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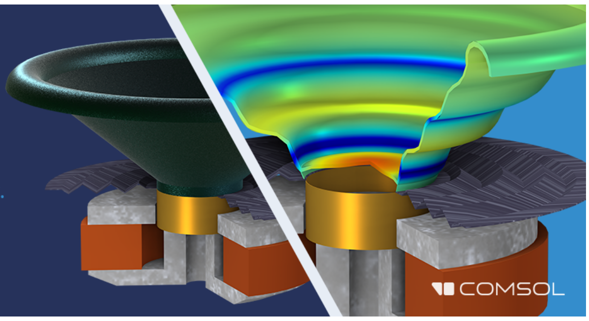

Pre-Sabine room acoustic design guidelines based on human voice directivity

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With the work of Wallace C. Sabine on the lecture hall of the Fogg Art Museum and concert hall of Boston Symphony Hall, a foundation for the field of architectural acoustics as a science was laid between 1895 and 1900. Prior to that, architects employed various notions in acoustic design. Previous studies by the authors have reviewed 18th and 19th century design guidelines that were based on the quantification of the perception threshold between direct sound and first order reflections, with these guidelines being followed in the design of several rooms with acoustical demands. This study reviews an alternate metric guideline, based on the directivity and propagation distance of the human voice, which was utilized in several halls also during the 18th and 19th centuries. The related acoustic experiments tested how far sound was perceivable towards the front, sides, and rear of a speaking person. These ratios were used in the acoustical design of at least five lecture halls, four theater halls, one opera hall, and one concert hall, constructed in Germany, England, and the USA. These historic designs, and comparisons to modern measures and guidelines, are reviewed.
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I. INTRODUCTION

With the development of the reverberation formula by Wallace Clement Sabine in 1898, architects were presented with an acoustic guideline to design concert halls (Sabine, 1922). This discovery also laid the foundation for architectural acoustics as a science. However, many concert halls with outstanding room acoustical reputations, such as the Wiener Musikvereinssaal (1870) and the Amsterdam Concertgebouw (1888), were constructed before Sabine's work (Beranek, 1996). This makes acoustical design practices in the pre-Sabine era interesting for historical room acoustics studies.

Two design approaches observed in the pre-Sabine era were the *copying* of acoustically satisfying spaces, such as the small concert hall in the Concertgebouw, which was a copy of the Felix Meritus (van Royen, 1989), or the *up-scaling* of dimensions of acoustically satisfying rooms, such as the Wiener Musikvereinssaal that had proportions similar to its predecessor, the Redoutensaal (Barron, 1993).

Barbieri (1998) and Barbieri (2006) identified two pre-Sabine "physics-based" design approaches: undulatory and geometrical acoustics. The first can be traced back to the writings of Vitruvius (Morgan, 1914, p. 132). Vitruvius stated that sound propagates in a circular shape, like the waves caused by a stone cast in still water [called "undulatory" acoustics by Barbieri (2006), distinguishing it from the wave-based approach as it neglects frequency content]. Based on this assumption, Vitruvius discussed four room acoustic indicators:

- *Dis-sonantes*: When the wave is affected by a hard and sharp-cornered architectural element; being partly reflected, it disturbs the "circulation" of the subsequent wave, so that the sound is "dissipated" and sounds "indistinct."
- *Con-sonnantes*: When the environment facilitates the wave's "circulation."
- *Circum-sonnantes*: When the wave, in the presence of a curved surface, returns to its starting point creating a reverberation.
- *Re-sonnantes*: When the wave is reflected back on itself, giving rise to an echo.

Based on these quality indicators, Vitruvius argued that the voices of actors should be unobstructed, in order to create favorable room-acoustic conditions [according to Barbieri (1998) termed *circulation of sound* or *unobstruction of propagation*]. Therefore, a theater should be constructed so that a line drawn from the first to the last seats should touch the front angle of the tops of all seats and he recommended a cornice to be constructed halfway up the perimeter walls in order to prevent the sound from dispersing upwards.

Besides Greek and Roman room acoustic design, Vitruvius's approach influenced room acoustic designs between the Renaissance and Sabine's work as these quality indicators were the only ones available up until at least the end of the 17th century. In the Renaissance period, Vitruvius's approach led to rounded auditorium shapes, rounded proscenium arches, and the avoidance of obstacles, which "slowed the circulation" or "broke the voice." For instance, based on observations by Fabrizio Carina Motta (Motta, 1676), Nicodemus Tessin Junior designed theaters in

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1688 with rounded off back walls as this was considered better for the acoustics. Similar views survived at least up until the end of the 19th century when the "circulation of sound" approach was employed in the design of the Amsterdam Concertgebouw (1888), where the corners of the stage are rounded off to prevent their "slurping up" the sound (Thooft, 1882). Other examples of this approach were attempts to avoid obstacles, which "slow the circulation" or "break the voice" such as limiting relief depth on balcony fronts, and the rounding-off of straight angles in loges. "Undulatory" acoustics appeared to be sufficient for treating outdoor theaters. However, this approach showed severe limitations for indoor spaces.

The 17th century saw the emergence of geometrical acoustics, based on the assumption that the trajectory of sound was analogous to sound rays reflected from a surface (Barbieri, 1998). Architects employed this concept to "guide" the sound by adjusting the space's geometry. From the late 17th century, geometrical acoustics was employed almost exclusively in the design of Italian theaters (Barbieri, 2006). The similarity of light and sound was first conjectured after experiments by Biancani (1620) and Batista Della Porta (1589). Because rays spread evenly over a plan after being reflected from parabolic or elliptically shaped walls, Cavalieri (1632), Mersenne (1627), and Bettini (1642) all proposed elliptical plans for auditoria. A practical example is Bibiena's Teatro Ducale in Milan, which was bell-curve shaped (Tamburini, 1983). Other practical design aspects included splayed proscenium arches, in order to direct sound towards the audience, and ceilings, which were designed not to be concave as this could lead to sound concentrations. In these approaches, only first order reflections were considered.

