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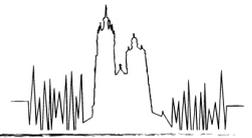


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A History of the Use of Reflections Arrival Time in Pre-Sabinian Concert Hall Design

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Summary

A theory regarding echoes which developed during the 17th, 18th, and 19th century is described. This theory stated that at a certain difference in path length or arrival time between direct and reflected sound echoes would occur. It was used in the acoustical design concept of at least one lecture hall, three theater halls, and three concert halls, constructed during the 19th and beginning of the 20th century in Germany, France, and the USA. The echo theory is most comparable to what is currently described as early reflections. It agrees with the current knowledge that reflections arriving within a certain time period of the direct sound are beneficial for the acoustics. Furthermore, in venues with speech purposes a shorter time interval was used than in venues for music purposes. However, this theory only took into account first order reflections instead of the energy and it did not consider the arrival direction of the reflections.

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1. Introduction

Before Sabine's work on reverberation and its use as a design element, basic ideas of "echo theory" attempted to quantify the perception threshold between direct and reflected sounds. Various methods to determine this threshold resulted in different outcomes. A number of conclusions from these theories on echoes were used in the architectural design of buildings intended for both speech and music. This "echo theory" most resembles recent studies on early reflections.

In a previously published paper this quantified acoustic guideline which influenced the design of three concert halls was discussed [1]. It developed from theories on echoes which were proposed during the 17th, 18th, and 19th centuries. In the current article additional literature on "echo theory" is included, new information regarding the use of "echo theory" in the three previously considered concert halls is given, and three new venues are described in which this theory on echoes was used in their design.

Section 2 presents a brief overview of a number of studies carried out concerning the relation between path length differences and the detection of echoes. Section 3 then presents examples of several constructions which used these results as an acoustic and architectural guideline. This work concludes with a dis-

cussion of modern criteria in relation to these historic works in Section 4.

2. Echo theory before the discovery of Sabine's reverberation formula

In 1620 Guiseppe Bianciani performed experiments on the occurrence of echoes [2]. He stated that the reflection consisting of the sound of exactly one syllable was perceived when the observer was located ≈ 18 m from a reflecting surface.

In 1636 Marin Mersenne carried out experiments regarding echoes as well [3]. He found that it took exactly one second to reflect the sound of seven syllables. Because he calculated with a sound speed of 157 m/s, he concluded that a reflection consisting of exactly one syllable was perceivable when the reflected sound traveled ≈ 22 m more than the direct sound.

In 1751 Jean le Rond d'Alembert stated that when a violinist played more than ten tones per second, the tones were not separately distinguishable anymore [4]. Therefore, he concluded that the human ear could not distinguish tones which followed within a very short amount of time after each other. He concluded that not all reflections were echoes because there was a minimum extra path length reflections had to travel to become separately audible from the direct sound.

In 1759 Joseph-Louis Lagrange described that the human ear can distinguish two tones when they are separated by a time period of at least 63 ms [5].

In 1778 Jean-Etienne Montucla concluded from an experiment with a violinist that the human ear could

distinguish 12 tones/s. He therefore stated that an echo was audible when the reflected sound arrived 83 ms later than the direct sound [6]. Using a sound speed of ≈ 360 m/s, he concluded an echo was observable with a path difference of more than ≈ 30 m.

In a comparable way to Montucla, Johann Gehler in 1787 determined that the human ear could distinguish 9 tones/s [7]. Using a sound speed of ≈ 350 m/s, he concluded that an echo was observable when the reflected sound had an extra path length of ≈ 39 m.

In 1800 this theory led to a guideline for architects. Johann Rhode described that through careful observations it had been established that echoes occurred when a wall was more than ≈ 19 m away from the observer [8]. He concluded that when all listeners were within 19 m of the sound source in an auditorium the shape did not influence the acoustics. When listeners were > 19 m from the sound source the architect needed to take extra measures for the acoustics.

