.8	-58.8
	Std. Dev.	0.263	0.311	1.83	0.183	0.785	0.455	0.310	0.436
	Range	0.5	0.7	3.7	0.4	1.7	1.0	0.7	0.9

RECITAL HALL

Recital Hall at Arizona State University is an intimate, semi-circular space seating 125 audience members around a small, low stage with a Hamburg-manufactured Steinway Model B grand piano. Its low ceiling and shallow depth (refer to figure 12, page 32) make for a hall with less volume per audience member than any other hall tested for this document, and thus can be presumed before analysis to have the loudest sound pressure level responses and closest agreement between on-stage and audience seating area overtone data.

Sound pressure level data, shown in table 19, shows that most of the data is rather uniform from on-stage to the audience seating area; however, Recital Hall has a considerable difference in sound pressure level for the audience seating area between short stick and the other stick heights. The intimate design of Recital Hall combined with the focusing effect of the piano on short stick to make a considerably louder sonic environment for the audience seating area than what the performers on stage would encounter. Interestingly, there is not a noticeable difference for the audience between full stick and no stick sound pressure levels.

Table 19. Sound pressure level data for Recital Hall at Arizona State University shows that the short stick iteration is unique among the halls tested in that it is considerably louder for the audience seating area.

	Audience Seating Area			Standing On Stage			Sitting On Stage		
	Full Stick	Short Stick	No Stick	Full Stick	Short Stick	No Stick	Full Stick	Short Stick	No Stick
Sound Pressure Level (dB-A)	79.7	86.8	78.6	81.4	81.4	82.4	83.1	84.1	81.7
Percent difference from full stick		+8.9	-1.4		0	+1.2		+1.2	-1.7
Standard Deviation	1.61	1.64	1.88	1.12	0.567	0.228	1.64	0.462	1.35
Range (dB-A)	8.9	7.5	9.3	2.5	1.4	0.6	3.8	1.2	3.2

Heat map data, shown in figure 23, reveals that though there is a high average sound pressure level throughout Recital Hall, there is also a greater variance in the levels than what would be expected for a small, intimate venue. Full-stick imaging, as expected, shows an area of greater sound pressure level intensity in the front row right-of-center, though without the generally greater sound pressure level readings across the hall that have been seen in other halls. Interestingly, even though the ranges are roughly equivalent with what have been seen in other halls, the heat map data for Recital Hall suggests a considerable variance in sound pressure level across the audience seating area, with the stage-left area farthest from the stage being notably quiet compared to the rest of the hall.

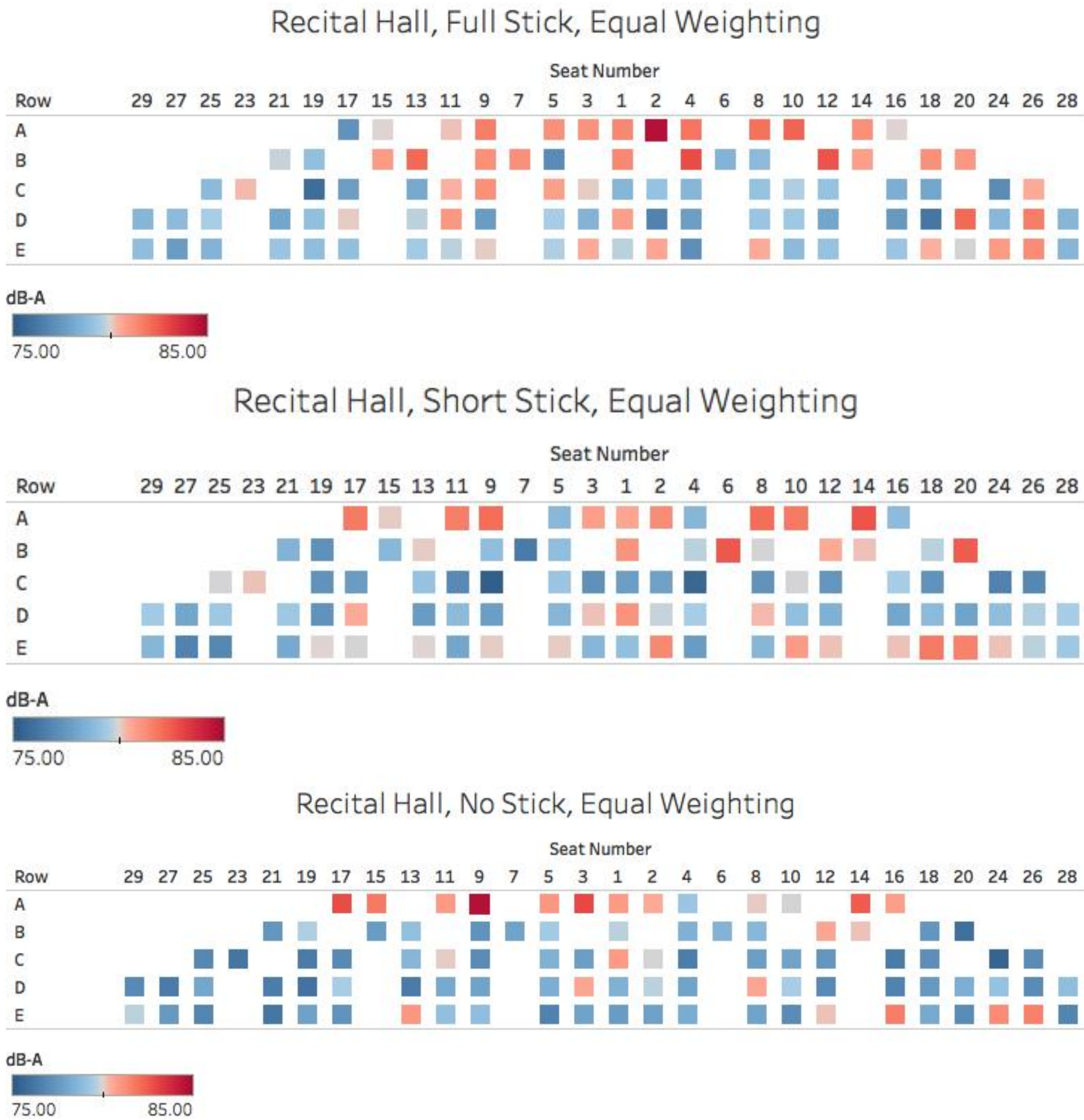


Figure 23. While Recital Hall has high average sound pressure levels, heat mapping shows that there is more variance in the hall than would be expected with an intimate venue.

