




An archaeoacoustic study on shape: the case study of the Iffland Theatre's history (1802–1817)

Barteld N.J. Postma^{1,*} and Brian F.G. Katz² 

¹ dieBauingenieure - Bauphysik GmbH, Karlsruhe, 76185 Deutschland, Germany

² Sorbonne Universite, CNRS, Institut Jean Le Rond d'Alembert, 75005 Paris, France

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Abstract – Previous studies have discussed six pre-Sabine quantifiable guidelines employed in room acoustic design: voice directivity, audience rake, “echo theory”, stage acoustics, reverberation, and length, width, and height ratios. Around the turn of the 18th century, these notions led to two shapes that were theoretically regarded optimal for rooms with acoustical demands: ellipse and semi-circle. The first of these shapes to be tested was the ellipse in the design for the Iffland Theatre (1802–1817). As the resulting acoustics were notoriously poor, contemporary architects and acousticians discussed the grounds for the failed acoustics as well as possible corrections. Multiple subsequent halls were also based on lessons learned from this acoustic failure. As part of this archaeoacoustics research, geometric acoustic numerical simulations were employed to estimate the actual and renovated room acoustic conditions. Three configurations of the hall have been reconstructed. Results show that the hall's shape led to sound focusing and that the rounded proscenium arch likely induced echoes. Proposed solutions of the time to increase the scattering or absorption appear unlikely to have solved the observed acoustic problems.

Keywords: Archaeoacoustics, Room Acoustics, Theatre acoustics, Geometrical acoustics

1 Introduction

In 1898, Wallace Clement Sabine introduced a reverberation time formula, which marked the beginning of objective and quantifiable principles in architectural acoustics design [1]. Sabine's work laid the groundwork for the development of architectural room acoustics as a scientific field. Nevertheless, there are several concert halls renowned for their exceptional acoustics, such as the Wiener Musikvereinsaal (1870) and the Amsterdam Concertgebouw (1888), that were constructed before Sabine's contributions [2]. Therefore, investigating acoustical design practices from the preSabine era is of interest when studying historical room acoustics.

1.1 Late 18th century room acoustic theories on shape

Our previous studies described six pre-Sabine quantifiable notions that were employed in the design of rooms with high acoustic demands during the 18th and 19th centuries:

- *Voice directivity*: Acoustic experimentation was used to determine how far sound was perceivable around a speaking person, to the front, sides, and rear. Results were

employed in the acoustical design of at least 11 19th-century rooms with acoustic demands [3].

- *Audience rake*: Based on the theories of Russell (1839) and Lachez (1848), at least eight 19th-century rooms throughout the UK and USA had a curvilinear audience rake. The methodologies for calculating optimum sightlines and soundlines from a source on stage to throughout the audience are still used in contemporary auditorium design [4–6].
- *“Echo theory”*: Quantifying the perception threshold between direct sound and first-order reflections to prevent echoes aided in the design of at least seven 19th-century rooms [7, 8].
- *Stage acoustics*: Referred to various acoustical effects linked to stage acoustics and room geometry near the stage, 19th-century acousticians regarded room acoustic aspects like self-perception, perception of others, sound projection from stage to the audience, and the amplifying influence of early reflections [4].
- *Reverberation*: Notions of reverberation influenced the design of at least 14 rooms before Sabine quantified his reverberation formula [4].
- *Length, width, height ratio*: The length, width, and height ratio in multiple 19th-century rooms was a common multiple. This was based on the assumption that a desirable “note” would occur, supporting sound transmission [9].

*Corresponding author: b.postma@dieBauingenieure.com

Table 1. Shapes of existing theatres as described by [10] and [12].

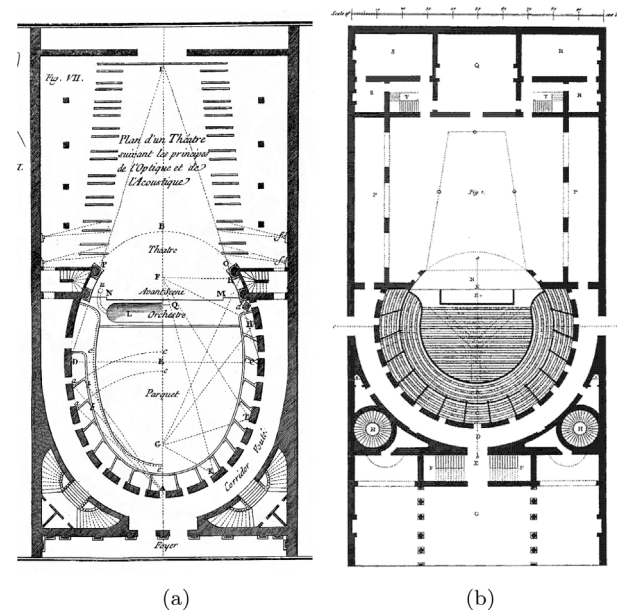
Name	Shape	indoor/ outdoor	Opening year	Mentioned by
Theatre of Hercules, Naples	Semicircle	Outdoor	–	[10]
Theatre of Bacchus, Athens	Semicircle	Outdoor		[12]
Theatre of Marcellus, Rome	Semicircle	Outdoor		[12]
Theatre, Pompeii	Semicircle	Outdoor		[12]
Theater, Montpellier	Semicircle whose sides are	Indoor	–	[10]
Theatre, Brest	Prolonged outwards semicircle whose sides are prolonged	Indoor		[10]
Olympic Theatre, Vicenza	Semi-oval placed length-wise towards stage	Indoor	1580	[10, 12]
Theatre, Parma	Oblong, rounded of at the end	Indoor	1618	[10, 12]
Late Opera house, London	Oblong, rounded of at the end	Indoor	1706	[10, 12]
Theater of Argentina, Rome	Semicircle whose sides are prolonged	Indoor	1732	[10, 12]
Covent Garden theatre, London	Oblong	Indoor	1732	[10, 12]
Theatre at San Carlo, Naples	Semicircle whose sides are prolonged	Indoor	1737	[10, 12]
Teatro Regio, Turin	Oval cut off at one end	Indoor	1740	[10, 12]
Theatre, Nancy	Semicircle whose sides are prolonged	Indoor	ca. 1755	[10]
San Benedetto, Venice	Bottle-shaped	Indoor	1755	[12]
Theatre, Lyon	horseshoe	Indoor	1756	[10]
Theatre, Bologna	Semicircle whose sides are prolonged	Indoor	1763	[12]
Theatre of Tordinon, Rome	Horseshoe	Indoor	1765	[10]
Opera, Paris	Horseshoe	Indoor	1770	[10]
Opera, Versailles	Horseshoe	Indoor	1770	[10]
Royal theater, Madrid	Semicircle whose sides are prolonged	Indoor	1770	[10]
La Scala, Milan	Horseshoe	Indoor	1776	[12]
Theatre, Imola	2/3 of an oval	Indoor	1780	[12]
Grand Théâtre, Bordeaux	Circle, one fifth cut of	Indoor	1780	[12]
Theatre de la Nation, Paris	Through stage horseshoe	Indoor	1782	[12]
Theatre Italien, Paris	Three fourth of an oval	Indoor	1783	[12]