In 1848 Gustave Schilling stated that the human ear could distinguish ten sounds of speech and song per second [9]. Therefore, he concluded that the difference in path length between direct and reflected sounds should not exceed ≈ 34 m.

In 1865 Emil Winkler stated that the average single sound lasts for approximately 125 ms [10]. In this time interval sound travels ≈ 43 m. Therefore he argued that a perfect echo occurred when the path difference between direct and reflected sound is 43 m.

In 1869 Rudolphe Radau stated that if the reflection of the first syllable reached the speaker again during the first 100 ms after it was produced it was found to enhance the sound of this syllable [11]. Because Radau built in a safety margin, he stated that to create an echo the reflection should travel an extra path length of ≈ 32 m instead of Schilling's 34 m.

Table I presents a summary of the different studies on echoes, highlighting the type of sound stimuli used. Some studies resulted in direct distances of these measures, while others were calculated from time measurements and an assumed speed of sound. Due to the large historical variations in the value of this constant, revised conversions have been included to allow for a more coherent comparison.

3. Venues in which these theories were used

3.1. Iffland Theater, Berlin (1800-1817)

In 1800 Carl Gotthard Langhans wrote about the acoustics of the Iffland Theater, of which he was the architect, referring to Gehler's theory regarding echoes [12]. He stated that in the design of the Iffland theater the maximal distance between direct and reflected sound would be 4 m because of the elliptical shape of the theater. Langhans argued that this would not cause an echo.

Despite the room-acoustical study in advance of the construction, the acoustic properties turned out to be poor. Ludwig Catel argued that echoes were perceivable and hence proposed to install cloth on the inside of the theater [13]. Carl Ferdinand Langhans, son of Carl Gotthard Langhans, tried to explain the poor acoustics of the theater [14]. As superintendent during the construction of the Iffland theater, Langhans Jr. also used Gehler's theory which stated that an echo could be perceived when the reflected sound arrived 111 ms after the direct. He added that an unpleasant prolongation of sound was experienced when the reflected sound arrived between 56 ms and 111 ms later than the direct, which he called reverberation.

Langhans Sr. did not seem to take into account the reflections from surfaces other than the walls. Therefore, Langhans Jr. studied the curved ceiling of the theater which according to him reflected sound which had an extra path length of 16 m or a delayed arrival time of 46 ms. He concluded therefore that echoes or reverberation were not the cause of the disappointing acoustics. Subsequently he turned his eye to the elliptical shape of the theater in which, according to Langhans Jr., focal points would arise. In regard to music he argued that each instrument of an orchestra, while playing near the first focal point of an elliptical auditorium, would have its own acoustical focal point near the second focal point of the elliptical-shaped theater. This would disturb ensemble playing because the sound strengths of the instruments would vary.

Furthermore, regarding the spoken word he stated that speech consists of the connection between vowels and consonants. It is important that the vowels and consonants are not perceived simultaneously. The duration in speech between a vowel and a consonant is shorter than the 56 ms, making reflections, which arrive before 56 ms, important to study. Langhans Jr. argued that due to the sound concentrations in the elliptical theater hall, the reflected sound in the focal points is almost as strong as the direct sound, making at that position the reflections of the previously spoken vowel as loud as the direct sound of the following spoken consonant, causing an unnatural merging of the two.

3.2. Lecture hall in the Smithsonian Building, Washington D.C. (1854-1865)

In 1857 Joseph Henry described his experiences during the period he was the acoustical consultant of a lecture hall in the Smithsonian Building (see Figure 1) [15]. Unlike Langhans, Henry did his own experiments on the occurrence of echoes. By clapping his hands in front of a wall of the west facade of the Smithsonian Building, he determined the distance at which the direct sound and reflected sound were not separately audible anymore. He found that the reflection was distinctly heard from the direct sound when the distance was ≈ 9 m. He called this the "limit of perceptibility".