Overtone analysis of the full-stick iteration for Recital Hall, shown in table 20, shows that average decibel levels for the higher overtones in the audience seating area are higher than in the larger halls; additionally, the lower overtones are more uniform as well as being louder overall, presumably due to the small size of the space. Somewhat larger standard deviations are indicative of a greater variance in the overtone intensities, but smaller ranges indicate that the hall has fewer outliers. When compared to the standing iteration, the overtone intensities match up quite well with most overtones showing up to a four-decibel difference, excepting C4 (9.1-decibel difference), suggesting that the sonic environment on-stage closely resembles the environment in the audience seating area. When compared to the sitting iteration, however, there is a noticeable difference in the sonic intensity between the stage and audience seating area, as well as more variance in the differences between the two. Differences in overtone intensities between the two areas range from 1 to 12 decibels, though most are within 5 to 7 decibels. As is consistent with other iterations, the differences become smaller in the higher overtones, suggesting that attenuation and diffusion of the higher overtones is more uniform than the lower ones.

Table 20. Overtone analysis of the full-stick iteration in Recital Hall indicates that standing in front of the piano results in a greater resemblance to the audience seating area sonic environment than sitting in front of the piano.

		F3	A3	C4	F4	G4	A4	C5
Audience	Avg.	-42.8	-42.0	-39.0	-41.8	-48.9	-49.8	-46.8
	Std. Dev.	5.94	5.46	5.59	5.11	4.56	4.18	4.38
	Range	24.7	29.7	27.7	20.5	25.5	22.5	20.0
Standing	Avg.	-42.2	-43.6	-29.9	-41.9	-46.3	-49.2	-43.7
	Std. Dev.	0.555	0.346	1.00	3.24	0.896	1.47	6.07
	Range	1.4	0.8	2.4	8.3	2.5	3.8	13.4
Sitting	Avg.	-36.6	-36.4	-29.9	-38.5	-43.9	-45.3	-45.7
	Std. Dev.	1.31	0.356	2.74	6.10	0.924	0.476	3.85
	Range	3.5	1.0	6.6	12.5	2.5	1.3	9.1

		D#5	E5	F5	G5	A5	A#5	B5	C6
Audience	Avg.	-53.8	-56.5	-52.0	-56.1	-57.1	-61.3	-67.8	-60.4
	Std. Dev.	4.90	3.81	4.39	4.20	3.48	5.97	5.48	3.74
	Range	22.9	22.6	20.1	25.9	18.2	32.8	28.7	21.8
Standing	Avg.	-58.2	-57.2	-50.8	-58.7	-54.6	-61.9	-71.6	-56.8
	Std. Dev.	1.81	0.923	2.95	6.93	0.611	1.49	2.59	2.06
	Range	5.0	2.1	6.7	17.3	1.5	3.8	6.1	5.0
Sitting	Avg.	-41.2	-55.2	-54.2	-53.5	-55.0	-51.8	-59.0	-55.2
	Std. Dev.	0.811	0.644	1.94	3.03	0.858	1.01	1.18	1.76
	Range	2.1	1.3	5.2	8.0	2.1	2.4	2.9	4.6

Shown in table 21, overtone analysis of the short-stick iteration at Recital Hall suggests that there is greater variance in the differences between overtone presence on stage and in the audience seating area for the sitting iteration, but not as much in the standing one. The lower overtones (F3 to A4) are generally within 3 to 4 decibels of each other in the standing iteration and the audience seating area iterations, and higher overtones are aligned more closely together (2 to 3 decibels difference). When compared to the sitting iteration, the data suggest that the lower overtones are considerably stronger on stage than in the audience seating area, with the higher overtones roughly as present on stage as in the audience seating area. More significant outliers occur in the sitting iteration however, with overtones F3 and B5 averaging significantly different than the neighboring overtones or the audience seating area and standing iterations' data. Higher standard deviations also indicate that for the case of short stick, the sound quality varies more than on full stick.

Table 21. Overtone analysis of the short-stick iteration at Recital Hall suggests a greater variance in the sonic environment between on-stage and the audience seating area than the full-stick iteration.

		F3	A3	C4	F4	G4	A4	C5
Audience	Avg.	-44.4	-39.1	-39.0	-42.5	-49.9	-49.0	-47.2
	Std. Dev.	7.47	5.56	4.93	5.29	6.08	4.42	4.08
	Range	30.9	26.4	28.6	28.7	42.0	24.4	20.0
Standing	Avg.	-45.4	-37.7	-30.0	-40.8	-44.0	-45.2	-49.9
	Std. Dev.	4.41	0.349	3.08	2.69	1.40	0.740	2.75
	Range	10.7	0.9	7.7	7.1	2.9	2.0	6.7
Sitting	Avg.	-49.4	-33.9	-28.2	-33.9	-44.8	-55.4	-53.0
	Std. Dev.	4.19	0.397	4.21	1.10	0.390	1.65	2.64
	Range	9.7	1.0	8.3	2.9	1.0	3.9	7.0

		$D^{\#}5$	E5	F5	G5	A5	$A^{\#}5$	B5	C6
Audience	Avg.	-53.1	-56.4	-52.7	-57.1	-58.0	-60.6	-66.1	-60.7
	Std. Dev.	5.97	3.93	4.40	3.78	3.31	4.45	5.25	3.62
	Range	38.0	27.7	17.8	15.7	17.1	24.0	31.2	18.1
Standing	Avg.	-47.4	-54.7	-53.3	-54.6	-60.2	-54.8	-69.4	-58.0
	Std. Dev.	0.988	0.436	2.69	3.14	1.36	0.758	2.03	0.891
	Range	2.5	1.1	6.9	7.5	3.5	1.7	5.6	2.4
Sitting	Avg.	-49.6	-54.9	-52.1	-57.0	-60.9	-56.9	-81.4	-57.9
	Std. Dev.	0.740	0.812	3.31	1.33	1.86	1.06	1.87	1.43
	Range	1.7	2.1	7.6	3.0	4.5	2.9	4.8	3.3

Analysis of the no-stick iteration at Recital Hall suggests that there is more uniformity in the overtones' presence between the stage and audience seating area than had been seen in either the full-stick or short-stick iterations. As seen in table 22, differences between the standing and audience seating area iterations are smaller than seen in the previous stick heights in Recital Hall, generally up to a 3-decibel difference, with 8-decibel outliers at A4 and $D^{\#}5$. Standard deviations remain indicative of variance in the audience seating area, with somewhat higher ranges in the data suggesting a more diverse sonic environment. Overtone intensities are generally 3 to 5 decibels greater in the sitting iteration when compared to the audience seating area, with a 7-decibel outlier at F4. Interestingly, the F3 overtone for sitting in front of the piano at both no stick and short stick is quieter than the standing overtone strength for the same cases, suggesting that the lowest overtones may attenuated by closing the lid in a small hall.

Table 22. Overtone analysis of the no-stick iteration in Recital Hall suggests that there is a greater variance with more outliers for the no-stick lid position in a smaller hall.