A more recent guideline based on geometrical acoustics, was "echo theory" (Postma, 2013; Postma and Katz, 2014), which arose at the end of the 18th century. This concept was based on a quantification of the perception threshold between direct and reflected sounds. If a first order reflection exceeded this threshold, an echo would be perceived, which was considered detrimental for the acoustics. In at least seven rooms with acoustical demands, architects based the shape of the auditorium and/or placement of reflective or absorbent materials on this echo theory.

This paper explores an alternate acoustic guideline, developed and employed in room acoustic design during the 18th and 19th centuries, based on the undulatory "circulation of sound" and "unobstructed propagation" approaches. In developing this guideline, studies were carried out to determine how far the human voice propagated while remaining audible or intelligible in different directions. The observed distances were used to design buildings intended for both speech and music.

Section II presents an overview of seven historical studies quantifying this distance in both indoor and outdoor conditions. Section III then presents examples of several buildings, which used these results as an acoustic and architectural guideline. This study concludes with a comparison of historic buildings to contemporary room designs (see Sec. IV).

II. STUDIES ON VOICE DIRECTIVITY AND THEIR ASSOCIATED ARCHITECTURAL DESIGNS

A. Christopher Wren (1632–1723)

After the great fire of 1666 destroyed large parts of London, Christopher Wren was appointed supervisor of the reconstruction. Among the subsequently erected buildings were 52 churches (Wren, 1903). Concerning the placing of the pulpit, Wren stated that he observed that a priest speaking with a moderate voice can be heard maximally 50 ft in front, 30 ft to the sides, and 20 ft to the rear.[1] Furthermore, he stated that it was difficult to seat more than 2000 attendees and still have a room in which it was possible to see and hear a speaking person. Wren thought it reasonable that a new church should be at least 60 ft wide and 90 ft long. These proportions can be varied in ways that enable every person to conveniently hear and see, however, constructing a larger auditorium would "create noise and confusion."

Wren designed additional rooms with high acoustical demands: the Sheldonian theater (Oxford, England, 1669) and a lecture hall in the College of Physicians (London, England, 1675).[2] The Sheldonian theater seats 750 people and is semicircular with a length of 80 ft and a width of 70 ft. The lecture hall in the College of Physicians was oval and octagonal in shape with an internal diameter of 40 ft (Smith, 1861a, p. 102). The dimensions of both of these venues seem to follow the length and width of the presented guidelines.

B. Pierre Patte (1723–1814)

Whereas Wren discussed indoor acoustical conditions, architect and theoretician Pierre Patte compared indoor and outdoor conditions (Patte, 1782, p. 22). He stated that a moderate human voice in indoor conditions can be perceived up to 72 ft away; this finding was confirmed in multiple books about acoustics including Rhode (1800). In contrast, in an open field a human voice could scarcely be perceived at two-thirds of that distance. According to Patte, the radiation pattern of the voice was shaped as an "elongated spheroid."

Using these acoustic considerations, Patte conceived an elliptical theater with a 72 ft major axis [see Fig. 1(a)]. One end of this ellipse was cut off at one-fourth of the diameter to accommodate the stage.

C. Giordano Riccati (1709–1790)

The first scholar to propose a sound radiation pattern corresponding to a mathematical law was Giordano Riccati in 1788 (Barbieri, 1998), as shown in Fig. 2. When the human mouth was positioned at point O and emitted maximum intensity I_o along a horizontal line, the sound in other directions will radiate an acoustic intensity $I = I_1 + I_0 \times \cos\theta$ [see Fig. 2(a)]. However, no direct evidence was found in the course of this study that Ricatti based theater plan guidelines on this voice radiation pattern.

D. George Saunders (1762–1839)

George Saunders was an architect active at the end of the 18th and the start of the 19th centuries. One of his major

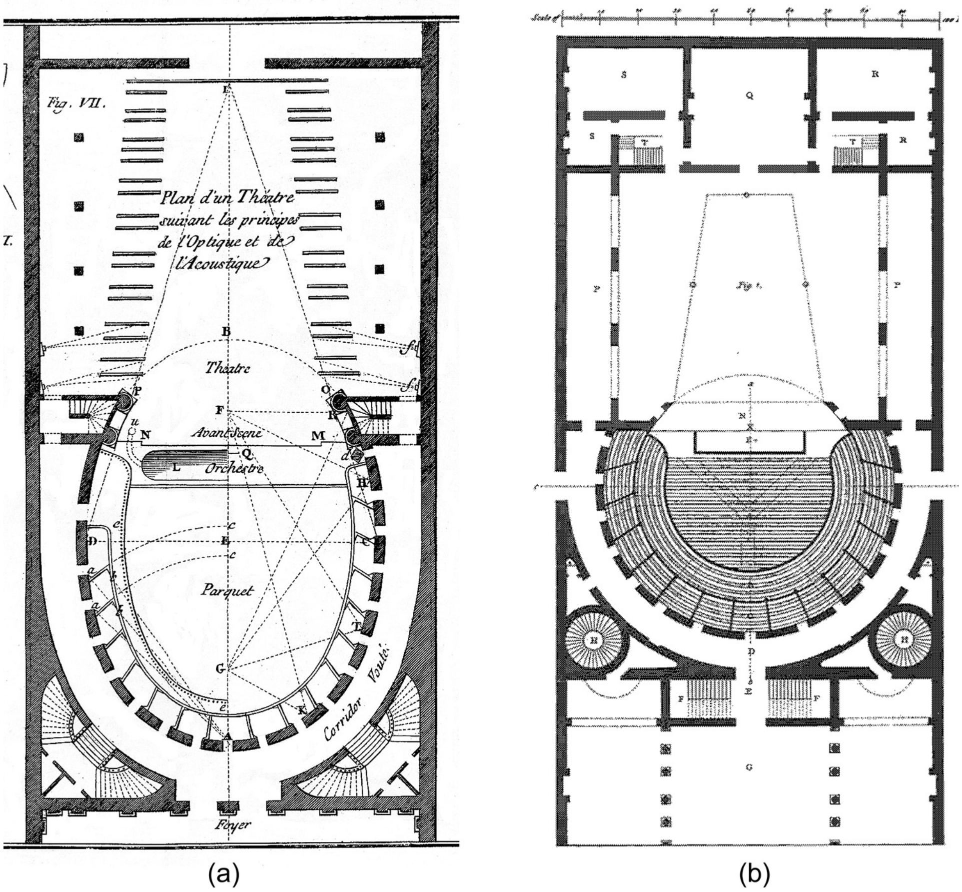

FIG. 1. Concept theaters. (a) From Patte (1782). (b) From Saunders (1790).