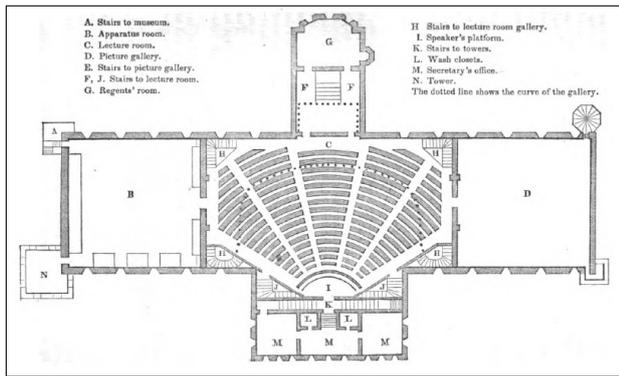


Figure 1. Map of the lecture hall in the Smithsonian Building. ([15] p.232)

Using a speed of sound of 343 m this would equate to 53 ms to distinguish between two sounds. He however concluded that it took 63 ms. Henry designed the lecture hall to have a height of 8 m which ensured that reflections from this surface reached the audience within the “limit of perceptibility”. Furthermore, he stated that the speaker’s position was between two oblique walls which were positioned within the “limit of perceptibility” of the center of the platform.

3.3. 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 [16]. In a book published about the design of both theaters the architect discussed the occurrence of echoes. According to him, the lowest frequency perceivable by the human ear was 32 Hz. He argued therefore that the shortest perceivable interval between two separate tones was $1/32$ of a second or 31 ms. Using a sound speed of 327 m/s, he argued that the reflected sound had to travel an extra path of ≈ 10 m to be heard as an echo, but then stated that this was an extreme case and in practice this limit could be raised to 15 or 20 m.

For this reason, in both designs the acoustic concept was based on the consideration that the back wall of an auditorium, and the ceiling when too high, should never be used to reflect sound back into the hall. Furthermore, the architect stated that only the wall behind the stage in an auditorium could be used for reflections because this surface is close enough to the emission point not to cause an echo.

3.4. Palais du Trocadero, Paris (1878-1934)

Even though Davioud was, together with Jules Bourdais, the architect of the Palais du Trocadero they did not use his earlier statement that echoes occurred when the path difference between direct and reflected sound was more than ≈ 10 m. To come to the acoustic concept of this concert hall they used the assumption that echoes arose when the extra path length of the

reflections was 34 m, possibly adopted from Schilling’s theory [17]. The concert hall was “horse shoe” shaped, 62 m in length and 55 m in height. Therefore, numerous surfaces were > 17 m from the center of the stage and additional measures had to be taken. The architects covered all surfaces < 17 m from the center of the stage with plaster and surfaces located > 17 m from the center of the stage were covered with painted silk.

Davioud and Bourdais realized that this measure alone was not enough to generate satisfying acoustics. Therefore, they placed 100 reflectors on the back wall of the stage. Each reflector directed towards a different $1/100^{\text{th}}$ of the audience. This was tested with an optical acoustic scale model. The outcome of the first test was that the sound would be evenly distributed over the concert hall. These result however did not satisfy the architects as they thought the most remote parts in the hall needed more reflections. Therefore, the reflectors of the back wall were realigned and the test was repeated. Both architects were satisfied with the results of a second scale model test. Despite this acoustic study, the acoustic properties of the Palais du Trocadero turned out to be poor.

Between 1903 and 1911, under the leadership of Gustave Lyon, an attempt was made to improve the acoustics. He suspected that echoes were the basis of the acoustical difficulties. He based his search for reflecting surfaces causing echoes on the difference of path lengths between the direct and reflected sound [18]. When this differed by:

- 0–8.50 m: The sound was warm, colored, and enveloping. These reflections were necessary reinforcement for good listening conditions. Sounds arrive with a maximum delay of 25 ms.
- 8.50–11.33 m: These reflections are useful reinforcement. The maximum delay is 33 ms.
- 11.33–17 m: These reflections are tolerable. The maximum delay is 50 ms.
- 17–23 m: These reflections are the cause of resonance and this is the area where it becomes troublesome. The maximum delay is 63 ms.
- 23–34 m: These reflections caused echoes and made listening impossible. The maximum delay is 100 ms.