		F3	A3	C4	F4	G4	A4	C5
Audience	Avg.	-46.2	-40.4	-39.5	-41.9	-50.7	-50.1	-48.6
	Std. Dev.	7.31	5.49	4.64	4.87	5.46	4.55	4.02
	Range	32.1	29.5	21.8	23.9	26.1	24.0	22.2
Standing	Avg.	-45.3	-38.0	-36.4	-38.6	-47.5	-42.5	-45.6
	Std. Dev.	0.980	0.876	1.66	1.54	3.79	1.06	2.32
	Range	2.6	2.0	4.3	3.7	7.9	2.0	6.4
Sitting	Avg.	-49.0	-38.6	-35.1	-34.8	-50.5	-54.9	-52.8
	Std. Dev.	1.08	0.274	2.50	1.98	0.829	0.438	1.27
	Range	2.6	0.7	6.1	4.9	2.1	1.1	3.4

		D$^{\#}$5	E5	F5	G5	A5	A$^{\#}$5	B5	C6
Audience	Avg.	-55.9	-57.1	-53.4	-57.0	-59.2	-63.9	-70.0	-61.6
	Std. Dev.	5.66	3.68	3.96	3.74	3.01	5.23	5.76	3.80
	Range	34.6	23.0	17.6	20.3	14.4	25.6	24.9	23.1
Standing	Avg.	-47.6	-54.8	-53.5	-59.1	-57.3	-65.1	-71.1	-57.9
	Std. Dev.	1.32	2.43	3.54	8.88	1.54	7.28	0.926	1.80
	Range	3.3	5.2	8.5	21.1	3.9	14.0	2.2	4.8
Sitting	Avg.	-51.1	-52.6	-48.2	-61.1	-62.4	-65.1	-74.8	-60.0
	Std. Dev.	0.492	0.396	1.92	0.566	0.709	0.915	1.54	2.67
	Range	1.0	1.1	4.0	1.4	1.5	2.0	3.7	5.9

CHAPTER 6

CONCLUSIONS

The data and analysis presented in this document suggest that having the piano at full stick would most closely give the musicians on stage the most accurate representation of what the sonic environment is for their audience. Overtone analysis showed that performing with the lid fully opened allows for more of the brilliant higher overtones to be projected, with the lower more fundamental overtones also being projected into the audience seating area.

Even though there are discrete differences in the sound pressure level when the lid is lowered to short stick or no stick, a well-skilled pianist’s touch and discerning ear should be more than adequate to avoid issues of balance. If the difference were 10 decibels between stick heights, an argument could be made about the validity of short stick or no stick. The small difference in sound pressure level, just over the threshold of noticeability, under most circumstances could be compensated for by the pianist. Additionally, lowering the lid may give false impressions to the performer on stage that the piano is quieter than it actually is, particularly if the performer is standing in front of the piano with the lid on short stick or fully closed. With the impression that the piano’s sound pressure level is less than what it is for the audience, the performer may actually create more issues of balance than trusting their collaborative partner and the response of the concert hall with the piano at full stick.

In smaller halls, the data suggest that it is counterproductive to lower the lid with the hope of making the piano quieter: data at Arizona State University’s Recital Hall showed an increase in sound pressure level in the audience seating area when the lid was lowered on the piano. The significantly louder results in Recital Hall for the short-stick iteration may also be explained by the short stage, with the piano lid more directly focusing the shortest-path convergence of sound energy from the piano to the audience. This hypothesis is supported by the short-stick data at the University of Arizona's Holsclaw Hall and Northern Arizona University's Ashurst Hall: in Holsclaw, which has a much taller stage, the area of more intense sound pressure level in the center-right part of the audience seating area is not as pronounced as it is in Ashurst Hall, which for this experiment had the lower stage set up, which is much shorter.

One noticeable result from the data collection is that sitting in front of the piano when its lid is in the short-stick position results in consistently higher SPL for the performer than the audience seating area experiences. For instruments such as cello and tuba, the perception of greater volume from the piano in this configuration may actually create more issues of balance, should an instrumentalist project more to overcome the perceived imbalance.

The data also suggest that sitting in the front rows of concert halls with the goal of hearing a performance as most closely-reflective of what the musicians on-stage hear may result in a sonic environment in which the piano dominates the other instrument. Research involving lid heights with the added variable of instrumental timbre and dynamic may be useful in further exploration of this question.

A recommendation for further research is to continue to study the acoustics of the piano in various halls with co-participants from within physics and engineering disciplines to examine the acoustics and the interactions of piano, air, hall surfaces, and materials to develop a more complete theoretical model of how the piano and the lid interact. To this end, finite element analysis may be useful, as it would be able to mathematically model the interactions of the air and the boundaries between materials, reflections, and absorption. Research into the interactions between a partner's instrument and the piano's response may also be useful for a more thorough understanding of the behavior of sound and the effect of the piano lid.

An additional recommendation is that many more halls should be examined, so as to encompass the practical range of hall design types. Hall design types to be tested would include spaces such as the James R. Cox Memorial Auditorium at the University of Tennessee, where the audience seating area is 19 rows deep, but an average of almost 50 seats wide, seating 900 people. Additionally, spaces such as the 240-seat Recital Salon at Virginia Tech could result in interesting data, as that space is semicircular similar to Arizona State University's Recital Hall, but with stadium-style seating, where the top row of seats is 20 feet higher than the stage. By investigating more halls and hall geometries, it may be possible to say with more authority and breadth that the piano lid does not beneficially reduce piano volume output.

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APPENDIX A

DECIBEL DATA

Ashurst Hall

		Full Stick	Full Stick	Short Stick	Short Stick	No Stick	No Stick
Row	Seat	Piano	Forte	Piano	Forte	Piano	Forte
A	1	73.5	82	71	82.4	71.6	83.3
A	2	73.2	82.4	72.7	84.2	71.7	83.4
A	3	74.7	84.5	74.9	85.3	72.6	84.4
A	4	73.3	85.5	74.5	85.4	74.9	85
A	5	73.5	84	74.1	87.3	74.2	85.2
A	6	74.6	83.2	72.6	84.6	73.3	82.7
A	7	73.8	85.2	73.7	84.7	71.1	82.3
A	8	74.2	85.4	73.6	84.7	70.5	83.3
A	9	75.6	83.9	73.4	86.7	70.9	84.2
A	10	74.4	87.1	73.3	87.8	72.8	85
A	11	77.1	90.1	73.4	85.9	72.8	84.1
A	12	76.1	87.6	74.2	86.3	74	83.8
A	13	76.2	86.6	75.3	87.9	72	84
A	14	77.9	84.8	75.3	86.4	75.3	84.1
A	15	76.2	86.5	74.1	85.9	72.4	85.8
A	16	74.7	84.3	72.2	84.9	71	82.1
A	17	75.6	83.8	72.3	85.6	71	83.7
A	18	74.7	84.7	73.7	86.4	73.6	84.7
A	19	71.9	85.4	74.3	84.9	73.2	84.4
A	20	75.4	85.6	74.8	87	74.6	86.1
B	1	77.5	83.2	72.9	84.4	74.8	83.1
B	2	73.7	82.1	71.5	84	71.4	80.9
B	3	73.1	82.4	73	84.1	71.7	82
B	4	73.7	82.7	70.8	83.1	70.2	81.9
B	5	72.5	84.2	70.2	84.9	71.5	82.8
B	6	72.3	82.9	70.3	83.3	71.6	81.2
B	7	73.4	82.6	70.7	86.4	73.8	84.5
B	8	71.6	83.7	70.6	84	70.8	83.1
B	9	73.8	84	68.2	84.9	72.9	82.9
B	10	75.3	83.4	74.3	83.8	73.8	85.6
B	11	75.8	89.2	76	86.8	73.3	83.4
B	12	73.1	88.1	73.8	86	71.6	82.1