contributions was his authorship of the book *A Treatise on Theaters* (Saunders, 1790). This book described an experiment on the human voice which observed that a person reading from a book [positioned at *A* in Fig. 2(b); it was hypothesized that reading resulted in a more constant level of voice] was distinctly audible in still, open air at a maximum distance of 92 ft in front, 75 ft on each side, and 31 ft behind the reader. An additional observation was that the voice was distinctly audible in a semi-circle centered on *B* along which the human voice was heard equally well [the distance between *A* and *B* was 17 ft, see Fig. 2(b)].

Saunders conceived a theater according to the guideline stated in his book [see Fig. 1(b)]. The plan was shaped

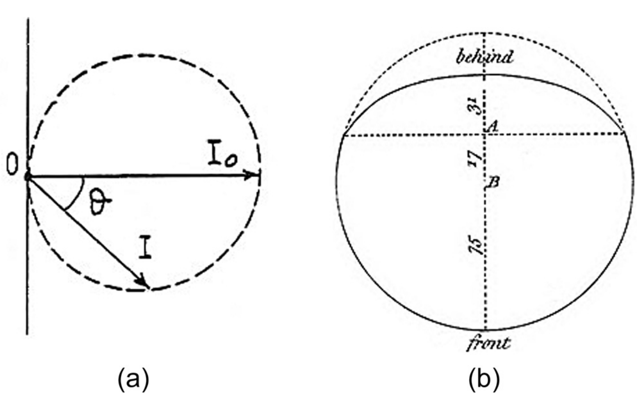

FIG. 2. Results of early voice directivity studies. (a) Radiation pattern of the human voice according to Riccati [from Barbieri (1990)]. (b) Shape of the maximum distance the human voice was distinctly audible according to Saunders [from Saunders (1790)].

according to the voice data; semi-circle with prolonged ends. However, the dimensions were scaled down; the width was 60 ft and the distance between stage floor and opposite central box was 45 ft. Therefore, the radius of the circle was 30 ft with 15 ft between center point and stage, leaving 2 ft on stage, which Saunders regarded to be the typical position for an actor. Reflections were not a design consideration as Saunders purposely avoided describing the decoration, although earlier in his book he stated that wood absorbed exactly the right amount of sound.

Little is known about Saunders's architectural projects, however, he certainly designed one room with acoustical demands: the theater of the Royal Institution (1802, currently known as the Faraday lecture hall). The first plans of the theater of the Royal Institution were drawn by Mr. Webster (C., 1847). These ideas were submitted to Saunders who modified the design. The theater is approximately 45 ft long and 60 ft wide (Smith, 1861a) (see Fig. 3), the exact dimensions of Saunders's concept theater. This lecture hall, with mainly wooden finishes, has established a good reputation for its acoustics (Smith, 1861b).

E. Benjamin Wyatt (1775–1852)

In 1811, Benjamin Wyatt, the architect of the 4th Drury Lane theater in London (1812–1822), repeated Saunders's experiment (Wyatt, 1813). He confirmed Saunders's finding and concluded that the voice of a "moderately-speaking" person was clearly perceived up to 92 ft in front, 75 ft to the sides, and 30 ft to the rear in free-field conditions. He also confirmed Saunders's finding on the semi-circular shape of the voice radiation pattern with the center point 17 ft in front of the speaker.

Wyatt used this finding in his theater design by distributing the sound of the actor's voice equally over the theater. According to Wyatt, at first sight this would lead to a semi-circular shape with a diameter of 75 ft. However, he argued that this was only true when the actor was positioned on the center of the stage. The voice also needed to be audible when the actor was at the extremity of either side of the stage. Therefore, he designed the circular-shaped theater to measure at most 38 ft to both sides of the stage and 53 ft to the front of the stage. The theater comprised mainly wooden finishes as wood "does not absorb the sound so much as some materials, and that it is sonorous and capable of producing soft, clear, and pleasing tones." Figure 4 shows the plan of the Drury Lane theater compared to the voice data pattern. Although Wyatt had made every effort to produce a perfect auditorium, certain acoustic deficiencies became increasingly obvious (Shepperd, 1970). The proscenium was too small for its width and the acoustics were far from perfect. Before the 1822 season opening, Samuel Beazley was contracted to improve the design in order to overcome these defects.

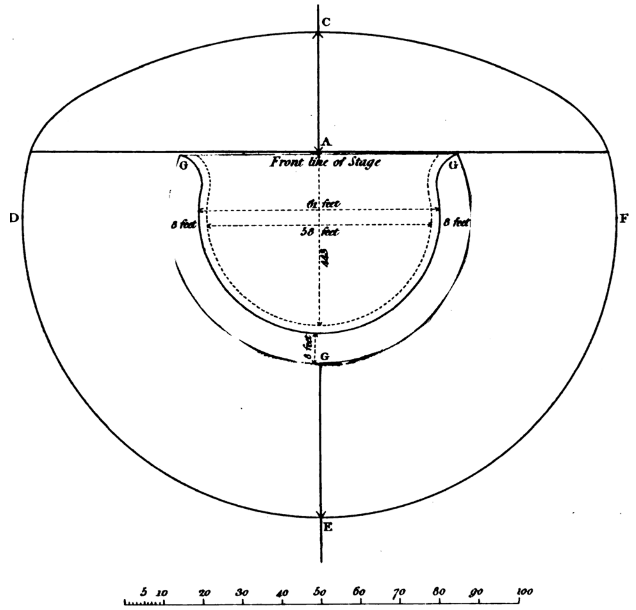

FIG. 4. Form describing the extent to which the human voice was heard equally well according to Wyatt's experiment (shape "CDEF") compared to the shape of the Drury Lane Theater (shape "G") [from Wyatt (1813)].

