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JASA FORUM

Forum—Pre-Sabine room acoustic assumptions on reverberation and their influence on room acoustic design

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ABSTRACT:

With his work on the Fogg Art Museum and Boston Symphony Hall between 1895 and 1900, Wallace C. Sabine laid a foundation for the field of architectural acoustics as a science. Prior to that, architects employed various quantifiable notions in acoustic design. Previous studies have reviewed metric guidelines based on the directivity of the human voice, which was utilized in at least 11 rooms in pre-Sabine times. Others studies have reviewed pre-Sabine design guidelines that were based on the quantification of the perception threshold between direct sound and first order reflections and which were followed in several rooms with acoustical performance needs. As the first studies concerned the direct sound and the second set concerned first order reflections, this study reviews opinions and knowledge regarding the later part of the acoustic response, also known as reverberation, during the 19th century. This effort brings to light a room acoustic design evolution showing why concert halls at the end of the 19th century mainly had surface finishes of wood and plaster as well as limited ceiling heights. While not equal to Sabine's thoroughness and completeness, numerous early experimental and theoretical reverberation approaches were found to hint at similar notions with both qualitative and quantitative efforts. © *2020 Acoustical Society of America*.

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I. INTRODUCTION

In 1898 Wallace Clement Sabine found an objective and quantifiable relationship that could be used in architectural acoustics with the proposal of the reverberation formula (Sabine, 1922). After numerous tests in 12 rooms with organ pipes as the sound source, his ears as receivers, and a stopwatch, he concluded that the sound absorption multiplied by the reverberation time and divided by the room volume was a constant. This clear quantification of the relationship between reverberation time and absorption was revolutionary with regard to predictive design in room acoustics. Sabine used this result to acoustically advise the architects of the Boston Symphony Hall. He changed the dimensions of the original design to achieve the same reverberation time as was observed in the Neue Gewandhaus, Leipzig. This discovery laid the foundation for architectural room acoustics as a science. However, many concert halls with outstanding acoustic reputations, such as the Wiener Musikvereinssaal (1870) and the Amsterdam Concertgebouw (1888), were constructed prior to Sabine's work (Beranek, 1996). This makes acoustical design practices in the pre-Sabine era a point of interest for historical room acoustics.

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, which had proportions similar to its predecessor, the Redoutensaal (Barron, 1993).

Barbieri (1998, 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), who 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*

[a)]Electronic mail: b.postma@dieBauingenieure.com *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 upward.

Based on undulatory acoustics a metric guideline arose, building on the directivity and propagation distance of the human voice, which was utilized in several halls also during the 18th and 19th centuries (Postma *et al.*, 2018). Acoustic experiments tested how far sound was perceivable toward 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.

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. At the end of the 18th century, based on geometrical acoustics, a numerical guideline arose (Postma, 2013; Postma and Katz, 2014). This "echo theory" 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.

In general, one can state that historic voice directivity guidelines concerned the *direct sound* and echo theory considered *early reflections*. These theories ignored the late arriving reflections or reverberations. However, several pre-Sabine acousticians had already considered the influence of sound absorption of materials and room volume on the acoustics of spaces with room acoustic demands.

This third study in the pre-Sabine trilogy examines early design concepts relating to the late or reverberant part of a room's acoustic response. Delving into publications about the acoustics of these spaces, the assumptions and knowledge of reverberation in pre-Sabine times is described. The mentioned rooms are not exhaustive as several architects either did not describe their acoustic concepts or their writings were not uncovered during the course of this study, such as for the Wiener Musikverein.

II. ROOMS FOR SPEECH PURPOSES

A. Ancient Greek and Roman theaters

Vitruvius already considered certain architectural acoustic properties (Morgan, 1914) over 2000 years ago. He wrote ten books about architecture; the fifth book includes some remarks regarding architectural acoustics in his description of the construction of theaters. As part of the "circumsonant" indicator, Vitruvius described the "resonation" of materials, employing a comparison between Greek and Roman theaters. He considered Roman theaters acoustically superior as they were constructed from wood, which he argued would resonate with the sound.