These notions influenced, among others, 18th century ideas on the ideal shape for spaces with acoustical demands. For instance, [10] described several contemporary theatres (see Tab. 1) and a “concept theatre”. Although no treatise on the theory that Gabriel-Martin Dumont based his design on is included, the concept theatre was of an elliptical shape, evident from the form of the back walls of the rows of boxes, as well as in the parapets of the boxes and the curvature of the ceiling.

In 1782, Pierre Patte [11] stated that a moderate human voice in indoor conditions can be perceived up to 72 ft¹ (22.6 m) away. 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 notions, Patte conceived an elliptical theatre with a 72 ft (22.6 m) major axis (see Fig. 1a), with the end of this ellipse cut off at one-fourth of the diameter to accommodate the stage.

In 1790, George Saunders [12] described an experiment on the human voice which observed that a person reading from a book was distinctly audible in still, open air at a maximum distance of 92 ft (28.8 m) in front, 75 ft (23.6 m) on each side, and 31 ft (9.7 m) behind the reader. An additional observation was that the voice was distinctly audible in a

¹ Distances are presented in the Prussian feet (1 ft = 0.314 m) instead of metric units as all referred publications employed this unit.

**Figure 1.** Concept theatre study drawings. (a) From [11], (b) from [12].

semi-circle along which the human voice was heard equally well. Saunders conceived a “concept theatre” according to the guideline stated in his book (see Fig. 1b). The plan was shaped according to the voice data; a semi-circle with

prolonged ends. However, the dimensions were scaled down; the width was 60 ft (18.8 m) and the distance between the stage floor and the opposite central box was 45 ft (14.1 m). Therefore, the radius of the circle was 30 ft (9.4 m) with 15 ft (4.7 m) between the centre point and the stage, leaving 2 ft (0.6 m) 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.

As Dumont did, Saunders also described 17 contemporary theatres giving an idea of what was common practice regarding the shape of rooms with acoustic requirements (see Tab. 1). From the shape of these rooms, one could cautiously conclude that the original semicircle shape, employed in Greek and Roman amphitheatres, gradually evolved by prolonging its sides towards the “horseshoe” shape.

The previous paragraphs summarized the state-of-the-art at the turn of the 19th century. The main shape in contemporary theatres was the “horseshoe” even though the theoretical approaches opted for either an ellipse or semi-circular form. The first theatre to follow one of these theoretically preferred forms was the elliptically shaped Iffland Theatre (1802–1817) [13]. Its architect was Carl Gotthard Langhans, from here on referred to as Langhans Sr. To the authors’ best knowledge, the room acoustic concept of the Iffland Theatre is one of the first in history to be detailed by its architects. The theatre’s room acoustic concept employed voice directivity, “echo theory”, reverberation, and stage acoustics in order to come to the theatre’s shape that was mainly based on Patte’s concept theatre. Despite the use of these room acoustic theories, the acoustics were notoriously poor, being the object of discussion among contemporary acousticians. Additionally, observations from the room were employed in the Karlsruher Hoftheater [14]. This room was designed to have a semi-circular shape, as proposed by Saunders. Finally, it is well possible that the architect of the Königliches Schauspielhaus (precursor of the Konzerthaus Berlin) also regarded the failed shape in order to come to a rectangular shape.

In the interest of improving our understanding of the acoustics of this important point in design evolution, numerical simulations of the Iffland Theatre’s room acoustics and proposed solutions were carried out in order to enhance our understanding of preSabine acoustic evolution.

1.2 Historic room model calibration

To achieve a plausible acoustic reconstruction of the Iffland Theatre, it is imperative to create and, notably, calibrate a model [15]. Although geometrical acoustics (GA) software is commonly used for numerically computing room acoustics in complex geometries, not all GA software can faithfully simulate intricate acoustic conditions and fine details, especially when highly diffuse conditions cannot be assumed. Conversely, wave-based methods are computationally demanding, necessitating intricate geometrical

models and complex input data [16], while also demonstrating limitations in accurately simulating late reverberation in intricate spaces [17].