F. Joseph Henry (1797–1878)

In 1854, Joseph Henry became involved in the design of a lecture hall at the Smithsonian in Washington, DC (Henry, 1857). He stated that sound from an impulse expands equally in all directions while sound from directive sources such as the human voice results in a higher sound intensity along the axis compared to the sides and rear. Therefore, a speaking person is heard more distinctly directly in front than at an equal distance behind. Henry, while stating that many experiments had already been carried out regarding human voice directivity radiation pattern in free-field conditions, repeated Saunders's and Wyatt's experiment in an open space in front of the Smithsonian. He found in accordance with Saunders and Wyatt that the ratio for distinct hearing directly in front of a speaking person, to the sides, and behind was 100, 75, and 30 ft, respectively.

Henry employed these findings in the design of the lecture hall (see Fig. 5). It was 100 ft wide and 64 ft long, close to the ratio between in-front and to-the-sides of the speaker found in the experiment. The walls behind the speaker were composed of plaster on lathe; Henry neglected to mention the material composition of other surfaces. According to Henry, the room's acoustics were "entirely unexceptionable," or beyond reproach.

G. Alexander Saeltzer (1814–1883)

In 1872, Alexander Saeltzer wrote an account about the acoustics of buildings (Saeltzer, 1872). According to Saeltzer, many experiments had proven that in theaters the sound of a clearly speaking voice was distinctly audible to a

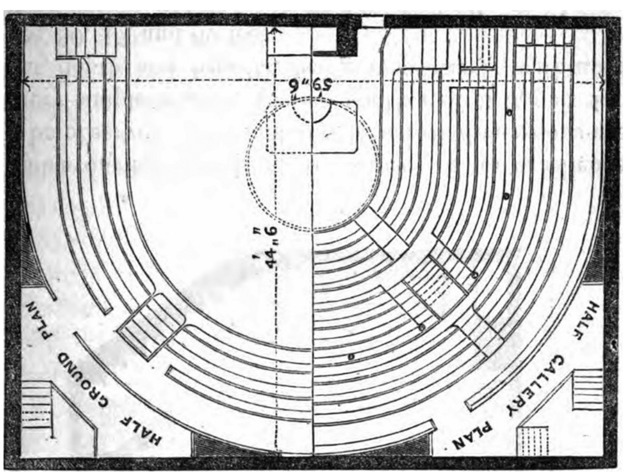

FIG. 3. Plan of the Theater of the Royal Institution [from Smith (1861b)].

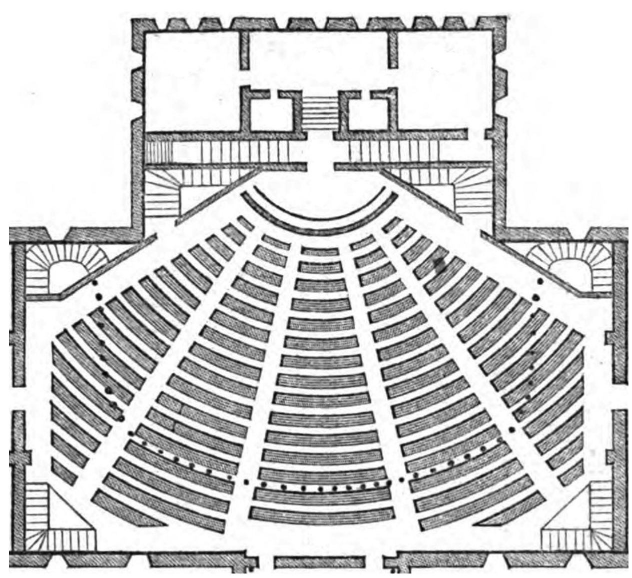

FIG. 5. Plan of the lecture hall in the Smithsonian [from Henry (1857)].

distance of 80 ft in front, 60 ft to the sides, and 40 to 50 ft to the rear. From this followed the conclusion that the best form for distinct hearing was a circle or ellipse. He additionally stated that a distinct sound for building types other than theaters, given the right arrangement of seating and form, allowed a voice to be audible over a distance of 150 ft in front, 80 ft to the sides, and 60 ft to the rear. Based on these observations, Saeltzer stated that the three-quarter circle form had proven itself the best for theaters.

During his career, Saeltzer designed at least two buildings with challenging room acoustic demands: Academy of Music (New York City, 1854–1926) and Fourteenth Street Theater (New York City, 1866–1938). The Academy of Music opened its doors in 1854. It seated 4000 attendees distributed over 5 floors and was "horse-shoe" shaped. The distance between stage-front and back wall was about 120 ft and the audience area was 114 ft wide (Anon, 1854a). The large dimensions could be justified by the function of the room for Opera performances. The whole interior of the room was covered with wooden panels. The New York Times declared it to be an acoustical "triumph," but "In every other aspect...a decided failure," complaining about the architecture, interior design, and closeness of the seating (Anon, 1854b). The academy of Music burned down in 1866 and was rebuilt in the same configuration. The Metropolitan's new opera house at Broadway and 39th Street, twice the size of the Academy, opened in 1883. The new opera house was an instant success resulting in the cancellation of the Academy of Music's opera season in 1886. In 1909 it was converted into a movie theater and it was eventually demolished in 1926.