		Full Stick	Full Stick	Short Stick	Short Stick	No Stick	No Stick
Row	Seat	Piano	Forte	Piano	Forte	Piano	Forte
B	13	75.3	86	73.2	86.2	70.4	83
B	14	74	85	73.3	84.5	70.5	82.9
B	15	74.8	84.6	71.8	84.4	71.2	82.9
B	16	74.2	85	72.9	85.6	70	82.6
B	17	73.5	84.3	73.4	85.6	71.7	83.8
B	18	72.9	84.8	73.3	84.9	73.7	84.9
B	19	72.7	85.2	73.5	85.4	72.2	84.9
B	20	71.7	84.7	73.3	83.4	71.7	82.8
C	1	74.7	83	71.1	84.5	70.2	84.2
C	2	74.9	82.8	73.4	82	71.4	83.1
C	3	73.9	85.5	74.7	82.9	74.1	82.1
C	4	72.2	84.2	72.7	82.2	74.7	83.6
C	5	68.8	84.3	68.9	81.1	73.3	82.1
C	6	74.3	82.6	72.5	83.4	72.1	82.3
C	7	72.9	83.3	70.1	82.3	69.3	80.7
C	8	72.2	82.9	73.5	84.1	73.9	83.4
C	9	73.8	84.6	72.2	83.2	73.8	84.1
C	10	74.3	84.6	71.9	84.8	72.8	83.2
C	11	74	86.8	72.7	83.4	72.5	81.3
C	12	76.1	86.4	72.4	85.3	72.4	82.7
C	13	73.3	86.1	71	85.3	74.3	82.3
C	14	70.8	83.6	72.5	86.2	72.3	81.4
C	15	75.6	85.3	71.4	85.5	71.7	85.1
C	16	75	85.1	71.5	85.7	72.4	82.3
C	17	73.6	84.8	72.6	83.1	73.5	81.6
C	18	73.4	83.5	72.2	83.9	70.8	80
C	19	75	82.8	72.3	82.7	71.3	81.6
C	20	76.2	84	73.5	84.6	72.7	83
D	1	71.7	81.2	70.4	81.1	70.1	80.3
D	2	75.3	83.9	71.5	84.1	73.2	81.6
D	3	75.2	84	72.8	84.3	73	83.2
D	4	71.2	82.7	71.5	84.2	69.8	81
D	5	71.7	82.9	70.8	82.7	71.4	80.3
D	6	71.1	83.2	69.7	81.5	71	81.2
D	7	74.4	85.3	70.5	84.2	72.1	83.4

		Full Stick	Full Stick	Short Stick	Short Stick	No Stick	No Stick
Row	Seat	Piano	Forte	Piano	Forte	Piano	Forte
D	8	72.6	82.8	70.4	82.9	70	82.2
D	9	74.8	85.3	72.2	85.6	74.4	83.8
D	10	71.8	84.3	69.8	83.3	70	82.8
D	11	71.6	83.3	74.3	83.8	73.7	81.6
D	12	73.4	84.9	71.4	85.4	72.7	81.4
D	13	75.1	84.3	71.8	85.8	74.1	82.9
D	14	72.7	84.3	72.2	86.2	71.5	84.1
D	15	72.6	84.9	72.2	83.4	69.3	81.4
D	16	72.3	83.9	69	82.5	71	82.3
D	17	74.3	84	74.6	83.8	72.3	82.7
D	18	74.1	84.9	71.1	84.9	73.3	82.4
D	19	72.3	83.6	70.6	84.3	72.7	83.3
D	20	74.1	82.5	69.7	84.3	69.8	82.7
E	1	73	85.5	73.6	83.5	69.7	84.1
E	2	72.9	82.4	69.6	80.5	68	80.5
E	3	71.5	82.9	68.4	81.7	70.2	83
E	4	69.8	82.5	68.4	81	69.1	81.7
E	5	70.6	81.6	69.2	82.7	69.4	80.4
E	6	70.7	83.8	71	83.3	70.5	82.4
E	7	71	86	71.1	85.2	72	83.9
E	8	74.6	82.5	70.6	81.2	69.2	81.4
E	9	73.4	83.7	71	81.7	69.6	80.9
E	10	69.7	83.4	70.1	83.9	70.1	82.1
E	11	71.1	84.3	72.9	82.7	71.5	83
E	12	69.1	84.8	72.5	83.6	71.3	80.9
E	13	71.1	84	71.5	84.5	69.6	82.4
E	14	72.8	82.8	72	83.8	71.7	82.9
E	15	70.3	82.7	68.9	81.1	69.8	81.9
E	16	72.5	84	73.2	84.7	73	82.8
E	17	74.2	83.9	71.7	84.9	69.9	82
E	18	73.6	84.3	73.3	84.7	71.5	84.4
E	19	71.3	85.5	72.5	87.3	70.7	84.9
E	20	72.2	84.5	70.8	84.9	71	83.2

	Full Stick	Full Stick	Short Stick	Short Stick	No Stick	No Stick
	Piano	Forte	Piano	Forte	Piano	Forte
Standing 1	83.7	90.4	78.4	86.1	77.4	87.9
Standing 2	82.7	89.4	78.8	87.1	77.5	87.7
Standing 3	80.4	90	77.4	89.2	77.1	88.3
Standing 4	82.4	89.5	78.9	88.4	77.4	88
Standing 5	86	89.6	79.9	88.3	77.6	89.6
Sitting 1	82.4	90.3	80.5	89.2	78.5	88.9
Sitting 2	79.7	90	78.9	90.4	79	88.8
Sitting 3	81	91.7	79.7	89.5	79.3	88
Sitting 4	80.3	91.1	80.8	90.6	79.2	89
Sitting 5	79.8	89.2	78.5	90.2	79.3	88