When the building under study is still extant, the ideal approach for calibration involves conducting measurements, creating a room acoustic model accordingly, and adjusting the model to represent historical configurations across various acoustic parameters [18–21]. However, alternative calibration approaches must be employed when the building no longer exists. In the best-case scenario, archived recorded Room Impulse Responses (RIRs) are available. For example, the study of the Fogg Art Museum used such RIRs, where Wallace C. Sabine performed his first reverberation tests, resulting in an acoustically accurate historic GA room model [22]. Calibration was carried out based on balloon measurements in a later configuration of the hall before its demolition in 1973. Subsequently, the model was reverted to the state in which Sabine conducted his tests. Observations in different modelled conditions were consistent with documented critiques regarding speech intelligibility.

A step removed from direct measurements is the use of previously reported room acoustic parameters, limited by potential differences in analysis methods and various unknowns in measurement protocols. For instance, in a study of two historic Leiziger Gewandhaus concert halls, Weinzierl et al. [23] performed virtual reconstruction, calibrating one of the models based on reverberation time measurements conducted in 1933. Similarly, model calibration in the context of an archeoacoustic study of the Palais du Trocadero (1878–1937) [24] was based on published data from 1906. These historical measurements were conducted in unoccupied and occupied conditions, utilising an unconventional sound source called an “artificial mouth”, which employed an air source, rotating perforated wheel, and mouth resonator, with specific wheel and resonator settings for each vowel. The GA model was created and calibrated for both occupied and unoccupied conditions, with calibration efforts focused on the main absorbing surface, “stuffed cloth”, which covered the audience area walls and the audience.

Further removed from data-based calibration methods is reliance on alternate historical documents, introducing more possibilities of interpretation, bias, and errors for modern research. Consequently, such GA models can be challenging to consider as “calibrated” in a strict sense; instead, they are historically informed (comparable to historically informed performance (HIP) in musicology). While they may not provide detailed absolute results, they are well-suited for investigating variations around a reference model. For example, Vissilantonopoulos and Mourjopoulos [25] presented historic auralizations of lost spaces, aiming to simulate acoustic characteristics described in the literature. The models were based on architectural drawings found in archaeological and other records, with no additional calibration carried out. In the case of the Acheron Necromancy, a purpose-built temple where rituals requiring high speech intelligibility occurred, they hypothesised that it had “dry” acoustics to ensure good speech intelligibility across receiver

positions. In contrast, the Olympia echo hall, famous for its seven-times repeating echo, was shown to provide sufficient speech intelligibility only for listeners positioned within 5 m of the speaker. Additionally, [26, 27] created auralizations of lost theatres in Finland, using GA models based on surviving building plans, with absorption coefficients selected through visual inspection of surviving photos and scattering coefficients attributed according to [28]. They conducted a “perceptual calibration” of the resulting auralizations based on descriptive observations in historical sources, such as newspapers.

In cases where the building no longer exists and no acoustic parameter results are available, calibration is based solely on present materials or descriptive observations. Realistic doubt may arise regarding such results, given potential variations in material properties due to construction/installation variances. Additionally, the behaviour of GA tools concerning scattering and late energy propagation may introduce uncertainties in results not calibrated according to a range of metrics. In such scenarios with limited reference data, employing variant studies rather than absolute predictions is more appropriate, offering a higher probability of meaningful results.

In the present study, no acoustical parameters were available for the calibration of the GA model. Therefore, a broader approximate “calibration” was employed, relying on informed estimations for reasonable ranges of values for different material acoustic properties. The focus was on relative differences between model configurations rather than absolute acoustic parameter results. Furthermore, the study concentrated on the early response (0 ms to 250 ms) rather than the later reverberant part of the room’s acoustic response. To carry out the simulation study, the following approach was employed:

- The geometrical model was created based on available information.
- Materials employed were identified through archival research.
- Relevant absorption coefficients for the identified materials were collected from various databases. Variations across sources for comparable materials were used to define reasonable value ranges. Simulations were performed for conditions according to both the maximum and minimum absorption coefficients (in line with suggestions by [29]).

When acoustic anomalies such as sound concentrations/focusing or echoes were observable in the two extreme simulation conditions, it is reasonable to infer that such anomalies would have also occurred in the actual hall.

2 The Iffland Theatre

2.1 The building’s history

At the suggestion of August Wilhelm Iffland, Frederick William III commissioned a new theatre on the Gendarmenmarkt, Berlin, in 1800, which opened in 1802 [30]. The room was to be used for concerts, opera, theatre plays, as well as

royal festivities. Frederick William III refused to organise a design competition as he wanted to speed up the theatre’s completion. Instead, he personally named Langhans Sr., who was the Brandenburg Gate’s architect. The theatre hall obtained a notorious reputation for its faulty acoustics. On 29 July 1817, the theatre burned down during rehearsals for Schiller’s “die Rauber”.

2.2 The room’s design

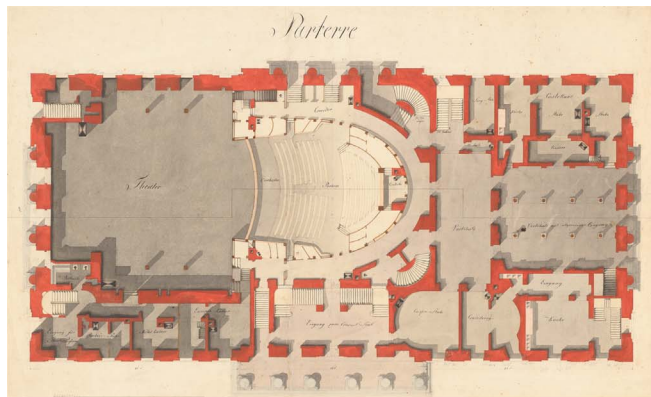
Figure 2 shows a plan and longitudinal section drawings of the Iffland Theatre as well as study documents by Carl Ferdinand Langhans, son of Langhans Sr., from here on referred to as Langhans Jr., who was supervisor during the Iffland Theatre’s construction. The following observations were made:

- Due to the introduction of the powerful Argand lamps, stage sizes could be severely increased, as was the case in the Iffland Theatre.
- The loge fronts a , as well as the back walls b , were constructed in an elliptical form (see Fig. 2c) in which focal point c was where the performers typically spoke and focal point d was in the Parterre.
- The proscenium arch consisted of two levels, of which the forward was rounded off (see surface h in Figs. 2c and 2d).
- The audience wall on the first floor was covered with curtains.