With these starting points, Lyon looked for the surfaces which caused the echoes. He divided the stage into 2×2 m sectors from which he made a sound by clapping two pieces of wood together [19]. When auditors, positioned in various seats of the concert hall, heard an echo they raised their hand. Lyon determined, from the results of the experiments and the above five statements about the perception of echoes, in a mathematical way the reflecting elements which caused the echoes, as depicted in Figure 2.

To check his theoretical findings, Lyon constructed a device comprising a sound box with two long metal tubes connected to the box via rubber hoses as depicted in Figure 3. A sound was created in the box

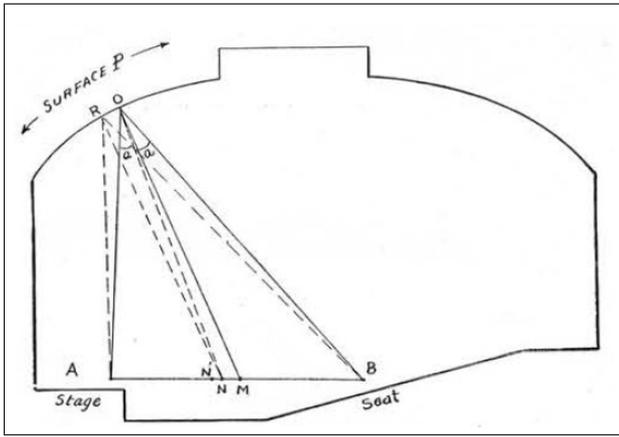


Figure 2. Position of the reflecting surface causing the echo. ([19] p.462)

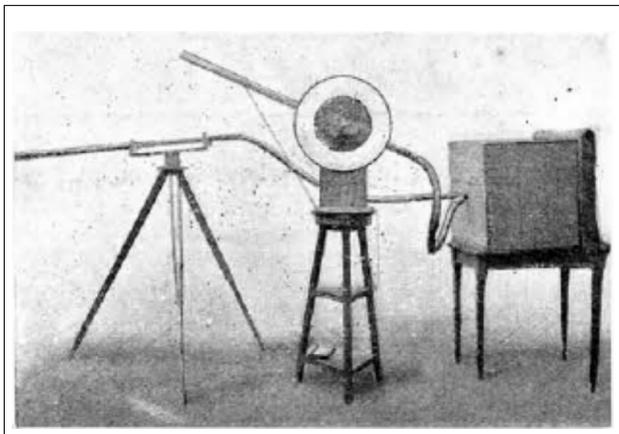


Figure 3. First device to prove the position of the reflecting surface causing the echo. ([19] p.462)

which was “aimed” via one of the metal tubes at a surface which supposedly caused the echo and the other metal tube was directly pointed at the position where the echo was supposed to be audible. When the sound was heard double at the test position Lyon concluded that the considered surface was responsible for the echo. To demonstrate this in a more striking manner Lyon devised a second larger apparatus. From his calculations and experiments Lyon concluded that 90% of the echoes were caused by the concave ceiling above the organ, surface *P* in Figure 2. To suppress the reflections Lyon covered this surface with a double layer of cloth with a few inches air space in between.

3.5. Neue Gewandhaus, Leipzig (1884-1944)

Architects Martin Gropius and Heino Schmieden of the Neue Gewandhaus paid special attention to the acoustics of the concert hall. “Echo theory” was adopted from the Palais du Trocadero. In an article published after construction, Schmieden stated that an echo was perceived when reflected sound arrived 83 ms later than the direct sound [20]. The architects realized that to avoid echoes in the rectangu-