B. Theater of the Royal Institution (1802; presently Faraday lecture hall)

George Saunders designed the Theater of the Royal Institution. Besides the shape being based on his voice directivity experiments, it was lined with wood (Smith, 1861a). He confirmed Vitruvius's finding while describing why wood was a good surface finish for rooms with acoustic demands (Saunders, 1790, p. 21–22):

> [W]ood is sonorous, conductive, and produces a pleasing tone…; for not absorbing too much as some, and not conducting so much as others, this medium renders it particularly suitable to rooms for musical purposes; the little resonance it occasions being rather agreeable than injurious.

This lecture hall has established a good reputation for its acoustics (Smith, 1861a).

C. Iffland Theater, Berlin (1802–1817) and Hoftheater, Karlsruhe (1809–1847)

In 1802, Carl Gotthard Langhans's Iffland Theater opened its doors. The ellipsoid design was chosen to distribute the human voice over the space, and the size was kept moderate in order to reduce the additional pathway of first order reflection arrival times to be less than 0.11 s (Langhans, 1800). The wall finishes were reflective (Catel, 1802). Despite the design's intentions, the acoustics turned out to be poor with disturbing perceivable focusing effects and echoes (Langhans, 1810).

The Hoftheater in Karlsruhe opened in 1809. The architect, Friedrich Weinbrenner, designed a room that was a semicircle with a diameter of 100 ft (30 m; Weinbrenner, 1809). This shape was chosen to have the optimal voice coverage over the space. In reaction to the acoustic failure of the Iffland Theater, the walls were covered with cloth according to Catel's proposals in order to prevent echoes from occurring and reduce reverberation (Weinbrenner, 1809, translation of extract p. 9):

> …, the Karlsruher Theater, with a much larger interior space of construction, by paying the most careful attention to every detail that can increase the vibration of the sound, and reflect such, has received the great advantage that even a pistol shot in it does not result in the least lasting effect.

During its existence, the acoustics of the Hoftheater were well-liked (Haass *et al.*, 2013).

In 1810, Carl Ferdinand Langhans (Carl Gotthard Langhans's son) discussed the acoustics of both rooms. He postulated that the elliptical form of the Iffland Theater was responsible for sound concentrations and caused the disappointing acoustics. He advocated installing sound scattering elements in order to prevent sound concentrations. Langhans disagreed with dampening all reflections by referring to the lighting arrangements within a room. Rooms with black surfaces compared to lightly colored rooms seem much darker when lit by torches with the lightly colored rooms being nicer environments to live in. For sound, Langhans explained this as follows (Langhans, 1810, translation of extract p. 39):

> A gradually slow fading sound in small and large buildings is pleasant and necessary, to make us enjoy the magic of music and sounds. So we cannot suppress such an echo….

In reference to the use of materials, Langhans adhered to Vitrivius's views on resonating materials. However, he thought that in large rooms the resonating sound of these bodies would lead to overlong reverberation. Langhans considered marble, gypsum connected to a solid wall, or solid wood coated with lacquer and gold plating to have the best effects on the acoustics for their clear way of reflecting sound. In large rooms, only the stage could be constructed of "resonating" materials because in this situation direct and reflected sound covered almost the same path length.

D. Drury Lane Theater, London (1813)

Architect Benjamin Wyatt based the plan of the fourth Drury Lane Theater on voice directivity experiments. The theater comprised mainly wooden finishes as (Wyatt, 1813, p. 12):

> [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….

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. He used a longer and narrower form with smaller balcony overhangs than Wyatt.

E. House of Commons, London (1836)

David Boswell Reid consulted the House of Commons on acoustics and ventilation (Reid, 1836). He decided to reduce the volume of the room by lowering the ceiling. According to Reid, this would cut off a large portion of air, which the speaker's voice had to fill. Considering the sound absorption of materials, Reid removed the soft and yielding canvas as it impaired the support a voice should receive. Reflecting glass and wood were installed above the galleries, and inclined panels were positioned under the galleries and above the floor.

Reid also described observations made in a preparation chamber of Montrose in which surfaces were covered with lead. He found that sound produced in it continued for 7 or 8 s after the impulse, which had given rise to it, had ceased. He considered this excessive reverberation, which would interfere with communication, and mentioned various solutions for this. According to Reid, the introduction of drapery, curtains, and other such materials, particularly carpets, sofas, and soft furniture in general, have a great power in absorbing sound.