Holsclaw Hall

Row	Seat	Full Stick	Short Stick	No Stick
A	1	74.9	72	70.3
A	3	74.9	71.8	72.6
A	4	74.5	73.6	69.5
A	6	78.6	70.8	71
A	8	79.9	70.3	70.2
A	9	76.7	69.5	70.1
A	11	78.3	69.8	71.5
A	13	77.3	70.1	72.2
A	14	75.2	71	72.5
B	1	74.4	71.6	71
B	3	73.4	68.2	69.9
B	4	74.1	72	70.2
B	6	73.9	69	70.6
B	8	73.5	69.8	70.3
B	9	74.6	69.9	69.3
B	11	73.8	71.9	69.8
B	13	72.9	69.8	68.7
B	14	71.6	70.4	69.2
B	15	74.2	69.7	69.1
C	1	74.6	71.2	71.7
C	3	70.4	73.1	70.9
C	4	74.5	69.8	71
C	6	75.2	68.2	69.4
C	8	74.2	70.4	68.3
C	9	73.7	68.8	65.9
C	11	73.4	70.9	69.4
C	13	73.5	71.4	68.6
C	14	73.2	72.5	68.9
D	1	76.7	68.4	70.6
D	3	70.4	70.7	70.4
D	4	72.4	69.2	69
D	6	74.4	68.8	69.2
D	8	73.8	71.5	71.4
D	9	71.4	68.9	70.8
D	11	73.3	71.5	69.5

Row	Seat	Full Stick	Short Stick	No Stick
D	13	72.1	70	69.9
D	14	73.4	70.4	69.3
D	15	71.3	71.1	69.8
E	1	71	70.7	70.4
E	3	72.6	70.3	70.4
E	4	73.6	71.4	70.6
E	6	75.9	71.6	72.3
E	8	75.2	73.2	73.4
E	9	72.5	71.1	71.2
E	11	71.8	69.6	70.3
E	13	73.8	69.9	69.6
E	14	73.1	70.2	70.2
F	1	73.8	72.6	71.3
F	3	71.5	69.8	70.2
F	4	72.5	73.2	72
F	6	72.4	71	69.6
F	8	73.4	71	70.7
F	9	72.4	69	70.4
F	11	72.1	71.2	70.5
F	13	71.5	72.9	70.6
F	14	71.3	71.1	68.4
F	15	73.9	70.1	71.7
G	1	72.5	69.9	69.4
G	3	74.5	71.1	68.8
G	4	74.1	73	71.3
G	6	72.8	70.3	70.8
G	8	74.1	68.9	70.2
G	9	70.6	71	70.8
G	11	73.5	70.7	68.9
G	13	72	69.3	71.4
G	14	73.8	70.2	70.1
H	1	76.5	70.5	72.5
H	3	72	71.9	71.4
H	4	71.2	72.8	70.3
H	6	73.6	72.4	70.6
H	8	72.2	72.1	69.9
H	9	71	69.8	69.8

Row	Seat	Full Stick	Short Stick	No Stick
H	11	72.7	69.9	71
H	13	72.1	71.2	69.4
H	14	74.4	71.6	70.2
H	15	70.7	71.4	69.9
I	1	70.5	68.2	69.7
I	3	73.4	70.3	70.3
I	4	73	71.7	69.8
I	6	74.2	70.4	70.9
I	8	70.6	69.8	71.3
I	9	70.8	70.9	69
I	11	73.4	72.2	71
I	13	71.8	68.7	68.7
I	14	70.1	72.2	70.5
J	1	72	69.8	68
J	3	73.4	70.5	71.2
J	4	73.5	72.1	69.5
J	6	71.6	70.2	68.4
J	8	73.1	70.6	67.1
J	9	72.5	70.5	70.4
J	11	73.4	72.5	69.3
J	13	73.4	71.1	68.9
J	14	72.7	67.7	70.4
J	15	75.6	72.3	71.9
K	1	73.8	71.6	72.3
K	3	73.8	71.2	69.1
K	4	70.7	70.6	69.3
K	6	72.2	69.7	70.1
K	8	73.1	72.7	70
K	9	70.7	71.9	69.5
K	11	73.2	71.5	69.9
K	13	71.4	70.8	68.6
K	14	71.6	71	69.8
L	1	71.4	71.1	69.3
L	3	73	70.5	70.8
L	4	72.9	70.2	70.2
L	6	73.1	68.6	68.2
L	8	72.6	69.6	70.7

Row	Seat	Full Stick	Short Stick	No Stick
L	9	72.9	69.1	69.2
L	11	72.3	68.5	71.9
L	13	73	68.7	68.5
L	14	74.6	70.8	68.1
L	15	72.8	69	68
M	1	73.7	70.3	68.8
M	3	68.4	69.5	67.2
M	4	72.7	70.2	68.4
M	6	72.8	67.5	68.3
M	8	72.6	69.4	68.1
M	9	73.8	70	68.9
M	11	72.2	70.3	70
M	13	70.2	69.8	68.4
M	14	73.2	70.6	68.7
M	15	72.9	72.4	70.3
N	1	73.7	71.7	72
N	2	72.4	68.8	67.4
N	6	74.5	69.7	70.8
N	7	74.3	70.5	70.7
N	8	71.2	71.3	69.1
N	9	73.9	69.3	69.7
N	10	70.9	68.5	69
N	14	72.6	68.8	67
N	15	72.7	69.9	69.9

	Full Stick	Short Stick	No Stick
Standing 1	77.1	75.3	74.9
Standing 2	76.9	75.7	74.9
Standing 3	77.2	75.3	71.9
Standing 4	76.5	75.9	74.7
Standing 5	77.2	75.4	74.5
Sitting 1	74.3	77.4	70.4
Sitting 2	73.4	76.8	68.7
Sitting 3	73.4	76.1	71.6
Sitting 4	73.8	77.8	71.7
Sitting 5	73.9	76.5	71.7

Crowder Hall

ROW	NUMBER	Full Stick	Short Stick	No Stick
A	1	69.2	69.7	67.3
A	3	69.5	69.2	69.5
A	6	71	69.8	67.9
A	7	73	71.5	69.5
A	9	74.5	73.7	72.4
A	12	77.2	75.9	71.6
A	14	76.6	74.1	68.4
A	17	71.1	72.5	70.6
A	19	71.5	69.9	67.4
A	22	67.7	68.3	65.1
A	25	67.8	69.1	66.1
B	7	70.7	71.6	71
B	9	71.6	71.6	67.8
B	12	73.8	73.4	67.9
B	14	72.5	70.5	69.4
B	17	71.5	69.2	68.3
B	19	69.1	68.7	66.3
C	1	70.1	68.3	65.5
C	3	68.4	68.3	66
C	6	72.1	70.2	69
C	8	70.6	69.1	68.9
C	10	69.8	69.6	67.6
C	12	73	71.9	70.1
C	14	70.8	69.8	69.8
C	17	71.7	70	69.8
C	19	69.9	68	69.3
C	22	69.5	67.9	69.1
C	24	68.9	69.6	69.8
C	26	67.9	67.1	62.5
D	1	68.7	68.2	69.6
D	3	69.8	69.4	66.1
D	6	70.3	69.5	69.2
D	7	71	69	68.9
D	9	69.7	69.6	66.3
D	12	71.8	71.1	69.8