In 1866, the Fourteenth Street Theater opened its doors (Frick, 1984). The theater seated 1000 attendees, with a length of 53 ft and width of 30 ft.[3] Draperies, upholstery, and carpeting were employed throughout the room. By the mid 1910s it was being used as a movie theater, until it was turned into the Civic Repertory Theater in 1926. Due to the Great Depression it was eventually demolished in 1938.

III. VENUES WHICH USED STUDIES ON VOICE DIRECTIVITY

Table I summarizes the results concerning the maximum perceptible distances at frontal, side, and rear directions from the different reported studies. The described findings were used in the design of various acoustic venues. An overview is presented here. It should be noted that various theater and lecture halls such as The National Theater (K. von Fischer: Munich, 1813), the Schauspielhaus (K. F. Schinkel: Berlin 1821–1944), Königsstädtisches Theater (C. T. Ottmer: Berlin, 1824–1932), Staatstheater Mainz (George Möller: Mainz, 1831), and the Semperopera (G. Semper: Dresden, 1841–1869) have similar semi-circular shapes and comparable dimensions, suggesting the use or influence of voice directivity based architectural guidelines. However, no direct evidence of this connection was found in the course of this study.

TABLE I. Maximum distance and front-normalized ratios for distinctly audible human voice in front, side, and rear directions for the different studies.

	Dimensions (*ft*)			Ratio		
Study	Front	Side	Rear	Side	Rear	Condition
Wren (1903)	50	30	20	0.60	0.40	indoor
Patte (1782)[a]	72	—	—	—	—	indoor
Patte (1782)[a]	50	—	—	—	—	outdoor
Ricatti (Barbieri, 1998)[b]	—	—	—	0.50	0	—
Saunders (1790)	92	75	31	0.82	0.34	outdoor
Wyatt (1813)	92	75	30	0.82	0.33	outdoor
Henry (1857)	100	75	30	0.75	0.30	outdoor
Saeltzer (1872)	80	60	40	0.75	0.50	indoor

[a]Patte did not provide measurements to the sides or rear.
[b]Riccati presented only ratios, no distances.

A. Iffand Theater, Berlin, 1802–1817

In 1800, Langhans wrote about the acoustics of the Iffand Theater that he was in the process of designing (Langhans, 1800). He referred to Patte's theories, Saunders's experiment, and considered the shape of several existing theater halls. Finally, without clearly stating his reasons, he selected Patte's concept theater shape [see Fig. 6(a)]. Additionally, based on Patte's concept theater design, he concluded that the maximum distance between the front of

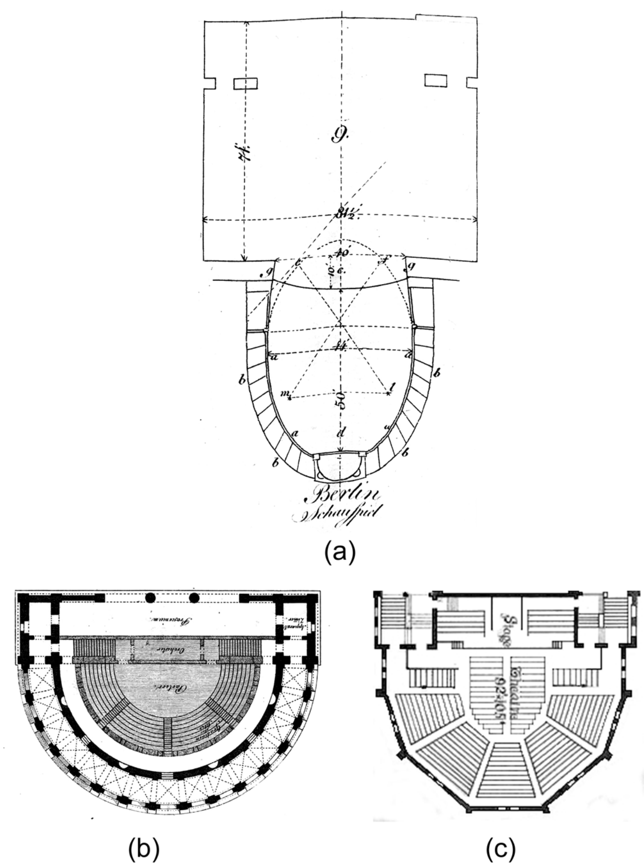

FIG. 6. Plans of several built theaters. Distortions in the Iffland plan are in Langhans (1800). (a) Iffland theater [from Langhans (1810), Fig. 9]. (b) Hoftheaters [from Weinbrenner (1809)]. (c) Sanders Theater [from (Bunting, 1998)] (footnote 4).

the stage and the loge seating at the rear of the theater should not exceed 50 ft. In the final design this distance was 53 ft, for which one could hypothesize that this excess was due to the slight difference in *ft* standards between countries.[1] The wall finishes were reflective (Catel, 1802). Additionally, Langhans also referred to echo theory, stating that the reflections which arrived within 0.11 s of the direct sound were beneficial for the acoustic experience and reflections arriving beyond this time limit were detrimental (Postma, 2013; Postma and Katz, 2014). Despite the design's intentions, the acoustics turned out to be poor, with disturbing perceivable focusing effects (Langhans, 1810). In 1817, the Iffland theater was destroyed by a fire.

B. Hoftheater, Karlsruhe, 1809–1847

In 1809, the Hoftheater in Karlsruhe opened its doors. The architect Friedrich Weinbrenner based his design on the semi-circular shape of ancient Greek and Roman theaters (Weinbrenner, 1809). However, the main dimension was based on Saunders's findings. The diameter of the semi-circle was 100 ft and the stage was rectangular with a depth of 17 ft [see Fig. 6(b)]. The audience area was a 2× scaled up version of the theater of the Royal Institution; the depth of the stage was based on the distance found in Saunders's experiment between the speaker and the voice expansion's center of the frontal semi-circle. In order to prevent disturbing reflections, the walls were covered with cloth according to Catel's proposals, to prevent echoes from occurring as were observed in the Iffland Theater (Catel, 1802). A fire broke out during a performance on the 28th of February 1847, destroying the theater completely. During its existence the acoustics of the Hoftheater were well-liked (Haass *et al.*, 2013).