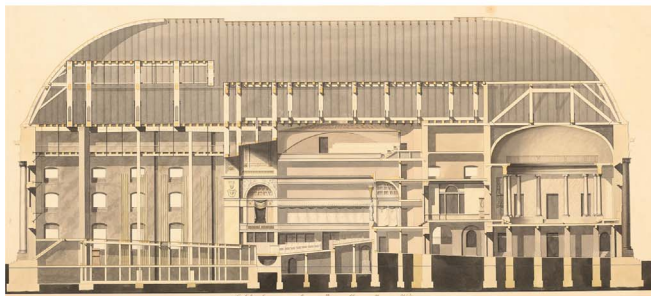
2.3 Room acoustic design concept

In 1800, Langhans Sr. wrote about the acoustics of the Iffland Theatre that he was designing [32]. From the concept, three main subjects can be distinguished: 1) shape, 2) “echo theory”, and 3) stage acoustics:

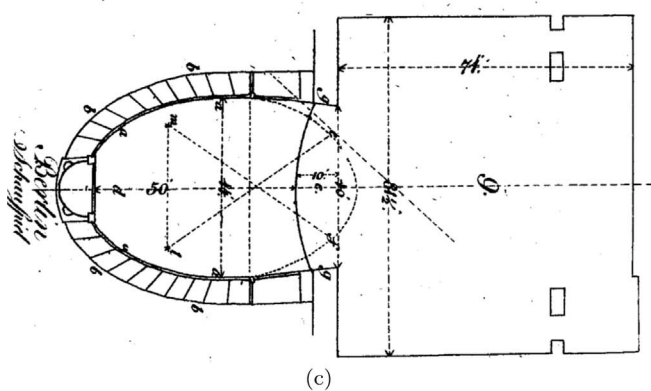
1. The elliptical theatre’s shape was based on Patte’s theories [11] regarding limiting the stage opening width and historical voice directivity experiments. Langhans Sr. stated that since the stage opening determines the diameter of the circular line, one must still try to gain as much space as possible, naturally resulting in an ellipse. Additionally, he concluded that the maximum distance between the front of the stage and the loge seating at the rear of the theatre should not exceed 50 ft (15.7 m), which was the minimum of the natural audibility of the human voice of 70–75 ft (22.0 m to 23.6 m) [12] and the maximum distance the facial expressions of the actors can still be seen of 50 ft (15.7 m). In the final design, this distance was 53 ft (16.6 m), for which one could hypothesise that this excess was due to the slight difference in *ft* standards between countries at the same period (see e.g. [3]).
2. Langhans Sr. also employed “echo theory” in his room acoustic concept. He stated that the reflections which arrived within 0.11 s (based on [33]) of the direct sound were beneficial for the acoustic experience, and reflections arriving beyond this time limit were detrimental. He stated that in the Iffland Theatre’s design, the



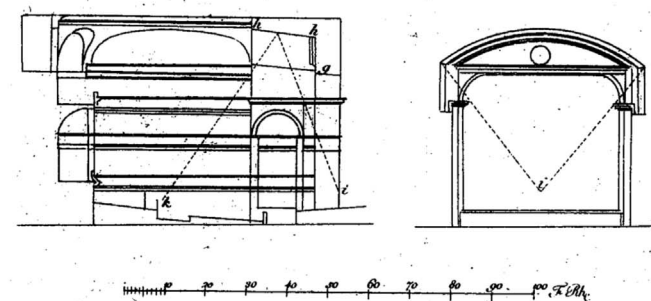
(a)



(b)



(c)



(d)

Figure 2. Iffland Theater (a) plan and (b) section drawings [31], note: additional plans available]. Langhans Jr.'s (c) plan and (d) section support drawings for his explanation of the theatre's room acoustics [13].

maximal time difference between direct and reflected sound would be 50–60 ms because of the elliptical shape of the theatre. This would prevent the occurrence of echoes.

3. Additionally, Langhans Sr. was the first architect to consider stage acoustics. He stated that the size of a theatre depends primarily on the stage opening width. He looked at other theatres in Europe and found that in Paris, London, and throughout Italy, no stage opening widths were more than 40 to 43 ft (12.6 m to 13.5 m), aside from St. Carlos in Naples which was 48 ft (15.1 m), according to Langhans Sr. However, he ignored this theatre as it was merely an opera house and designed a stage opening of approximately 40 ft (12.6 m).

2.4 Reactions to the room acoustics

Despite the above-described acoustic study prior to construction, the resulting acoustic properties turned out to be poor. Various reactions to the acoustics were uncovered during this research. Already during the construction, concerns were raised regarding the room acoustics. Johann Gottlieb Rhode, who had just finished his book on room acoustics [34], warned minister von der Schulenburg of a long reverberation and bad intelligibility [30].

After completion, Ludwig Catel (1776–1819, architect) found the large stage size of the Iffland Theatre acoustically problematic [35]. Furthermore, he argued that echoes were perceivable and hence proposed to install cloth on the inside of the Iffland theatre. Additionally, he generally recommended constructing semi-circular theatres as it prevented sound focusing from occurring and provided the optimal voice coverage over the space.

