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AN ARCHAEOACOUSTIC STUDY OF THE HOFTHEATER'S (1808-1847) HISTORY

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ABSTRACT

Previous studies have identified six measurable pre-Sabine principles applied in early room acoustic design: voice directivity, audience rake, "echo theory", stage acoustics, reverberation, and the ratios of length, width, and height. Around the late 18th century, these concepts inspired two shapes theoretically considered optimal for spaces with acoustic requirements: the ellipse and the circle. Following the elliptical design of the Iffland Theater (1802-1817), the next form tested was the three-quarter circle shape in the design of the Hoftheater in Karlsruhe (1808-1849). The theater's acoustics proved notoriously poor, prompting contemporary architects and acousticians to investigate the reasons for this failure. The hall underwent renovations between 1830 and 1831, in part to address acoustic shortcomings. Insights from this failure also influenced the design of several later halls with room acoustic needs. As part of this archaeoacoustic study, geometric numerical acoustic simulations were performed to assess the original acoustic conditions. The results are compared to those of a previous study on the Iffland Theater to examine the acoustic lessons learned from this earlier theater hall.

Keywords: *Room Acoustics, Archeoacoustics, Simulation*

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1. INTRODUCTION

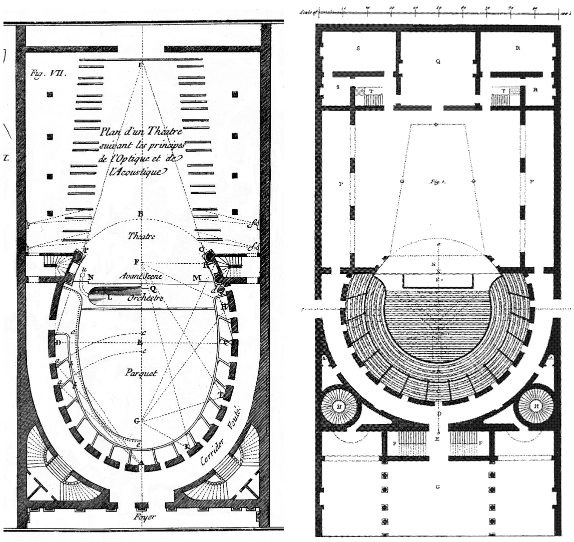
In 1898, Wallace Clement Sabine introduced the reverberation time formula, establishing a quantifiable foundation for architectural acoustics [1]. This marked the beginning of room acoustics as a scientific discipline. Notably, famous halls like the Wiener Musikvereinssaal (1870) and Amsterdam Concertgebouw (1888) were built before Sabine's work [2], highlighting the relevance of pre-Sabine acoustical principles.

Previous research identified six quantifiable principles used in acoustically demanding rooms before Sabine:

- *Voice Directivity*: Experiments informed planning in at least 11 rooms [3].
- *Audience Rake*: Curved seating was applied in at least 8 rooms, guided by 19th-century theories [4].
- *"Echo Theory"*: Used to prevent echoes in at least seven rooms [5, 6].
- *Stage Acoustics*: Addressed audibility and sound projection from the stage [4].
- *Reverberation*: Influenced design well before Sabine's formalization [7].
- *Room Ratios*: Recurrent length-width-height ratios aimed to enhance sound [4].

These ideas shaped 18th and 19th century thinking on ideal room shapes. The elliptical Iffland theater (1802–1817) was the first to apply such a concept but suffered from echo and sound focusing issues, as shown in [8].

The second was the Hoftheater in Karlsruhe (1808), designed by Weinbrenner, who detailed its circular shape and acoustical rationale in a booklet [9]. Based on voice directivity studies [10], the design proved acoustically problematic, leading to renovation efforts in 1830–1831.



(a) From [11]: First to suggest elliptical designs based on voice directivity.

(b) From [10]: Proposed circular designs based on human voice perception.

Figure 1. Concept theater study drawings.

This study examines the original configuration of the Hoftheater. Using numerical simulations, we analyze its original acoustics and compare it to the acoustics of the previously studied Iffland theater.

2. PRE-1808 THEORIES ON THEATER SHAPE

At the start of the 19th century, interest in ideal theater shapes began to emerge [12], sparked by debates surrounding the acoustics of the Iffland Theater [8]. These discussions set the stage for Weinbrenner's design of the Hoftheater.

2.1 Elliptical shape

In 1782, Patte [11] noted that the human voice could be heard up to 72ft. [1] (22.6 m) indoors, with less range outdoors. He described vocal projection as an *elongated spheroid*, leading him to propose an elliptical theater layout.

The Iffland Theater (1802) was the first to adopt this concept [13, 14]. However, it quickly drew criticism for echoes and sound focusing, confirmed in a modern archeoacoustic study [8]. This led to the widespread rejection of elliptical forms by German acousticians and architects [14, 15], and they have not been reused in German theaters since.

[1] Badenian feet (1ft = 0.300 m) are used throughout for consistency with sources.

2.2 Circular shapes

Saunders [10] conducted experiments showing that a speaker's voice was best heard in a three-quarter circle around them. He proposed a theater layout based on this, featuring a semi-circular plan with extended sides and a maximum radius of 30ft. (9.4 m). While voice projection guided the design, reflections were not considered; Saunders noted wood's ideal absorption without addressing surface treatments.

In 1802, Catel proposed a concept theater based on semicircular Roman designs [15]. His plan included a wide 60ft. (18.8 m) stage and a vast, vaulted auditorium modeled on ancient cavea structures. Though ambitious, it far exceeded typical theater dimensions of the time.