C. Royal Albert Hall, London, 1871

Whereas the discussed design guidelines regarding voice directivity were typically used with rooms for speech, they were also employed in the design of the Royal Albert Hall, a space for music. In 1865, Henry Scott took over the task of designing this concert hall from Captain Fowke, who had passed away (Scott, 1871). Scott used as his acoustic consultant Thomas Smith, who showed a great admiration for the acoustics of churches constructed by Wren, stating: "Wren's churches can, almost all of them, be adduced as affording examples of a disposition favorable to sound…" (Smith, 1861a, p. 103).

Scott and Smith started from a rough model made by Fowke with the dimensions 204 ft in front of the speaking person, 82 ft to the sides and 76 ft behind, a ratio of 1:0.40:0.36. These dimensions were compared to the experiments carried out by Wren and Saunders, and to the dimensions of La Scala in Milan and Covent Garden theater (1857) designed by Edward Middleton in London (see Fig. 7). The dimensions of La Scala, which they considered to be "the largest and most perfect lyric theater existing" measured 66 ft in width and 88 ft in length (Barry, 1860). Architect Edward Barry designed the Covent Garden Theater to be a "more or less elongated" horse shoe shape with dimensions of 63 ft wide, 80 ft long, based on the shape *Her Majesty's Theater*. These rooms closely approximated the ratio of Wren's findings.

As Saunders carried out his experiments in free-field, while Wren's concerned indoor conditions, Scott and Smith preferred Wren's ratios. According to Scott, because of the chosen width of the initial design, Fowke must have attributed more influence than Wren to the effect of side walls in carrying the sound forward. The dimensions were changed by Scott and Smith to 163 ft in front of the solo singer, 92.5 ft to the sides at the broadest part, and 56 ft behind, which closely approximates the dimension ratios given by Wren (Royal Albert Hall = 1:0.57:0.34; Wren = 1:0.60:0.40). The upscaling was justified by the assumption that indoors the voice carries much further than in open air (Smith, 1858). Based on the acoustic properties of, among others, the Theater of the Royal Institution, the high wall behind the orchestra, the wall of the picture gallery, and coving of the ceiling were generally covered with wooden lining over an air space.

Immediately after opening the acoustics were disliked (Anon, 1871). Initially, comments were dominated by mentions of the severe echo from the dome. The same year as the opening, attempts were already undertaken to remedy this acoustic effect by suspending a large drape horizontally below the dome. In 1949 this drape was removed and replaced with fluted aluminum panels below the glass ceiling, in a new attempt to eliminate the echo (Shepperd, 1975). However, the echo was not properly removed until 1969 when a series of large fibreglass acoustic diffusing discs were installed below the ceiling. Despite the acoustical study and these renovations, the acoustic reputation of the Royal Albert Hall is considered rather poor, due to its large

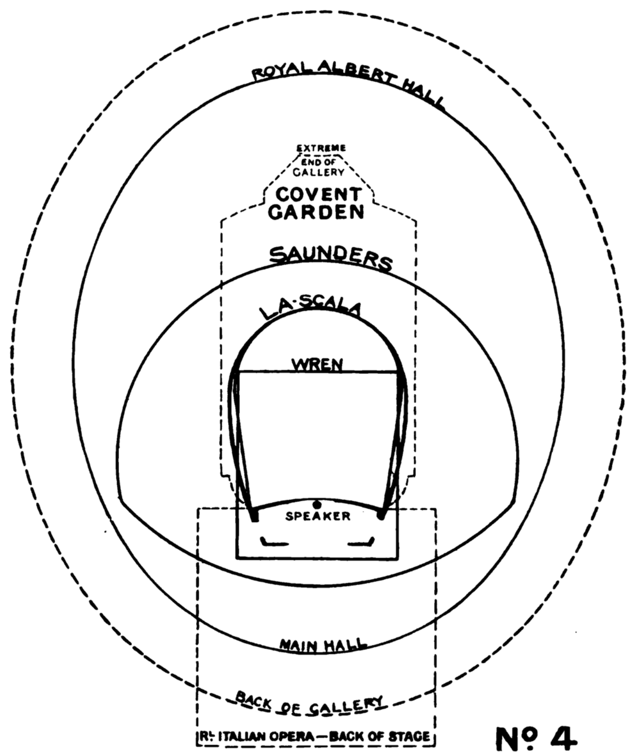

FIG. 7. Dimensions of the Royal Albert Hall compared to La Scala, Covent Garden Theater, and the voice experiments of both Wren and Saunders [from Scott (1871)].

size resulting in a weak sound and an early reflection design, which is far from ideal (Barron, 1993).

D. Sanders Theater, Boston, 1876

As a memorial to the American Civil War, Harvard University erected a building in its commemoration. After a design competition, alumni William Robert Ware and Henry Van Brunt were selected as its architects. The building contains a dining hall, gallery, and theater. The theater was named after Sanders, a sponsor of the building, and was renowned early on for its acoustics (Anon, 1875). It was even used in Sabine's historic research, which led to his reverberation formula. The design was inspired by Christopher Wren's Sheldonian Theater (Ware and Brunt, 1867). Figure 6(c) shows its semi-circular plan with a diameter of ≈50 ft. The architects argued that the semi-circular shape led to similar viewing and hearing conditions for all spectators. The surfaces of the theater were mainly covered with wooden finishes.

IV. DISCUSSION

Several observations can be made regarding the historical works presented in the current study.