F. Lecture room in the Smithsonian (1854–1865)

In 1857, Joseph Henry wrote about the acoustic design of a lecture room in the Smithsonian (Henry, 1857). This article contained some clear views about reverberation. Henry was the first to transcend the contemporary view that a space should not be larger than could be filled by a human voice. He stated that (Henry, 1857, p. 227):

> [T]he larger a room, the longer time will be required for the impulse along the axis to reach the wall; and if we suppose that at each collision a portion of the original force is absorbed, it will require double the time to totally extinguish it in a room of double the size, because, the velocity of sound being the same, the number of collisions in a given time will be inversely as the distance through which the sound has to travel.

Henry also performed some tests on the sound absorption and resonance of materials with a tuning-fork, concluding that hard materials would reflect a large amount of the acoustic energy, resonating materials would resonate with the sound absorbing it while enhancing its loudness at the same time, and soft materials would absorb most of the acoustic energy.

For these reasons, the lecture hall in the Smithsonian's volume was kept modest, and the walls behind the speaker were lined with plaster on lath. According to Henry, the room's acoustics were "entirely unexceptionable" or beyond reproach.

G. The theaters at the Place du Châtelet, Paris (1862)

The Théâtre du Châtelet and the Théâtre-Lyrique, today called the Théâtre de la Ville, both designed by Gabriel Davioud, opened in 1862 (Daly and Davioud, 1865). Davioud realized that a room should not be made up in such a way as to muffle sounds. He distinguished between rooms which resonated themselves, such as the case of a musical instrument and rooms which reflect the sound, without giving a preference. In the first case, the surface finish needed to be lightweight with thin walls, and in the latter the surface finish needed to be built of solid stone.

The architect chose to create a "resonant" stage for both rooms. He ensured that the stage floor was made of very light, very dry wood whose surface of contact with the supports was reduced as much as possible. Due to construction difficulties with lightweight materials, the rest of the theater was constructed of masonry. Echoes were avoided by employing echo theory.

III. ROOMS FOR MUSIC PURPOSES

A. Boston Music Hall (1852)

The Boston Music Hall, the precursor of the Boston Symphony Hall, was constructed in 1852. The dimensions were a common multiple for the proportion in length, width, and height [130 ft, 78 ft, 65 ft (40 m, 24 m, 20 m, respectively)]. The surface finish was plaster on lath in order to prevent excessive reverberation (Upham, 1853).

Involved with its construction was Jabez Baxter Upham (1820–1902), president of the Boston Music Hall association at the time. Upham performed some experiments during the construction of the Boston Music Hall. Based on Reid's observation in the preparation chamber, where he counted the reverberation time to be 8 s, Upham judged the reverberation time of the Boston Music Hall during several stages of its construction. This was short after the floor had been laid, and the walls and ceiling were lathed all around in preparation of the plaster. He stated (Upham, 1853, p. 350):

> [T]he amount of reverberation was found to be inconsiderable [too little], while a good degree of resonance was furnished by the solid masonry which formed the main body of the walls.

After the plaster had been applied and it was still wet (Upham, 1853, p. 350):

> [T]he reverberation of the hall was at its minimum and its resonance at the same time almost wholly gone.

Upham considered this detrimental for the acoustics. Although the voice was heard very distinct, there was a deadness in the tone. This improved when the plaster dried and hardened (Upham, 1853, p. 351):

> [B]oth the resonant and reverberatory qualities of the room returned.

When the plaster had hardened completely and was smoothed, the staging was removed and the room was devoid of upholstery and carpeting, it was observed that a powerful tone of voice was prolonged for 4.5 s. The cure for this overlong reverberation was, according to Upham (1853, p. 351):

> [W]hen the floor of the main hall and balconies was covered with benches, having cushioned seats and backs, the aisles carpeted and the semi-circular windows near the ceiling shielded with curtains of canvas, the change was very marked, and the presence of a moderately large audience so completed the cure as that no injurious excess of sound remained. Should it be required, on any occasion, to reduce still further this reverberatory property, it can (in the opinion of the writer) be readily and perfectly accomplished by the use of additional upholstery, and the adoption of a simple contrivance with canvas, placed against the walls just below the cornice.

Before his experiences at the Boston Music Hall, he already had experience with the reverberation of rooms. In 1846, he visited Girard College in Philadelphia, which was being constructed at the time. Due to the excessive reverberation in the eight recital rooms, Upham considered these unsuitable for their purpose. The recital rooms were finished with solid smooth walls and an arched ceiling. He stated that (Upham, 1853, p. 348):

> [T]he prolongation of sound in these rooms continued a fully 6 s.