In reaction to the acoustic failure of the Iffland Theatre, Friedrich Weinbrenner designed a semicircle room, according to Saunders [12] and Catel [35], with a diameter of 100 ft (31.4 m) in order to have the optimal voice coverage over the space. Weinbrenner's Hoftheater in Karlsruhe opened in 1809 [14]. Weinbrenner attempted to find a compromise between Langhans and Catel; he stated:

... the Karlsruhe Theatre, with a much larger inner auditorium space than that of the Berlin Theatre, has received the great advantage that even a pistol shot does not cause the slightest reverberation there, solely due to its construction and careful attention to every detail that can increase and reflect the vibration of the sound. Nevertheless, even the most moderate sound is increased at any place of the auditorium ([14], p. 9).

Langhans Jr. performed acoustic experiments and extensively explained the theatre's acoustics [13]. Firstly, he studied the effect of the rounded proscenium arch. According to him, this curvature reflected the actor on stage's sound to the parterre's listener, as if the actor spoke with

a megaphone. This was not perceived as reverberation or an echo but as an amplification of the sound. In order to confirm this effect, Langhans Jr. had the rounded proscenium arch covered with canvas and paper to alter its round shape. The effect was that the reflection under study disappeared.

Subsequently, he turned his attention to the theatre's elliptical shape for which focal points were assumed to arise. Regarding 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 theatre (see Fig. 2c). This would disturb ensemble playing because the sound strengths of the instruments would vary. Regarding the spoken word, he stated that speech is comprised of the connection between vowels and consonants. It is essential that these vowels and consonants are not received overlapping, with the duration in speech between a vowel and a consonant being less than 56 ms, making reflections arriving within the first 56 ms important for study, an obvious similarity to the temporal parameters of the current C_{50} speech clarity metric. Langhans Jr. argued that due to sound concentration/focusing in the elliptical theatre hall, the reflected sound in the focal points is almost as strong as the direct sound, making the reflections of the previously spoken vowel at those positions as loud as the direct sound of the following spoken consonant, resulting in an unnatural merging of the two. For these reasons, Langhans Jr. rejected Patte's concept theatre design (Fig. 1a) that was the basis for the Iffland Theatre.

In order to prevent sound focusing from occurring, Langhans Jr. also disapproved of Catel's proposal to cover all surfaces with absorbing materials as "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...." According to Langhans, the solution must be sought in convex surfaces and straight walls.

In 1821, the successor concert hall/theatre Schauspielhaus opened its doors. The architect, Karl Friedrich Schinkel, has to the authors' best knowledge, never described his acoustic concept. However, it should be noted that Langhans Sr. schooled both Schinkel as well as Langhans Jr. in architecture. Additionally, Schinkel also produced one of the plans for the Iffland Theatre [30]. It is well possible that the acoustic failure and Langhans Jr.'s book influenced Schinkel in his choice of a rectangular hall.

From these historical observations, the following goals were established for the current study:

1. Propose a GA model to study the acoustic situations of the Iffland Theatre.
2. Identify potential acoustic problems from a current design perceptive.
3. Identify where Langhans Sr.'s room acoustic concept failed and where it succeeded.
4. Examine whether Langhans Jr.'s explanation that the failed acoustics were due to sound focusing is plausible.
5. Examine whether Catel's proposition to cover all surfaces with sound-absorbing materials would have resolved the identified acoustic problems.

6. Examine if Langhans Jr.'s proposition to apply sound scattering generously would have resolved the acoustic problems.

In order to accomplish these goals, three configurations of the room acoustic model were created:

Iff_{orig}	The theatre as it was constructed, as reference.
Iff_{abs}	The reference model with the audience walls and loge fronts covered with curtains.
Iff_{scatt}	The reference model with increased scattering coefficients for all surfaces except the audience.

3 GA model creation and simulation properties

GA model creation and calibration were performed using CATT-Acoustic (v.9.1.g, TUCT v2), a software package previously shown to be capable of creating accurate and realistic room acoustic simulations, both via objective and perceptual analysis [36]. The geometry of the Iffland Theatre model was determined from available architectural plans and sections. The model comprised 1440 polygons with a volume of $\approx 9500 \text{ m}^3$. Regarding calculation parameters, simulations were made using *algorithm 2* (longer calculation, detailed auralization), 2×10^5 rays, and an impulse response length of 4 s for parameter maps and impulse response calculations. For the initial model, one source position was positioned at the centre of the stage. As sound focusing and echoes were most likely to occur in the parterre, parameter mapping was limited to this region, with an additional 13 receiver positions distributed over the parterre audience for detailed RIR analysis.

3.1 Sound Absorption coefficients

In order to obtain plausible acoustic conditions, careful consideration was given to the material selection and calibration procedure. The books by the two Langhanses [32, 13], as well as the original plans and sections (see Fig. 2), were reviewed for information concerning materials. Subsequently, the attribution of absorption coefficients was based on generally published data sources [37–39]. The variation across data for comparable materials aided in defining a reasonable range of values for which simulations were made using the extent of likely absorption coefficients. Information on specific materials is provided below, with a summary of attributed acoustic material properties given in Table 2.

- *Panel:* The proscenium arch g (see Fig. 2c) was constructed from smooth thin board paneling [13].
- *Walls and ceiling in loges:* The material employed for these surfaces was assumed to be plaster on lathe as the plans seem to indicate this and as it appears to be a contemporary material of choice [9].
- *Audience:* The section (see Fig. 2b) showed that the chairs were either not, or only lightly, upholstered.
- *Floor:* Sections show that the floor was boards positioned on joists; therefore, similar materials were considered for the associated absorption coefficients.

Table 2. Absorption coefficients, $char_{depth}$ (mm) as the single value using equation (1), and associated surface area (m^2) in the calibrated GA model. † have defined scattering coefficients of [30%, 40%, 50%, 60%, 70%, 80%].