- Wren and Patte described different distances at which the human voice is perceivable in indoor conditions. Wren discussed church acoustics while Patte referred to theaters, so one could hypothesize that the reverberant conditions lead to varying perceivable distances.
- Wren found different ratios than Saunders, Wyatt, Henry, and Saeltzer, which could be explained by the different conditions of the experiments. Wren carried out tests in indoor conditions while Saunders, Wyatt, and Henry performed their tests in outdoor conditions.
- Patte, who only studied the reach of the human voice in the frontal direction, found a different distance (48 ft) in outdoor conditions than Saunders, Wyatt, Henry, and Saeltzer (80–100 ft). This could be explained by different voice levels or speaking style during the experiments. According to Olsen (1998), this difference could be up to 6 dB and therefore explains the doubling of the observed distance. Another basis for this distance difference could be differences in background noise level, affecting audibility and intelligibility judgments.

Comparisons to modern practice in room acoustics follow two approaches. The first considers historical voice propagation studies relative to modern measurements. The second examines historical considerations regarding auditorium shapes to modern design criteria.

A. Voice directivity measurements

There are multiple studies concerning the radiation pattern of the human speaking voice (Chu and Warnock, 2002; Dunn and Farnsworth, 1939; Flanagan, 1960; Katz *et al.*, 2006) and singing voice (Cabrera *et al.*, 2011; Kob, 2002; Katz and d'Alessandro, 2007). As an example, Chu and Warnock (2002) simultaneously measured spoken phrases with two sets of eight microphones arranged at fixed positions on two fixed orthogonal meridian arcs in an anechoic chamber surrounding a human talker. To measure the whole radiation sphere, each talker rotated to six fixed positions in 15° increments.

The results of the historical studies are compared here to modern anechoic directivity measurements of the human voice (Chu and Warnock, 2002). As Patte did not provide measurements to the sides or rear and Riccati provided a purely theoretical assumption, those writings are omitted from the discussion. A second consideration is the loudness of the human voice employed during the historical experiments: Saunders, Henry, and Saeltzer made no mention of human voice loudness. However, Wren and Wyatt mentioned that the voice was "moderately" exerted, therefore historical studies are compared here with contemporary measurements for a normal-speaking voice. As a normal-speaking male voice peaks in intensity around 400–630 Hz (Olsen, 1998), the average of these 1/3rd octave bands was employed for comparison. It should be noted that meteorological conditions and sound/ground interaction are neglected (Bass *et al.*, 1990). Figure 8 summarizes the directivity results across the different studies. One can observe that the differences between Saunders, Wyatt, and Henry's results are within perception thresholds. Saeltzer is comparable to these experiments between −100° and 100°, while attributing a louder sound level to the back of the speaking person.

Comparing historical studies with those of Chu and Warnock (2002) (see Fig. 8 and Table II) it can be observed that the modern and historical outdoor findings agree well in front of the speaking person. However, Saeltzer's is the only experiment which agrees within the perceptual thresholds

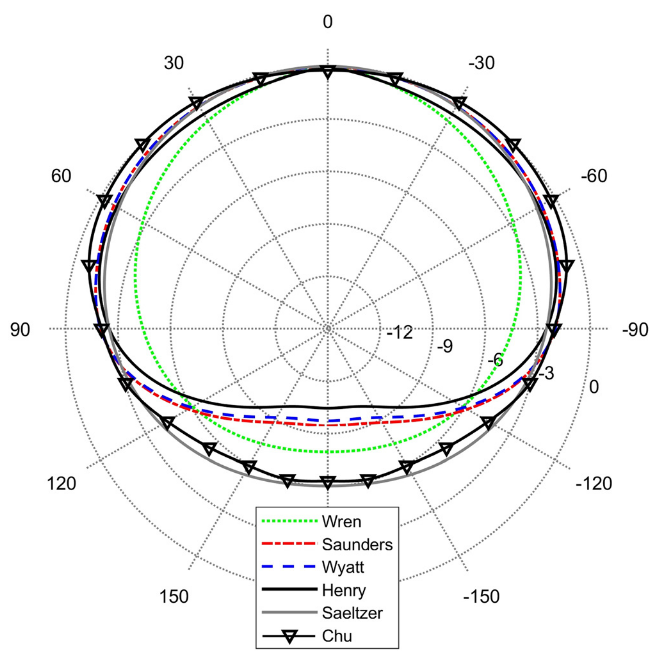

FIG. 8. (Color online) Spline interpolated (1° steps) directivity patterns (dB) from data reported in the historical studies by Wren, Saunders, Wyatt, Henry, and Saeltzer. Contemporary data from Chu and Warnock (2002) included for comparison.

TABLE II. Maximum, mean, and standard deviation (SD) of the differences (dB) between historical findings from the historical studies compared to modern anechoic measurements (Chu and Warnock, 2002).

Study	max(Δ)	mean(Δ) (SD)	conditions
Wren (1903)	2.7	1.7 (±0.7)	indoor
Saunders (1790)	3.2	1.2 (±1.1)	outdoor
Wyatt (1813)	3.6	1.3 (±1.3)	outdoor
Henry (1857)	4.3	1.7 (±1.5)	outdoor
Saeltzer (1872)	1.0	0.5 (±0.3)	outdoor

behind the speaker. The other results show differences, which increase to the order of 4 dB.

B. Acoustic design guidelines

Following these historic metric guidelines appears to have resulted in several acoustical successes. The exceptions are the Iffland theater, Wyatt's Drury Lane Theater, and the Royal Albert Hall. The Iffland Theater had reflecting surfaces throughout the room and the Royal Albert Hall was severely up-scaled in size. This could have lead to excessive reverberation times, higher than deemed suitable for their corresponding purposes. Wyatt's Drury Lane Theater had too wide a stage for its audience area. It should additionally be noted that in drama theaters, using the profile of limited speech intelligibility, it is a fallacy in practice to assume that actors always face forwards. They commonly face across stage to speak to other actors and the profile moves with them.