On revisiting after the rooms had been furbished, he repeated the experiments, concluding the results were striking (Upham, 1853, p. 349):

> In one room, which had been treated simply by papering upon the solid walls and extending festoons of cotton cloth from the apex of the dome to the corners and centre of the cornices in each side, the reverberation was reduced to 4.5 s; and in others, in which a partition of cloth was stretched across the room horizontally, from the opposite cornices, thus completely shutting off the arched ceiling of stone, and substituting a level surface of yielding canvas, its duration was only 0.5 s.

Upham also described an experiment he performed in the Melodeon, which had an imperfectly ellipsoidal hall with smooth walls and ceiling. It was 113 ft (34 m) in length, 57 ft (17 m) in width, and 35 ft (11 m) in height. A 33-ft^2 dome was positioned in the center of the flat ceiling. According to Upham, in a moderately filled hall the reverberation was 2.5 s, which for its length he considered detrimental to the acoustics. Upham considered walls of solid wood ideal for the acoustics because it gave a (Upham, 1853, p. 22):

> [F]ree admission and conduction of the sonorous pulses with the conditions favoring also the suppression of excessive echo and reverberation.

However, due to fire risks, Upham regarded this material not ideal. Another solution was (Upham, 1853, p. 22):

> [B]attening and wainscoting walls, or of lathing and plastering upon them, after the ordinary methods employed in carpentry.

These materials would greatly assist in absorption of the excess of sound; however, according to Upham, it would destroy the homogeneity of the sound field because it destroyed the resonation of walls. Furthermore, he stated that together with these measures, the clothing of the audience and the cushioned seats on the floor of the hall afforded sufficient material for the absorption of sound.

B. Royal Albert Hall, London (1871)

In 1865, after Francis Fowke's death, Henry Y. D. Scott took over the design process of the Royal Albert Hall (Scott, 1871). Scott was acoustically consulted by Thomas Smith, who already had written articles and books about room acoustics (Smith, 1858, 1861a,b). Smith was aware of the influence volume and sound absorption could have on the acoustics (Smith, 1861b, p. 39):

> [W]here there is too much resonance in a room, carpets or curtains may be advantageously employed to lessen it…

The shape of the Royal Albert Hall was based on voice directivity experiments. The concert hall was mainly lined with wood. According to the architect, the buildings most remarkable for their acoustic properties were all lined with wood, such as the celebrated Theatre of Parma, in which a speaker could be heard when speaking in a low tone of voice at a distance of 140 ft (43 m). Her Majesty's Theatre in the Haymarket, which was destroyed by fire, the Surrey Music Hall, which shared a similar fate, and the Theatre of the Royal Institution are all especially successful buildings with regard to sound, according to Scott, and were lined in this manner.

Immediately after opening, the acoustics were disliked (Anonymous, 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 size, resulting in a weak sound and an early reflection design, which is far from ideal (Barron, 1993).

C. Palais du Trocadero (1878–1937)

After a design competition, Bourdais and Davioud became the architects of the Palais du Trocadero. They based their acoustic design concept on echo theory (Postma *et al.*, 2019). They assumed that echoes arose when the path length difference between direct and first order reflections exceeded 34 m. Therefore, they covered all surfaces more than 17 m from the center of the stage with absorbing materials and the other surfaces with plaster on lath.

Directly after its opening, the acoustics were cause for discussion and complaints due to echoes. The design team noted both the importance of material absorption properties and the relative lack of information available at the time, and that such new knowledge would be useful in performing arts design (Exposition Universelle de 1878, 1878, translation of extract pp. 198–199):

> The degree of absorption of the fabrics was the only unknown of the problem, what would be called scientifically the absorption coefficient. No experience had been previously made on this subject; there is a new field of study to go in order to act for sure in the future constructions of large theaters.

In 1888, Aurel Sturmhoefel proposed two measures to improve the acoustics: (1) lowering of the ceiling above the orchestra to reduce the time period between the arrival of the direct and reflected sound, and (2) replacing the silk with sound scattering materials to prevent sound focusing, thereby improving the homogeneity of the sound field, based on Langhans's theories (Sturmhoefel, 1888). In 1898, Sturmhoefel wrote a book about architectural acoustics called "Akustik des Baumeisters" in which he added knowledge acquired during the years following said article (Sturmhoefel, 1898). Among such discussions were those related to quantification of the acoustic properties of materials. An overview of this work and comparison to modern measures is provided in the Appendix.