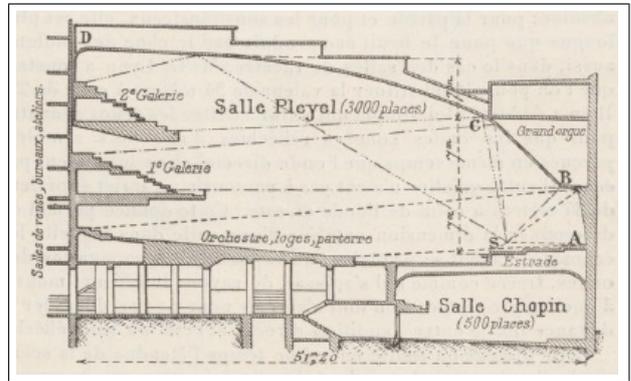


Figure 4. Longitudinal section of the Salle Pleyel. ([21] p.424)

lar form of the Neue Gewandhaus different measures had to be taken than in the round Palais du Trocadero. They decided to breach the wall opposite the stage where possible with columns and cover it with rough cloth. Furthermore, at this wall the openings of the lodges were equipped with thick curtains. To avoid flutter echoes between the parallel side walls, these were breached with columns which divided these walls into seven zones. These zones were covered with tapestry-like paintings.

3.6. Salle Pleyel, Paris (1927)

Gustave Lyon was involved in the acoustic design of another Parisian concert hall, the Salle Pleyel [21]. Before he began, Lyon undertook several acoustical experiments. He tested how far his voice reached in a wide open field covered with snow arriving at a distance of ≈ 11 m. Because the same voice carried for 2400 m over the lake of Annecy, Lyon regarded the action of reflectors as essential. To establish when echoes occur, Lyon undertook a second experiment. High in the mountains, two assistants simultaneously hit the ice with their ice axes at various distances. Lyon perceived the sound together unless the distance between both assistants was > 22 m. Therefore, he concluded that reflected sound arriving > 63 ms after the direct sound is perceived as an echo. Furthermore, he stated that this time difference was not the same for every sound, being longer for speech and music.

Lyon chose for the Salle Pleyel a shape and proportions to avoid echoes by ensuring that at every position the difference in path lengths between direct and reflected sound was ≤ 22 m. The concert hall was fan shaped with a maximum height of 20 m. The width of the stage was 20 m at the back and 21.5 m at the front. Furthermore, Lyon divided the hall into three stacked horizontal zones. For these zones the side walls were inwardly inclined to act as reflectors. The wall behind the orchestra possessed three different inclinations for the same purpose, as shown in Figure 4.

3.7. Summary

The relevant studies in this section are also included in the summary Table I. It shows that except for Biancani, acousticians who performed experiments using a speech syllable or musical impulses measured a time interval and then calculated the distance for which an echo would occur, while acousticians performing experiments using impulse stimulus determined the distance and then calculated the corresponding time interval. The average minimum time interval (sound speed corrected) for a perceived echo was 112 ms for a syllable, 98 ms for a musical tone, and 60 ms for an impulse stimulus.

4. Current findings regarding early reflections

The described works can be compared to the contemporary use of early reflections. The development of the parameters Definition, Clarity, Initial Time Delay Gap, and Center Time in the second half of the 20th century indicate the importance of designing with early reflections. Furthermore, it has been found that the time interval when early reflections are considered beneficial for the acoustics differs between speech and music. In this respect, Thiele in 1953 concluded that reflected sound was detrimental for speech when it arrived > 50 ms later than the direct sound [22]. In 1975, Reichardt et al. found that beneficial reflections for music arrive within 80 ms of the direct sound [23].

More recently, Jurkiewicz et al. in 2012 have stated that the acoustic success of a concert hall is possibly more dependent on early reflections than on reverberation [24]. This study proposed a formula to calculate early energy termed mean early strength (G_{em}) which is influenced by the surface area of the audience (s_{aud}), the total efficient solid angle (Ω_{eff}), and the average angle of incidence of early reflections on the audience (Ω_m). According to this formula a larger audience area results in a lower G_{em} . The Ω_{eff} , which is the solid angle of all efficient surfaces measured from the omni-directional sound source, can only be increased to a certain degree. The authors stress the importance of Ω_m . To create higher G_{em} in very large rooms, early reflections should arrive from surfaces positioned low in the room. Therefore, the authors conclude that reflectors with more visibility from the stage have a larger positive effect on G_{em} . However, they realize that increasing the solid angle to very large values increases the risk of excessive loudness. Furthermore, they state that the design should allow enough energy to remain for the late reverberant field.