		125	250	500	1000	2000	4000	$char_{depth}$	Area
Walls, Ceiling	Min.	0.14	0.05	0.04	0.03	0.03	0.02	20	1688
	Max.	0.42	0.25	0.22	0.15	0.10	0.08	20	1688
Audience	Min.	0.32	0.48	0.66	0.73	0.77	0.74	†	1228
	Max.	0.72	0.82	0.91	0.96	0.94	0.90	†	1228
Floor	Min.	0.10	0.07	0.06	0.06	0.06	0.06	20	1092
	Max.	0.15	0.11	0.10	0.07	0.06	0.07	20	1092
Stage-house	Min.	0.01	0.01	0.01	0.02	0.02	0.02	20	906
	Max.	0.10	0.05	0.06	0.07	0.09	0.10	20	906
Panel	Min.	0.14	0.05	0.04	0.03	0.03	0.02	20	561
	Max.	0.42	0.25	0.22	0.15	0.10	0.08	20	561
Curtains	Min.	0.04	0.05	0.11	0.18	0.30	0.35	20	102
	Max.	0.10	0.38	0.63	0.63	0.70	0.73	20	102

- *Stage-house*: For these walls, the absorption considered the range across data of brick walls.
- *Curtains*: The curtains on the first floor were modelled as flat against the wall. As no information was found regarding the fabric, the range was consciously kept broad.

3.2 Scattering coefficients

The frequency-dependent scattering coefficient ($scatt_{coef}$) can be roughly estimated as a function of a given characteristic depth ($char_{depth}$) representative of the surface's depth variations or roughness. The estimation algorithm in equation (1), available in CATT-Acoustic by the *estimate* function, can be used as well as specific values being directly assigned as a function of frequency.

$$Scatt_{coef}(f) \Big|_{\substack{\leq 0.99 \\ \geq 0.10}} = 0.5 \sqrt{\frac{char_{depth}}{\lambda}}$$

where λ is the wavelength. This method of defining $scatt_{coef}$ was selected for first approximations as it provides a more intuitive and physically relevant control parameter and reduces the possibility of creating unrealistic frequency variations in scattering properties for general materials with scattering increasing with frequency.

3.3 Explanations and proposed solutions

As the explanations for the poor acoustics concerned focusing and echoes, the early sound pressure level of the acoustic response was examined in 10 ms intervals. In addition, the echo criterion (EK_{grad}) was employed. This echo-disturbance criterion available within the GA software employed is displayed according to Dietsch and Kraak [40] and as applied by Roy and Gimbott [41]. The general hypothesis behind this criterion is that an echo is perceptible when it exceeds the general energy decay, with early reflections needing to be louder while later reflections require less energy to be considered audible echoes. This criterion employs a sliding evaluation of centre time (T_s).

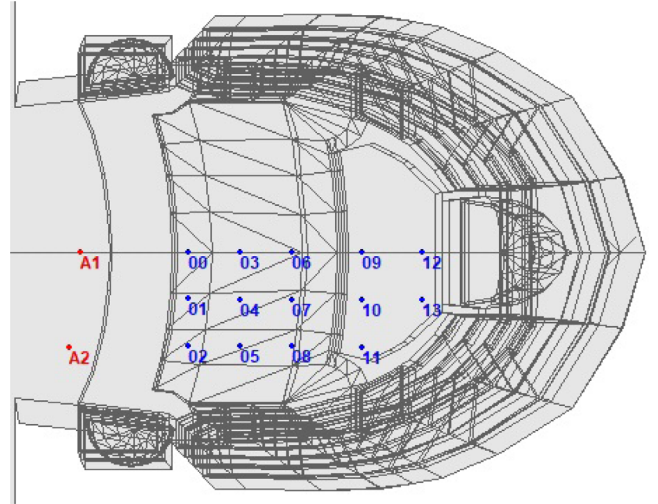


Figure 3. Plan view of the source and receiver positions in the GA model.

$$T_s(T) = \frac{\int_0^T t|p(t)|^n dt}{\int_0^T |p(t)|^n dt},$$

where $n = 2/3$ for speech and $n = 1$ for music. This function is subsequently smoothed with a 9 ms window for speech and a 14 ms window for music, with audible echo risks of 10% and 50% indicated. It should be noted that the predicted curves may indicate echo risks for reflections arriving before 50 ms, which is highly unlikely from a perceptual point of view.

Langhans Jr. stated that the hall's amplification of a sound source at different positions led to different locations of sound focusing. In order to resolve these problems, he proposed to introduce extra scattering. Therefore, room configuration Iff_{scatt} modified the $char_{depth}$ for all surfaces (except for the audience), increased to 100 mm. In contrast, Catel proposed to cover all surfaces with absorptive materials. Therefore, room configuration Iff_{abs} modified the audience walls and the loge fronts to be covered with curtains

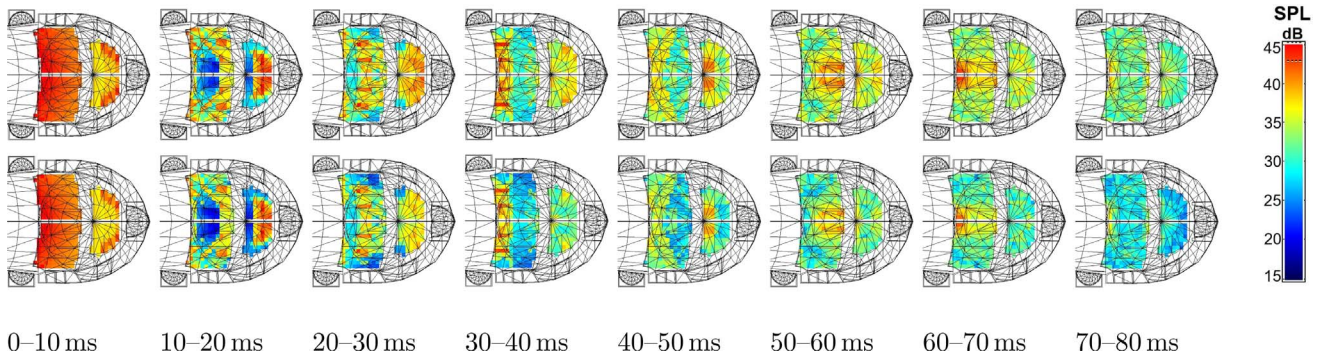


Figure 4. Sound Pressure Level (A-weighted) maps for source A1 with the (upper row) minimum and (lower row) maximum absorption coefficient conditions for the respective time intervals indicated.