D. Neue Gewandhaus, Leipzig (1884–1942)

The acoustic concept of the Neue Gewandhaus, which opened in 1884 in Leipzig, was based on the original Gewandhaus and the Palais du Trocadero (Schmieden, 1886). Architects Martin Gropius and Heino Schmieden copied the dimensions from the existing Gewandhaus and scaled them up by approximately 1.8 times. Additionally, they copied the walls which were constructed of wood. The architects argued that the orchestra would transmit its sound oscillations to all boundary surfaces of the hall, which would resonate like a violin. Additionally, the architects assumed this effect would further improve through the aging of the wood as this was also the case with a violin. From the Palais du Trocadero design guidelines, all surfaces located more than 17 m away from the stage had absorbing finishes. From its opening to its destruction by bombardments in 1944, the acoustics of the Neue Gewandhaus were renowned (Skoda, 1985).

E. Concertgebouw, Amsterdam (1888)

Adolf van Gendt became the architect of the Concertgebouw in 1883 following a design competition. Van Gendt never publicly explained the acoustic design concept behind this concert hall. However, notes of the jury and board have been preserved, giving some insight into the design concept (van Royen, 1989). Several design decisions were based on the Neue Gewandhaus. The hall surface finish was plaster on lath, probably based on Vitruvius's material resonation theory. Furthermore, the jury stated that the ceiling height was limited as "the sound would loose itself in the large volume." It is likely that this conclusion was drawn from halls among which the Royal Albert Hall and Palais du Trocadero were certainly examples. Following a renovation of the stage in 1899, the Concertgebouw's acoustics is considered by some to be among the best in the world (Beranek, 1996).

IV. DISCUSSION

Table I presents an overview of the described rooms' main surface material and dimensions and grounds for choosing them. Vitruvius's theory on resonating surfaces vibrating with the coinciding sound and consequently producing the same fainter sound was wrong. However, this was grounds to install wooden and plaster on lath surfaces for several rooms with acoustic demands. A serendipitous effect is that these materials have a higher absorption coefficient at lower frequencies than at middle and higher octave bands, compensating in some manner for the general lack of low frequency absorption of building materials and audiences. This results in a somewhat "flatter" or uniform reverberation time with frequency, which is considered beneficial in current room acoustics practice (Kleiner and Tichy, 2014).

Examples, such as those by Langhans and Upham, show that during the 19th century basic notions of ideal reverberation times already existed. Both held that a certain degree of reverberation was necessary, while too much reverberation was unwanted. Upham even quantitatively defined a too short and too long reverberation time in terms of seconds.

Upham based his experiments on Reid's single trial, counting the time sound was still audible after a sound had ceased in a preparation chamber. Whereas Upham, in a basic sense, quantified reverberation time, Henry theoretically defined the influence of volume on reverberation time. It should be noted that both Upham and Henry were Americans, and Upham even carried out his room acoustical experiments in Boston. For these reasons, it is very well possible that Sabine was familiar with and inspired by these experiments. However, the sizable amount of both theoretical and practical proof had not yet been acquired nor did a

TABLE I. Overview of the employed surface finishes and dimensions of the discussed rooms.