5. Discussion & Conclusion

During the 17th, 18th, and 19th centuries a number of studies were carried out to determine the threshold

when an echo was heard. These studies either directly determined the distance at which an echo was audible, used a certain number of tones per second which were separately audible, or determined the time it took to reflect the sound consisting of exactly one syllable. The selected method influenced the determined time interval or propagation path distance difference for which an echo was audible. In contrast to our current understanding, early acousticians determined a shorter time interval for musical stimuli than for a speech syllable stimulus. However, modern values are related to impressions of clarity and intelligibility, and not directly to single echo perception. As expected, acousticians who used an impulsive stimuli obtained shorter values.

These theories on echoes were used as quantified acoustical and architectural guidelines in at least seven venues with both speaking and musical purposes. The architects of these venues were correct in assuming that reflections that arrived shortly after the direct sound are beneficial for the perception of music and speech. However, the architects probably did not base the decision of the employed time interval on the stimulus which was used during the experiment. For the venues with speaking purposes, “echo theories” were used which were based on a musical stimulus, impulse stimulus, or on a theory without reference to a stimulus (Iffland Theater = a fast playing violin, the lecture hall in the Smithsonian building = clapping of hands, and the theaters at the Place du Châtelet = theory without a stated stimulus), while the venues with musical purposes were based on an impulse or syllable stimulus (The Palace du Trocadero and the Neue Gewandhaus = syllable stimulus, and the Salle Pleyel = hitting axes on ice).

Nevertheless, it should be noted that the time intervals adopted for venues with musical purposes (Palais du Trocadero = 100 ms, Neue Gewandhaus = 83 ms, and Salle Pleyel = 67 ms) were significantly longer than those used in venues with speech purposes (Iffland Theater = 46 ms, lecture hall in the Smithsonian Building = 53 ms, and the theaters at the Place du Châtelet = 31 ms), which is in agreement with current knowledge. It can be observed that average time intervals used in venues with musical purposes (83 ms) and venues with speech purposes (40 ms) greatly resemble the currently used delimiting values of 80 ms for music and 50 ms for speech in the Clarity and Definition parameters. This is notable considering the limited measuring equipment available to 19th century acousticians.

When these historical findings are compared to parameters such as Clarity, Definition, Initial Time Delay Gap, and Center Time, the early applications of echo theory only take into account first order reflections while current parameters take the early acoustical energy into account. Furthermore, recent studies, such as Jurkiewicz, propose to take into account the

Table I. Time interval and distance of first reflection resulting in the perception of an echo in historical studies. Values in [-] determined from measured values in associated publications. Values indicated by † determined from statements on how many tones/s were separately audible. Revised values are provided using a common sound speed for comparison.

stimulus	Publication (year)	reported time interval (ms)	reported distance (m)	assumed speed of sound (m/s)	Recalculated values using a sound speed of 343 m/s	
					time interval (ms)	distance (m)
Syllable	Biancani (1620) [2]		36		105	36
	Mersenne (1636) [3]	142†	[22]	157	142	49
	Schilling (1848) [9]	100	[34]	340	100	34
	Radau (1869) [11]	100	[32]	340	100	34
Musical	d'Alembert (1751) [4]	100†			100	34
	Montucla (1778) [6]	83	[30]	360	83	28
	Gehler (1787) [7]	111	[39]	350	111	38
Impulse	Henry (1857) [15]	[63]	18	343	53	18
	Lyon (1909) [18]	[67]	22	340	67	22
no stated stimulus	Lagrange (1759) [5]	67†			67	23
	Davioud (1862) [16]	31	[10]	327	31	11
	Winkler (1865) [10]	125	[43]	343	125	43

arrival direction of the reflections and the energy distribution over the room.

6. Acknowledgments

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