(absorption coefficients according to Tab. 2). To examine the effect of these solutions, Source A2 was also included for comparison.

4 Results

Before analysing the configurations' results with increased absorption and scattering, maps of the early sound pressure level as a result of source A1 are presented. These are of specific interest in order to study the origins of sound-focusing complaints. Figure 4 presents time-segmented A-weighted SPL maps for the minimum and maximum absorption coefficients. One can observe that both conditions present similar results. The 20–30 ms interval highlights reflections from the loge fronts and back wall at the parterre's end. At the 50–60 ms and 60–70 ms intervals, the 1st-order reflections from the proscenium arch have reached the centre of the parterre, resulting in some observable focusing.

In order to judge whether this focusing would lead to echoes, *EKgrad* for receiver positions 00 and 03 (Fig. 3) are shown (see Fig. 5). For both configurations considered, one peak around 20–30 ms and another peak around 50–60 ms have likelihoods as perceived echoes between 10% and 50% for speech. The first peak, caused by the loge front and the back wall reflections, probably did not lead to the perception of echoes as it occurred well before the 50 ms limit. The second peak, caused by the proscenium arch reflection, arrived after 50 ms and is, therefore, more likely to have led to a perceived echo. As results between conditions show good agreement, subsequent analysis will examine only the maximum absorption coefficient conditions.

4.1 Sound focusing

In order to investigate Langhans Jr.'s observation that sources at different positions on stage resulted in sound focusing at different positions in the audience area, a second source (A2) position was considered. Figure 6 compares the A-weighted SPL between 20–30 ms, 50–60 ms, and

0–250 ms of the maximum sound absorption coefficient simulations previously presented with source A1. The 20–30 ms sound focusing occurs more to the halls' left, as seen from the stage. The 50–60 ms sound focusing occurs towards the left front of the audience area, as seen from the stage. From the 0–250 ms time interval, one can see that overall sound focusing also occurs. The difference between maximum and minimum A-weighted SPL is approximately 5 dB. Additionally, these sound-focusing instances occur at different positions when the source changes positions, as mentioned by Langhans Jr.

4.2 Proposed solutions

In order to investigate Catel's proposed solution to cover all surfaces with sound-absorbing materials, condition Iff_{abs} modified all loge fronts and walls in the audience space to be covered with curtains. Figure 6 compares the A-weighted SPL between 2030 ms, 50–60 ms, and 0–250 ms for the maximum sound absorption coefficient condition previously presented with the added absorption condition, Iff_{abs} . The sound focusing occurs at similar times and with similar strengths. The echo perceivable in Figure 6 would also occur in this configuration due to its association with the proscenium reflection.

In order to investigate Langhans Jr.'s proposed solution to introduce more scattering, Iff_{scatt} , Figure 6 compares the A-weighted SPL between 20–30 ms, 50–60 ms, and 0–250 ms for the maximum sound absorption coefficient condition with the increased scattering condition, Iff_{scatt} . The observed sound focusing occurs at similar times and with similar strengths. The perceivable echo in Figure 6 would also occur in this configuration.

5 Discussion

The study aimed to investigate the acoustic issues in a particular auditorium, focusing on sound focusing and audible echoes. A geometrical model was created based on contemporary plans and sections to analyse the acoustics. The absorption coefficients of the materials used in the

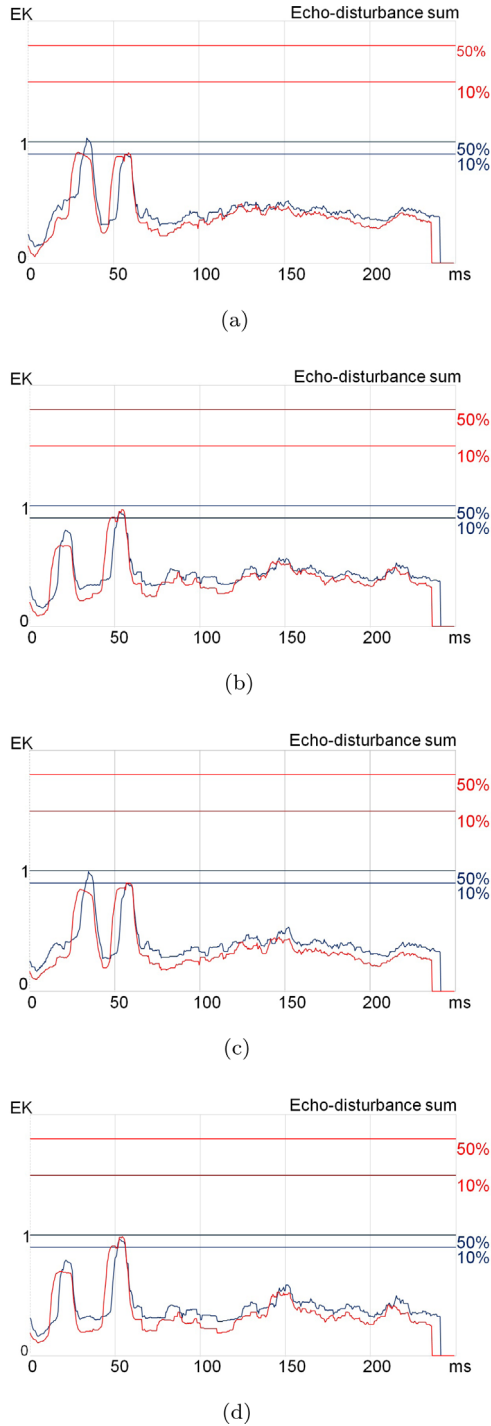


Figure 5. Estimated 10% and 50% echo-disturbance risks for the summed frequency bands for the minimum and maximum absorption coefficient conditions, source position A1 and receiver positions 00 and 03, considering (red) music and (blue) speech stimuli. (a) min. absorption; Rec. 00; (b) min. absorption; Rec. 03; (c) max. absorption; Rec. 00; (d) max. absorption; Rec. 03.