Room	Opened	Major surface finish	Rationale	Dimensions (m)	Rationale
Theater of the Royal Institution	1802	Wood	Right amount of absorption and resonating material	W:18; L:14; H:9	Voice directivity experiments
Iffland Theater	1802	Reflecting material (not specified)	—	W:14; L:16; H:8	Based on voice directivity experiments and echo theory
Hoftheater	1809	Absorbing material (not specified)	Based on echo theory and to prevent excessive reverberation	Semi-circle ø:30	Voice directivity experiment
Drury Lane Theater	1813	Wood	"Sonorous and capable of producing soft, clear, and pleasing tones"	W:23; L:16; H:15	Voice directivity experiment
House of Commons (renovation)	1836	Replacement of canvas with glass and wood	The absorption "impaired the support which a voice should have"	Reduced volume	Reduction of reverberation
Boston Music Hall	1852	Plaster on lath	Prevent excessive reverberation	W:24; L:40; H:20	Dimensions with a common multiple would create favorable acoustics
Lecture room in the Smithsonian	1856	Plaster on lath	"Elastic (resonating) materials would resonate with the sound absorbing it but enhancing its loudness at the same time"	W:40; L:20; H:8	Based on echo theory and observations on reverberation
Théâtre du Châtelet	1862	Wooden stage, masonry audience area	Both reflecting and resonating walls would create favorable acoustics	W:24.0; L:22.7; H:20.0	—
Théâtre-Lyrique	1862	Wooden stage, masonry audience area	Both reflecting and resonating walls would create favorable acoustics	W:20.5; L:19.3; H:17.0	—
Royal Albert Hall	1871	Wood	Copied from rooms which were considered to have good acoustics	W:56; L:50; H:41	Depth-width ratio based on voice directivity experiments
Palais du Trocadero	1878	>17 m from the stage: stuffed cloth; <17 m from the stage: plaster on lath	Based on echo theory	W:50; L:58; H:33	—
Neue Gewandhaus	1884	Wood	Resonating effect like a violin	W:19; L:42; H:15	Upscale of the existing Gewandhaus
Concert- gebouw	1888	Plaster on lath	—	W:28; L:44; H:17	Height probably based on other concert halls

reverberation formula exist. This formula, still employed in room acoustic practice, was the basis for the Boston Symphony Hall, which is still regarded by some as an acoustically superior hall (Beranek, 1996), and laid the basis for room acoustics as a science.

V. CONCLUSION

This study presented pre-Sabine notions and practice with regard to reverberation and their influence on room acoustic design. It is of interest to view room acoustic design as part of an evolution with architects designing halls inspired from the success of previous "good" halls and learning from the failures of "bad" halls. Part of this evolution was the design guideline based on voice directivity and echo theory (discussed previously), as well as the thoughts on volume and material usage presented here, basically analogous to the direct sound, early reflections, and late reverberation of an impulse response, respectively. It is therefore of interest to analyse what combination of design approaches led to room acoustic success and which did not. It should be noted that these conclusions are based on a limited number of rooms and therefore might oversimplify or overgeneralize.

In these studies, seven newly erected pre-Sabine halls for *speech* purposes (House of Commons was a renovation) were presented. The Theater of the Royal Institution and the Hoftheater took into account considerations related to both direct sound and reverberation. The lecture room in the Smithsonian, the Théâtre du Châtelet, and Théâtre-Lyrique took into account direct sound, early reflections, and reverberation. These turned out to be acoustic successes. The Iffland Theater took into account all three aspects, although suffered from a bad acoustic reputation due to sound focusing. The Drury Lane Theater design considered direct sound and reverberation, however, it had too small a proscenium for the hall's width. This seems to indicate that when the room was designed with a modest size, direct sound and reverberation should be taken into account in order to create room acoustic successes for rooms for speech usage. However, other acoustic effects, such as sound focusing, also need to be considered.

In these studies, five pre-Sabine halls for *musical* purposes were discussed. The Royal Albert Hall did not take into account echo theory and did not limit its size, as would be suggested by voice directivity theories. The Palais du Trocadero took into account early reflection design; however, it seemed to neglect direct sound and pre-Sabine thoughts on reverberation. Both these halls were room acoustic failures. The Boston Music Hall design chose its materials in order to create a good reverberation, and the dimensions were chosen to contain a common multiple, although it seemed to neglect early reflection design. This is confirmed by a comment by Higginson (owner of the Boston Symphony Orchestra) made to McKim (architect of the Boston Symphony Hall; Thompson, 2002):

> [O]ur present hall [Boston Music Hall] gives a piano better than a forte, gives an elegant rather than a forcible return of the instruments—noble but weak—I want both.

Both the Neue Gewandhaus and Concertgebouw took all three aspects into account. Both halls had a reduced volume, took into account echo theory, and were finished with resonating materials. The early reflection design of the Concertgebouw was not described by its architect, however, the height of the hall was constrained to 17 m and the maximum distance between stage center and back wall does not exceed 17 m, the same measure as was employed in the Neue Gewandhaus for its early reflection design. Both these halls were room acoustic successes. This seems to indicate that when all aspects of the room's response were taken into account, room acoustic success was possible for rooms with musical purposes prior to the discovery and general use of Sabine's reverberation formula.