ROW	NUMBER	Full Stick	Short Stick	No Stick
D	14	71.6	70	69.5
D	17	70.8	66.7	67.9
D	19	69.2	69	69.1
D	22	68.6	68.9	67.8
D	25	69.8	68.1	65
E	1	69	68.9	67.8
E	3	70.2	69.3	67.3
E	6	70.3	70.3	68.4
E	8	69.9	67.7	65.3
E	10	69.9	69.6	67.6
E	12	69.3	70.2	65.5
E	14	70.5	68.8	66.6
E	17	70.4	67.2	69.8
E	19	71.2	68.1	63.8
E	22	69.4	68.4	66.8
E	24	68.2	69.1	67.9
E	26	68.5	67.4	68.7
F	1	68.2	68.5	66.9
F	3	70.8	67.6	67.7
F	6	71.3	69.3	67.7
F	7	71.9	71	67.1
F	9	71.4	66.3	67.2
F	12	71.7	67.9	67.6
F	14	70.1	67.5	67.9
F	17	68.9	66.2	65.6
F	19	70.1	67	67.7
F	22	71.2	69.2	68.1
F	25	69.1	66.7	65
G	1	72.7	67.7	68.1
G	3	70.5	68.3	67
G	6	68.1	68.9	70.1
G	8	74.3	66.2	66
G	10	68.1	66.7	66.2
G	12	70.9	67.5	64.7
G	14	71.5	68.7	67
G	17	70.5	68	65.2
G	19	69.8	67.3	67.2

ROW	NUMBER	Full Stick	Short Stick	No Stick
G	22	70.1	66.4	66.7
G	24	69.8	67.3	66
G	26	68.8	66.3	65.7
H	1	70.2	69.5	70.4
H	3	68.4	65.2	66.6
H	6	71	68.2	65.3
H	7	70.3	67.3	66.9
H	9	68.2	67.7	69.4
H	12	69.4	67	66.3
H	14	69.8	66.1	67.5
H	17	68.6	65.7	66.2
H	19	70.4	68.5	67.4
H	22	70.7	66.3	66.7
H	25	68.9	66.1	66.1
J	1	70.3	68.3	65.7
J	3	68.7	67.6	65.5
J	6	71.2	69.9	66.4
J	8	72.6	67.2	70.1
J	10	70.2	66.3	64.9
J	12	71.5	69	67.3
J	14	68.3	69.2	68.8
J	17	68.8	65.7	65.6
J	19	68	64.7	67.1
J	22	68.1	68.5	67.1
J	24	69.2	68.3	65.8
J	26	69.6	66.9	64.8
K	1	70.6	68.2	66.5
K	3	72.8	67.3	67.5
K	6	70.8	68.5	68
K	7	68.9	66.1	64.8
K	9	69.5	67.5	66.3
K	12	72.2	68.8	67.3
K	14	69.2	67.9	63.9
K	17	69.5	68.1	66
K	19	68.8	67.9	66.2
K	22	67.1	68.2	66.3
K	25	65.8	68.6	65.2

ROW	NUMBER	Full Stick	Short Stick	No Stick
L	1	70.1	66.1	68.1
L	3	67.6	69.3	68.7
L	6	69.6	67.3	68.9
L	8	69.6	67.4	66.9
L	10	70.7	69.1	68.3
L	12	68.6	64.7	65.8
L	14	68.1	68.2	65.7
L	17	66.4	68.1	66.5
L	19	70.4	66.2	65.9
L	22	68.4	66.5	67.8
L	24	70.1	65.4	64
L	26	66	66.4	64.3
M	1	66.3	65.2	66.4
M	4	69.5	67.2	66.3
M	7	70.2	68.1	67.2
M	8	67.9	66.7	66.3
M	10	68.5	67.2	65.4
M	13	72	67.8	68.3
M	15	69.2	65.5	67.5
M	17	70	68.7	64.4
M	20	70.7	68.7	66.6
M	22	68.2	66.4	66.3
M	24	68.6	67.2	64.4
M	26	68.4	69.7	66.5
N	2	66.4	68.2	66.2
N	5	67.1	71.5	65.7
N	7	68.2	69.4	69.4
N	8	69.4	68.3	66.6
N	11	66.8	67.1	64.8
N	14	66.6	72.5	67.9
N	17	69.6	69.1	64.7
N	20	68.9	67.4	66.9
N	22	69.7	66.9	66.2
N	25	70.7	68.2	67.4
N	28	65.8	68.3	66.6
P	1	67.3	67.2	67.6
P	4	68.8	66.7	67.4

ROW	NUMBER	Full Stick	Short Stick	No Stick
P	7	69.8	68.4	66.6
P	8	69.5	67.1	65.1
P	10	66.9	64.8	64.4
P	13	66.8	67.8	64.6
P	15	69.7	64.8	64.2
P	17	69.8	69.3	64.5
P	20	69.3	70	64.2
P	22	68.3	68.1	65.9
P	24	67.7	67.3	64.3
P	26	69.1	68.7	66.5
Q	2	68.2	68.2	64.2
Q	5	69.1	67.4	64.4
Q	7	69.5	68.6	67
Q	8	68	67.3	63.6
Q	11	69.2	67.2	63.7
Q	14	68.9	65	66.6
Q	17	69.3	69.6	65.5
Q	20	67.9	67.7	66.2
Q	22	69.1	68	67.9
Q	25	66.3	68	69
Q	28	66.4	68.3	64.9
R	1	68.9	68.6	63.3
R	4	67.9	69.6	65.3
R	7	67.4	66	64.8
R	8	66.3	66.8	63.2
R	10	67.9	65.7	63.9
R	13	66.6	66.1	64.8
R	15	65.7	66.7	64.7
R	17	67.8	67.3	65.9
R	20	66.2	65.4	64.9
R	22	68.1	67.5	65.8
R	24	69.6	70.5	69.6
R	26	70.5	68	66.3
S	2	68.8	67	65.5
S	5	66.9	68.4	67.5
S	7	68.9	67.6	65.3
S	8	67.1	68.6	66.6