Current practices in modern theater and opera house design still employ distance guidelines. For instance, Barron (1993, pp. 272–273, Table VII.3) proposed the *early reflection ratio* as a rough means of relating the maximum distance between actor and audience to the minimum number of early reflections needed in order to achieve sufficient intelligibility and speech level based on basic theatre geometry. For example, considering a theatre in the round, an audience distance of 15 m requires two strong early reflections, an audience distance of 20 m requires 4, with spectators located at 150° relative to the actor's central head direction. In contrast, in a proscenium theatre only 1 and 2, respectively, strong early reflections would be needed with spectators located within 90°. This is due to the attenuation of the voice behind the actor which has less of an impact in a proscenium theatre than in the case of a theatre in the round.

In comparison to these simple metrics, modern acoustic design guidelines focus on room acoustic conditions, which are determined by the room's dimensions, volume, volume/seat, and the acoustic characteristics of the materials used (i.e., sound absorption, diffusion). Modern theaters should be designed with limited reverberation times, being less reverberant than theaters constructed during the Renaissance. For instance, the Teatro Olimpico (1585) in Vicenza and the Teatro Farnese Parma (1623), have $T20_{500\text{–}1000\ \mathrm{Hz}}$ of 3.3 and 3.2 s, respectively (Weinzierl *et al.*, 2015). A good early reflection design is also necessary. A means to project early reflections towards the audience area in modern theaters is to create reflective side walls. Additionally, the strength of the late sound is a significant aspect of modern room design. This is the key element which distinguishes enclosed rather than outdoor spaces. Ancient Greek theaters are considered to have held rather larger audiences than is possible in an enclosed space. The strength of the late sound is generally characterized by the reverberation time. Each type of venue space, such as drama theater, amplified lyric theater, concert hall, or opera house, is designed to a predefined acoustic condition, such as a reverberation time appropriate to the use of the space. For example, drama theaters have target reverberation times of 0.9–1.0 s, 1.4–1.6 s for opera and recital halls, and at least 1.8 s for concert halls. It is interesting to compare this modern approach to these pre-Sabine design guidelines, which did not consider anything other than the distance at which speech is audible or intelligible. Little attention appears to have been given to the acoustic details of the spaces in which these criteria were established, and how they may vary among spaces with different acoustics.

Based on available plans of the historic rooms and dimensions reported by the architects, estimations were made of the maximum distance between the center front of

TABLE III. Maximum distances between the center front of the stage and seats for the historic rooms and modern guidelines. All measures have been converted to English/American *ft*.

Room type	Room	Opening year	Closing year	Distance (*ft*)	Acoustic reputation	Experimental data source
Modern	Theater guideline	—	—	66	—	—
Lecture hall	Sheldonian Theater	1669	—	∼50	good	Wren (1903)
	College of Physicians	1675	—	40	good	Wren (1903)
	Royal Institution Theater	1802	—	30	good	Saunders (1790)
	Smithsonian Lecture hall	1856	1865	66	good	Henry (1857)
	Sanders Theater	1876	—	∼70	good	Wren (1903)
Theaters	Patte's concept theater	—	—	58	—	Patte (1782)
	Saunders's concept theater	—	—	45	—	Saunders (1790)
	Iffland Theater	1802	1817	51	bad	Patte (1782)
	Hoftheater	1809	1878	49	good	Saunders (1790)
	4th Drury Lane Theater	1812	1822	53	bad	Wyatt (1813)
	Fourteenth Street Theater	1866	1938	53	good	Saeltzer (1872)
Opera Hall	Academy of Music	1854	1909	120	good	Saeltzer (1872)
Concert Hall	Royal Albert Hall	1871	—	163	bad	Wren (1903)

the stage and seats (see Table III). All of these historic lecture halls, theaters, and opera halls are within or close to modern theater design guidelines. The only exception is the Royal Albert Hall, whose main function is concert performances, though it is also used for other purposes. One could hypothesize that by employing the measured speech propagation ratios the architect hoped the acoustics would be suitable for speech as well.

V. CONCLUSION

Historic theater halls, concert halls, and opera houses which are renowned today for their acoustic qualities can be considered the result of a Darwinian type evolution, with architects designing halls inspired by the success of previous "good" halls. One can distinguish two main room acoustic design approaches in pre-Sabine times, which were part of this evolution: "circulation of sound" and geometrical acoustics. This study presented a 18th–19th century guideline based on the radiation patterns of the human voice, which can be categorized in the "circulation of sound" approaches. These guidelines ran in parallel to other numerical guidelines such as those based on reflection arrival time or echo detection thresholds (Postma, 2013; Postma and Katz, 2014), which can be categorized as geometrical acoustics approaches.

Contrary to previous "circulation of sound" approaches, the discussed guideline assumed directional radiation patterns instead of uniform radiation. This historic guideline was based on simple measurements, which employed a speaking person and human observer judging audibility/intelligibility as a function of distance and direction. Taking this limited protocol into account, the observed voice radiation patterns are very similar to what modern measurements performed in controlled conditions have observed.

This voice directivity and propagation guideline limited the size of audience areas in lecture halls and theaters, which is also currently considered beneficial for the acoustics of rooms designed for speech. However, these early designs did not take into account volume, volume/seat ratio, or even the acoustic characteristics of materials. In contrast, modern room-acoustic design approaches also consider other aspects of the acoustic response, namely, early reflections and reverberation Barron (1993).

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[1]Distances are presented in *feet* instead of metric units as all referred publications employed this unit. It should be noted that the length of "1 ft" differed between countries: England and USA = 0.305 m, France (1668–1799) = 0.325 m, Prussia (before 1871) = 0.314 m. Consequently, contemporaries made slight errors when directly adopting dimensions from other countries. In the case of metric dimensions, these were converted to English/American *ft* units.

[2]Some literature ascribes the second Drury Lane Theater (1674–1791) to Wren. As this has not been established beyond reasonable doubt (Shepperd, 1970), this room was not included in the current study.

[3]The actual dimensions have not been uncovered during this study. The given dimensions have been estimated based on the number of seating rows multiplied by 2.8 ft and the width of the stage opening.

[4]http://www.e-rara.ch/zut/content/zoom/8694026 (Last viewed April 13, 2018).

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