APPENDIX: DERIVATION OF MODERN ABSORPTION COEFFICIENTS FROM STURMHOEFEL'S DATA

In the field of the history of science, specifically the history of acoustics, it is of interest to compare historical measurement methods and results with their modern equivalents. Sturmhoefel, in the course of his efforts to improve the acoustics of the Palais du Trocadero and other sites, devised a means for quantifying the acoustic properties of materials using a "Fallstäbchen," literally translated as a falling bar (see Fig. 1). He first determined that the sound of the falling bar was just audible at 115 m in the free-field (following ten repetitions). Subsequently, he observed that the reflection of a building façade covered with smoothed plaster was just audible at 47.5 m. He therefore derived a type of reflection coefficient for this material as $\xi = (47.5 \times 2)/115 = 83\%$. Employing the same

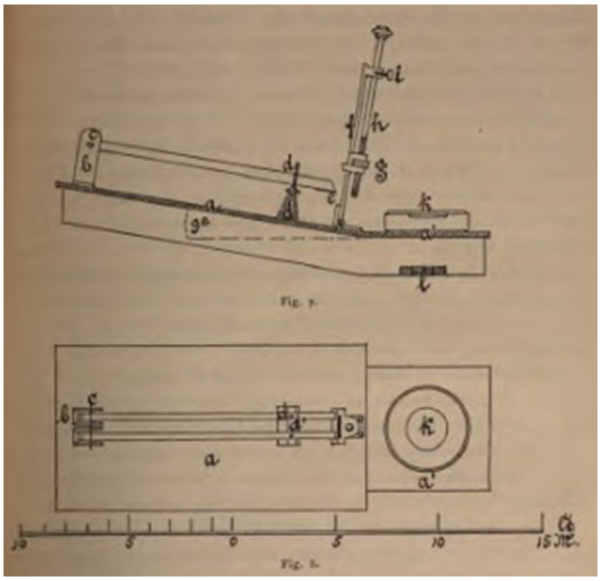

FIG. 1. (Color online) Device employed by Sturmhoefel to determine the absorption coefficients: "Fallstäbchen" or falling bar (from Sturmhoefel, 1898).

procedure, reflection coefficients of 75% for brickwork, 50% for a façade covered with bonded plaster smoothed by a trowel, and 17% for a forest edge were measured. From these few measured results, Sturmhoefel then estimated values for other materials, although the manner in which he estimated values for additional materials is not described (see Table II).

Taking the raw data of equal intensity reflection distance ratios from Sturmhoefel (1898), it is possible to derive respective absorption coefficients based on the modern definition of the term.

From the described experimental protocol, the following information is available:

$$\begin{pmatrix} I_{\mathrm{ref}}(d_0) = I'(\xi d_0) \\ \xi < 1 \\ d_0 = 115\ \mathrm{m} \end{pmatrix}, \qquad \text{(A1)}$$

where I_{ref} represents the level of the "direct sound" at the reference distance d_0, and I' is the level of the reflected sound off the tested material. Using Sturmhoefel's protocol, the distance for measuring I' is expressed in terms of d_0, and the reflection factor ξ, established as the point of equivalence of $I_{\mathrm{ref}} = I'$. One can therefore interpret $I_{\mathrm{ref}}(d_0)$ as the level of the reflected sound off an infinitely rigid surface at a distance of $d_0/2$ in the free-field.

To adapt this protocol to the modern definition of the absorption coefficient for normal incidence, it is necessary to include the measurement distance for which the levels were measured as these measurements were made in the free-field not in an impedance tube, and therefore the plane-wave assumption of propagation independent of distance cannot be made:

$$\alpha = 1 - \frac{I'(d_0)}{I_{\mathrm{ref}}(d_0)}. \qquad \text{(A2)}$$

Following Table II and the spherical propagation relation that $I \propto 1/d^2$, it is possible to determine $I'(d_0)$ and derive α as a function of ξ as follows:

$$\begin{aligned} I'(d_0) &= I'(\xi d_0)\frac{1/d_0^2}{1/(\xi d_0)^2} \\ &= I'(\xi d_0)\xi^2 \end{aligned} \qquad \text{(A3)}$$

such that

$$\begin{aligned} \alpha &= 1 - \frac{I'(\xi d_0)\xi^2}{I_{\mathrm{ref}}(d_0)} \\ &= 1 - \frac{I_{\mathrm{ref}}(d_0)\xi^2}{I_{\mathrm{ref}}(d_0)} \\ &= 1 - \xi^2. \end{aligned} \qquad \text{(A4)}$$