ROW	NUMBER	Full Stick	Short Stick	No Stick
S	11	65.8	65.7	63.3
S	14	65.2	68.4	67.9
S	17	68.4	66.8	64.1
S	20	65.1	67.8	66.2
S	22	69.3	68.8	66.8
S	25	69	66.6	64.3
S	28	68.6	69.7	66.1
T	1	69.9	65.9	64.7
T	4	69.3	66.5	64.5
T	7	68.3	67.8	64
T	8	69.7	69	68.7
T	10	67.5	66.8	64.6
T	13	67.2	68.7	67
T	15	68.1	67.2	63.9
T	17	66.5	68.9	67.1
T	20	66.8	68.4	66.6
T	22	70.8	69.4	67.8
T	24	69.9	66.9	64.3
T	26	70.4	68.2	66.9
U	2	69.2	67.2	63.6
U	5	70	69	66.7
U	7	69.3	66.7	64.3
U	8	68.9	67	65.5
U	11	67.6	66.7	67.5
U	14	69.7	67.4	65.5
U	17	66.9	68.4	64
U	20	70	67.5	66.1
U	22	69.3	69.6	65.5
U	25	69.8	69.9	65.7
U	28	68.2	69.5	65.3
V	1	68.6	67.8	65.1
V	4	68	66.4	63.2
V	7	66.6	66.5	64.2
V	8	68.8	70.1	66.2
V	10	68.5	68.5	66.5
V	13	69	68.5	67.1
V	15	69.1	67.1	63.2

ROW	NUMBER	Full Stick	Short Stick	No Stick
V	17	66.4	67.2	63.9
V	20	67	66.7	64.8
V	22	69.1	68.6	67.6
V	24	67.6	66.6	65.9
V	26	70.9	69.4	65.9

	Full Stick	Short Stick	No Stick
Standing 1	80.9	74.2	73.5
Standing 2	81.3	78.1	76
Standing 3	80.3	77.1	72.9
Standing 4	81	76.9	75.8
Standing 5	79.7	74.4	72.9
Sitting 1	75.2	77.1	76.2
Sitting 2	75.2	76.5	76.5
Sitting 3	75.3	76.7	75.1
Sitting 4	76	76	74.3
Sitting 5	75.4	76.4	74.4

Katzin Concert Hall

Seat	Number	Full Stick	Short Stick	No Stick
A	4	74.6	75.1	74.5
A	101	76.7	77.2	74.8
A	103	76.3	77.3	72.3
A	105	75.7	74.8	74.6
A	107	78.1	75.6	74.8
A	109	76.7	76.2	75.1
A	111	76.4	73.2	75
A	113	76.4	76.7	74.7
A	3	71.3	72.8	71
B	6	74.7	77.1	73.6
B	2	72.5	74.4	71.8
B	102	75.9	75.9	73.8
B	104	76.9	75.4	73.5
B	106	73.7	73.7	72.4
B	108	75.9	74.7	71.8
B	110	74.8	74.3	73.7
B	112	75.1	75.8	73
B	114	75.1	74.3	73
B	1	71	73	72.4
B	5	73.1	72.2	71.5
C	6	72.7	74.3	71.4
C	2	73.2	72.5	71.3
C	102	72.9	74.6	71.2
C	104	74.3	73.1	73
C	106	75.7	74.1	74.7
C	108	75.7	73.3	73.5
C	110	74.7	72.9	72.6
C	112	76.9	72.6	72.6
C	1	73.3	74.3	70.7
C	5	73.9	71.7	71
D	6	75.1	74.4	70.7
D	2	73.3	72	72.4
D	102	76.9	76.2	74.1
D	104	75.7	73.7	72.8
D	106	75.1	71.4	71.1
D	108	76.5	72.9	74.9
D	110	75.7	75.3	71.4
D	112	76.4	74.4	76
D	114	75.4	74.7	73.3
D	1	74	74.5	70.6
D	5	72.4	72.8	71.8

Seat	Number	Full Stick	Short Stick	No Stick
E	8	73.2	71.6	70.2
E	4	77.7	72.6	71.8
E	101	73.8	75	72.2
E	103	73.3	74	71.5
E	105	74.2	74.5	73.3
E	107	74	72.8	70.6
E	109	77.3	73.2	71.6
E	111	73.4	73.1	69.9
E	113	76	74.7	71.8
E	3	73.8	73.2	71.1
E	7	73.4	72	69.6
F	8	74.9	73.3	71.4
F	4	73.8	74.1	71.1
F	101	77.3	72.2	71.3
F	103	73.9	72.8	71.9
F	105	77	73.2	72.6
F	107	77.3	71.5	71.4
F	109	74.4	72.6	69.5
F	111	75.6	71.9	73.8
F	113	73.2	72.3	72.9
F	1	73.6	71.1	70.6
F	5	71.8	70.6	71.8
G	8	71.7	73.9	73.2
G	4	71.2	73.8	75.2
G	101	76.5	72	73.3
G	103	73.2	71.9	73.1
G	105	74.8	71.4	69
G	107	72.2	73	71
G	109	73.5	73.8	69.2
G	111	73.7	72.9	69.7
G	113	76.7	72.5	69.5
G	3	70.2	71.7	70.5
G	7	72.2	70.6	72.3
H	8	74.6	74.1	72.5
H	4	73.9	73.2	73.8
H	101	72.9	73.9	70.8
H	103	73	72.2	73.6
H	105	76.8	72	71.7
H	107	75.7	72.2	71.4
H	109	73.7	70.5	71.3
H	111	72	71.4	73.5
H	113	75	75.4	73.3
H	1	74.9	72.2	72.1

Seat	Number	Full Stick	Short Stick	No Stick
H	5	73	73.5	70.3
J	10	75	70.3	69.7
J	6	74.5	74.8	69.8
J	2	73.7	71.8	71.1
J	102	73.8	71.7	71.3
J	104	70	72.6	71.2
J	106	72.8	72.5	73.3
J	108	73.1	71.4	72.2
J	110	74.1	73.6	73.5
J	112	73.1	72.6	71.4
J	114	73	72.3	69.8
J	1	70	72.4	70.9
J	3	72	72.2	71
J	5	72.8	71.6	72
J	9	73.1	70.2	69.5
K	10	70.7	70.3	69.3
K	6	71.2	70.1	70.7
K	2	74.7	70.3	71.1
K	102	76	72.4	70.1
K	104	71.2	68.9	70.6
K	106	71.8	72.7	72
K	108	71.1	70.7	71.8
K	110	74.5	73.3	73.2
K	112	74.8	72.9	73.2
K	114	73.4	71.7	72.9
K	3	72	71.5	70.9
K	5	75.6	71.7	71.3
L	8	73.9	70.6	70.8
L	4	75	72	71.3
L	101	75	73.5	70.8
L	103	74.1	73.4	71.7
L	105	76	72.2	71.8
L	107	73	71.5	72.1
L	109	77.3	72.5	70.3
L	111	74.2	71.9	72.6
L	113	74.2	73.8	71.7
L	1	73	73.9	71.7
L	5	72.8	70.6	71.6
M	8	73.2	73.8	70.6
M	4	72	68.8	68.1
M	101	75.3	74.3	73.2
M	103	73.2	72	72.1
M	105	75.2	74.4	72.6