auditorium were defined within a range derived from existing databases. Two configurations of the model were constructed, representing the maximum and minimum absorption coefficients from this range.

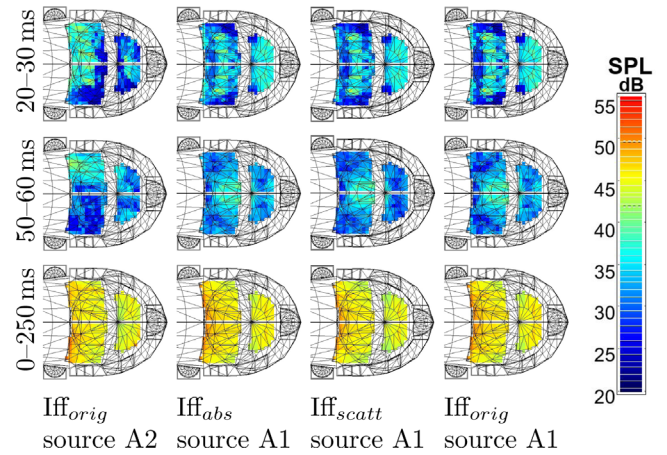


Figure 6. Sound Pressure Level (A-weighted) maps for source/configuration: A2 Iff_{orig} , A1 Iff_{abs} , A1 Iff_{scatt} , and A1 Iff_{orig} for the three different time intervals.

The resulting geometrical acoustic models showed similar results for sound focusing and echo characteristics. The acoustics of the auditorium were found to be affected by sound focusing and audible echoes.

The auditorium's acoustic concept, developed by Langhans Sr., consisted of three main components: the shape of the room, the “echo theory”, and the design of the stage acoustics. Langhans Sr. adopted Patte's theories on voice directivity to design the elliptical shape of the theatre. However, this shape led to sound-focusing problems. In an attempt to mitigate echoes, Langhans Sr. considered the time interval between the direct sound and the first-order reflections, as defined by Gehler (111 ms). However, studies have shown that echoes can still occur with a significantly shorter arrival time difference between direct sound and first-order reflections (approx. 50 ms). Langhans Sr.'s design of the rounded proscenium arch at a specific height may have contributed to the audibility of echoes.

Langhans Sr.'s son, Langhans Jr., correctly identified the sound-focusing issue caused by the elliptical shape of the hall. He also believed that the first-order reflections from the rounded proscenium arch positively impacted sound amplification and conducted tests to validate this assumption. However, simulations revealed that these first-order reflections likely caused noticeable echoes rather than enhancing the acoustics.

Proposals to address the sound focusing and echo problems by adding more curtains or increasing scattering would not have yielded satisfactory results. The additional curtains did not effectively target the primary source of echoes (rounded proscenium arch) or significantly increase absorption to resolve sound focusing. Similarly, while targeting the primary source of echoes, the increased scattering failed to fully resolve the problem of sound focusing.

In conclusion, the study highlighted the challenges of managing sound focusing and echoes in this particular auditorium design. The findings shed light on the acoustic issues caused by the room's elliptical shape and the influence of specific design elements, such as the rounded proscenium

arch. Addressing these acoustic challenges would require careful consideration and potential modifications to create a more acoustically balanced auditorium.

6 Conclusion

A room-acoustic history of the Iffland Theatre has been presented. Geometrical acoustic numerical simulations were carried out to investigate the grounds for its failed acoustics and proposed solutions. Models of the constructed hall and two modified configurations assumed to resolve its acoustics problems were studied. Due to implemented theories on voice directivity/shape as well as “echo theory”, sound focusing and audible echoes were observed. Neither the proposed solutions by Catel nor Langhans Jr. would appear to have resolved the hall’s acoustic problems.

It is interesting to view room acoustic design as part of a general evolution in room acoustics, with architects designing halls inspired by the success of previous “good” halls and learning from the failures of “bad” halls. Even though its acoustics were disliked, the Iffland Theatre is part of this evolution. The elliptical shape was tried for the first time [13]. This theatre was mentioned in the room acoustic concept of the Hoftheater, Karlsruhe (1809–1847), whose architect described avoiding elliptical shapes as it focuses sound. Instead, he opted for a semi-circular shape based on voice directivity observations from Saunders. Currently, voice directivity is still employed in current room acoustics, shapes that focus sounds are avoided.

The Iffland Theatre was the first room to implement echo theory. Decades later, similar time intervals were still employed in the Palais du Trocadero (1878) as well as Neue Gewandhaus (1884) [7], lasting until 1953 before the currently used time interval of 50 ms was prescribed. This seems to indicate that though the echoes in the Iffland Theatre should have been perceivable, contemporary acousticians left the employed time interval in “echo theory” unchanged, leading to echoes in later-built venues [24].

Langhans Sr. was the first architect to consider stage acoustics. Stage acoustics was mentioned in numerous following 19th century books on room acoustics and is today still a factor to consider while designing rooms with high acoustic demands.

Conflict of interest

The authors declare no conflict of interest.

Data availability statement

Data are available on request from the authors.

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