Equation (A4) is therefore used to determine the normal incidence absorption coefficient values presented in Table II as a function of Sturmhoefel's ξ. Potential issues identified

TABLE II. Acoustic material properties as reported by Sturmhoefel (1898) and the associated derived absorption coefficient using Eq. (A4), assuming free-field (normal incidence) conditions. Sound absorption data from modern sources is provided for comparison, taking the mean value over 250 Hz–2 kHz-octave band data. The upper four entries are Sturmhoefel's measured data, while the lower set of entries is the results of his subsequent gradings (method not described). All data are provided as percentages (%).

Material in German (English translation)	Sturmhoefel's equivalent absorption $(1-\xi)$	Derived α $(1-\xi^2)$	Modern $\bar{\alpha}$ (250 Hz–2 kHz)	Contemporary reference material
Glattgeputzte Wand (smooth plastered wall)	15–20	32	1	Glaze plaster on masonry wall (Cabrera, 2003)
Gefugte Wand (brickwork)	25	44	4	Standard brickwork (Cabrera, 2003)
Durch die Kelle glattgestrichene Rapputz (bonded plaster smoothed by a trowel)	50	75	4	Lime cement plaster on masonry wall (Cabrera, 2003)
Waldrandes (forest edge)	83	97	5	Tree with leaves (Watanabe and Yamada, 1996)
Wasserspiegel (water surface)	5	10	1	Water surface, i.e., swimming pool (Cabrera, 2003)
Polirte Stein-oder Kalkwand (polished stone or lime wall)	5	10	2	Smooth brickwork with flush pointing, painted (Cabrera, 2003)
Polirte oder lakirte Holztäfelung (polished or lacquered wood panelling)	5	10	5	Plywood mounted solidly (Cabrera, 2003)
Gestrichene Holztäfelung (painted wood panelling)	10	19	5	Plywood mounted solidly (Cabrera, 2003)
Reliefirte Wandfläche mit plattgeputztem Grunde (reliefed wall surface with flat plastered base)	35	58	17	Plaster decorative panels, ceilings (Cabrera, 2003)
Eben getretene Kiesfläche (leveled gravel surface)	50	75	20	Controlled sample of gravel (Cuenca and de Ryck, 2015)
Stippputz (stucco)	65	88	4	Stucco (Taborga, 2016)
Ausgesteifte Theaterdekorationen (stiffened theatre decorations)	70	91	17	Plaster decorative panels, ceilings (Cabrera, 2003)
Faltige Plüschdraperie (folded plush drapery)	80	96	90	Curtain fabric, folded, 15 cm from wall (Vorländer, 2008)

regarding the employed protocol are: (1) variations in atmospheric/acoustic propagation conditions during the "reference" measurement and the material measurement, which were not necessarily carried out the same day or place, (2) the normal incidence model applied to free-field conditions means that any scattering effects of the tested surface would translate into absorption, resulting in overestimation of the absorption coefficient, and (3) the limited size of the measured surface enabling acoustic energy to go around the object instead of reflecting back, resulting in overestimation of the absorption coefficient.

Estimated variances due to possible range of atmospheric conditions can be made according to ISO 9613-1 (1993) where for the upper frequency band of consideration (2 kHz), variations in humidity conditions could result in a change of intensity at 100 m on the order of 1 dB, or 12%. Other issues, such as thermal gradients and wind, could have additional effects which are difficult to estimate without further details of the measurement conditions.

Table II compares these data to current reference material absorption data (Cabrera, 2003; Cuenca and de Ryck, 2015; Taborga, 2016; Vorländer, 2008; Watanabe and Yamada, 1996) using the mean reported values in the 250 Hz–2 kHz octave bands as a standardised tapping machine when installed on a 22 mm particle board (comparable to Sturmhoefel's "falling bar") mainly produces sound in this frequency range (Wittstock and Stange-Kölling, 2011). The comparison shows that Sturmhoefel's values, in general, overestimated the absorption. Correcting for the definition of the absorption coefficient using Sturmhoefel's data (Sturmhoefel, 1898) and Table IV further overestimated the absorption coefficient values, which is probably due to the aforementioned reasons.

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