Seat	Number	Full Stick	Short Stick	No Stick
M	107	72.4	71.2	70.5
M	109	72	71.6	68.9
M	111	72.4	71.9	72.9
M	113	71.9	73.9	72.7
M	1	75.2	74.3	71.6
M	5	70.8	71.1	70.4
N	8	74.3	72.1	72.2
N	4	73	73	71
N	101	74	71.5	72.1
N	103	75.2	71.6	72.4
N	105	75	71.4	71.6
N	107	72.2	70.2	71.3
N	109	73.1	72.4	71
N	111	73	72	71.5
N	113	74.5	73.2	72.8
N	1	71.1	72.7	70
N	5	73.2	73	71.7
O	6	72.3	69.6	67
O	2	73.8	73.7	71.1
O	102	74.9	70.8	72.5
O	104	75.5	71.3	72.1
O	106	73.6	70.7	71.9
O	108	72.6	73.1	73
O	110	76.2	73.4	71.2
O	112	74.8	73.6	72.3
O	114	73	72.6	68.4
O	1	73.2	70.6	72.4
O	3	70.8	71.8	71.7
P	6	73.6	73.8	73.2
P	2	71.6	70.8	71.5
P	102	70.3	71.6	70
P	104	75.7	72.9	74.3
P	106	73.3	68.6	71.5
P	108	72.1	70.1	71.2
P	110	73.1	73.5	69.6
P	112	72.5	70.2	68.6
P	114	74.3	72.1	71.7
P	1	70	71.9	71.3
P	5	72.6	70.4	71.4
Q	6	70.4	72.4	72.1
Q	2	73.7	74.6	73.4
Q	102	75.4	72.9	71.4
Q	104	75.9	70.3	69.7

Seat	Number	Full Stick	Short Stick	No Stick
Q	106	73.4	71.1	71.9
Q	108	73.3	70.3	71.3
Q	110	73.5	73.5	70
Q	112	73.1	74.4	70.6
Q	114	75.2	72.9	70.5
Q	1	74	73.7	72.8
Q	5	71.7	70.9	69.4
R	2	72.5	74.5	72.6
R	102	73.2	71.7	72.6
R	104	73.9	70.8	70.5
R	112	73.7	72	72.4
R	114	74	70.3	69.7
R	3	72	71.9	70.8

	Full Stick	Short Stick	No Stick
Standing 1	80.7	75.9	76.9
Standing 2	79.5	76.9	75
Standing 3	80.1	76.6	78
Standing 4	80.2	74	75
Standing 5	80.1	76.8	77.2
Sitting 1	79.8	81	76
Sitting 2	78.6	78.6	76.3
Sitting 3	77.9	76	73.8
Sitting 4	76.2	80.6	75.8
Sitting 5	79	79.8	77

Recital Hall

Row	Seat	Full Stick	Short Stick	No Stick
A	16	80	78.8	80.8
A	14	81.2	82.7	82.5
A	10	82.3	81.8	79.9
A	8	82	82.1	80.1
A	4	81.9	78.6	79.2
A	2	84.7	81.3	80.5
A	1	81.4	80.6	80.9
A	3	81.1	80.8	83
A	5	81.2	78.7	81
A	9	81.7	82.1	84.7
A	11	80.2	81.7	80.9
A	15	80	80.1	81.8
A	17	77.3	81.8	82.9
B	20	81	82.5	75.9
B	18	81.2	79.7	77.4
B	14	80.8	80.2	80.2
B	12	82.7	80.5	80.6
B	8	78.8	79.9	78.7
B	6	78.5	82.6	78.5
B	4	82.9	79.7	78.4
B	1	81.4	81.1	79.7
B	5	77	78.9	79.4
B	7	81.2	76.3	77.9
B	9	81.2	78.9	77.3
B	13	82.2	80.1	79
B	15	80.9	78.7	77.6
B	19	79	77.2	79.6
B	21	79.8	78.5	77.4
C	26	80.5	76.8	77
C	24	77	76.6	75.4
C	18	78	77.3	77.1
C	16	78.3	79.5	76.3
C	12	79.1	77.4	77.4
C	10	79.6	79.9	77.9
C	8	79.1	77.3	77.7
C	4	78.6	75.5	76.4
C	2	79.1	77.8	79.9
C	1	78.6	77.7	80.9
C	3	80.1	77.2	77.7
C	5	80.8	79.2	78.4
C	9	81.2	75.2	77

Row	Seat	Full Stick	Short Stick	No Stick
C	11	80.4	76.9	80.1
C	13	78.1	79.1	78.6
C	17	77.7	77.6	76.9
C	19	75.8	77.3	76.3
C	23	80.3	80.2	76.1
C	25	78.8	79.9	76.8
D	28	78.6	79.5	78.9
D	26	81.7	79.6	77
D	24	78.7	78.9	79.1
D	20	82.2	77.9	78.3
D	18	76.1	78.8	77.5
D	16	77.5	78	76.6
D	12	78	78.4	76.9
D	10	79.3	79	79.5
D	8	79.2	80.3	80.6
D	4	77.7	79.5	77.9
D	2	76.6	79.8	79.7
D	1	80.8	81.1	78.4
D	3	78.5	80.2	80.6
D	5	79.5	78.6	78.3
D	9	77.6	77.7	77.9
D	11	81	78.8	78.1
D	13	79.7	77.6	76.3
D	17	80.1	80.5	79.5
D	19	79	77.3	76
D	21	78	79.3	76.4
D	25	79.5	79.3	78
D	27	78.8	78	76.3
D	29	78.6	79.4	76.9
E	28	78.6	79.3	76.7
E	26	81.3	79.7	81.6
E	24	80.9	80.2	81.3
E	20	79.9	81.6	77
E	18	80.4	81.8	78.1
E	16	79.2	80.2	81.7
E	12	79.1	80.2	80.2
E	10	78.8	80.9	77
E	8	80.5	78.6	77.9
E	4	77.1	77.6	78.2
E	2	80.6	81.4	77.8
E	1	79.7	79	77.6
E	3	80.5	78.6	77.9
E	5	79.6	80.1	76.6

Row	Seat	Full Stick	Short Stick	No Stick
E	9	80.1	80.1	78.9
E	11	79.7	78	79
E	13	79.4	80	81
E	17	79	79.9	77.3
E	19	78.9	80	77.8
E	21	79.2	78.1	76.1
E	25	78.5	76.8	76.7
E	27	77.6	76.6	77.5
E	29	78.9	78.6	79.7

	Full Stick	Short Stick	No Stick
Standing 1	82.9	80.8	82.3
Standing 2	80.8	81.6	82.5
Standing 3	82.2	80.9	82.1
Standing 4	80.4	81.4	82.7
Standing 5	80.5	82.2	82.3
Sitting 1	84.7	83.5	81.6
Sitting 2	81.8	83.8	82.4
Sitting 3	80.9	84	80.4
Sitting 4	84.1	84.3	80.5
Sitting 5	83.9	84.7	83.6