3. THE HOFTHEATER

3.1 The building's history

Following Baden's elevation to grand duchy in 1806, Grand Duke Karl Friedrich commissioned Friedrich Weinbrenner to build a new theater beside Karlsruhe Palace. After revising his designs during a research trip to Paris, construction began in spring 1807. The theater opened on 30 October 1808, though unfinished. In 1810, the court took over, and it became the "Großherzoglich-Badisches Hoftheater."

Modifications by von Schlick in 1830–1831 aimed to enhance acoustics and aesthetics but had unintended effects. A fire on 28 February 1847, worsened by these changes, claimed 63 lives [16].

3.2 The room's design

Before the fire, the theater accommodated 1800–2000 spectators across four levels. Fig. 2 illustrates the plans and section. Key design features include:

- Rounded shapes used on all levels per [10]; Weinbrenner avoided elliptical forms due to Iffland Theater issues.
- A flat ceiling replaced the vaulted one used in Iffland's design.

- The proscenium arch reflected sound back to the stage, avoiding echoes noted at the Iffland Theater [8, 14].
- Curtains were installed on the loge fronts of the 2nd and 3rd floors.

3.3 Weinbrenner's acoustic concept

In 1809, Weinbrenner published a book on the Hoftheater [9], criticizing existing theater theories and rejecting elliptical designs. Influenced by his visit to Paris and negative experiences with Langhans' Berlin Schauspielhaus, he turned to Vitruvian principles. He adopted a three-quarter circle layout, separating audience and stage spaces—an idea promoted by French theorists. The recessed box tiers reflected the "amphitheatrical" system, first introduced by Soufflot in Lyon (1752), referencing ancient Greek seating arrangements.

Despite invoking classical ideas, Weinbrenner's design resembled Saunders' concept more than ancient cavea forms. Both used recessed boxes and column-supported balconies, though Saunders' tiers were lower and included ascending rows. Their floor plans share striking similarities.

Weinbrenner's approach aligns with several pre-Sabine principles:

- *Audience Arrangement and Sight Lines*: The curved layout enhanced sound distribution and sight lines.
- *Echo Reduction*: Minimal ornamentation and careful geometry aimed to reduce echoes.
- *Room Ratios*: Balanced dimensions supported clear projection and natural acoustics.

3.4 Reaction to the acoustics

When comparing the Hoftheater's acoustics to the Iffland Theater, Weinbrenner satisfiedly stated [9, p.9]:

> In contrast, the Karlsruhe Theater, despite having a significantly larger auditorium space than the one in the Berlin Theater, has gained a great advantage solely through its construction and the most meticulous attention to every detail that could amplify or reflect sound vibrations. As a result, even a pistol shot does not produce the slightest echo. Nevertheless, even the most moderate tone is audible at every location within the auditorium.

Despite initial praise, later criticism emerged. The three-quarter circle and recessed boxes impaired sight lines and acoustics for those seated at the sides. Additionally, sound focusing was observed in the parterre area.

Carl Ferdinand Langhans addressed these flaws in his 1810 treatise [14], introducing a novel acoustic analysis method. Unlike earlier theorists who used single reflection paths, Langhans employed multiple lines to model sound reflections. His 2D method for detecting sound focusing marked a significant advance, as shown in Fig. 3.

Langhans Jr. considered three-quarter circular shapes just as unfavorable for the acoustics as ellipsis. He already knew that rooms with a rectangular floor plan were acoustically more favorable than those with elliptical or circular floor plans. However, for the sake of better acoustics and visibility, he tried to improve with two proposals upon Weinbrenner's design. Following studies will investigate the impact of Langhans Jr's proposals to improve the acoustics as well as the 1830-1831 renovation.

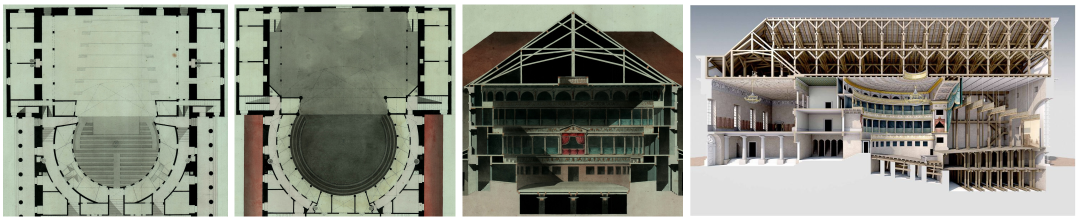
3.5 Study goals

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

- Propose a GA model to study the acoustics of the original Hoftheater.
- Identify any acoustic problems from a current design perceptive.
- Examine where Weinbrenner's room acoustic concept failed and where it succeeded.
- Compare the Hoftheater's result to that of the Iffland theater in order to study the lessons learned.

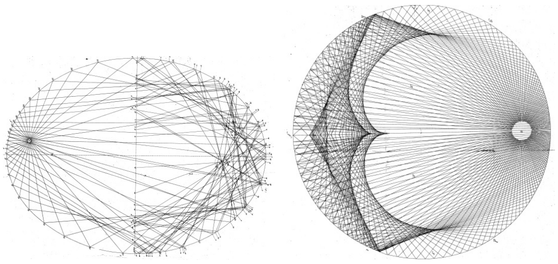
4. GA MODEL CREATION AND SIMULATION PROPERTIES

In order to achieve a credible acoustic reconstruction of the Hofheater, it is essential to establish and, notably, calibrate a model [20, 21]. When the structure under examination still stands, the optimal method for fine-tuning entails conducting measurements, creating a room acoustic model accordingly, and refining the model to reflect historical configurations across diverse acoustic parameters [22]. However, alternative calibration methods become necessary when the structure no longer exists. In the



(a) First floor from [17]. (b) Second floor from [18]. (c) Section from [19]. (d) 3D model from Sir Hanschke.

Figure 2. Plans of the first and second levels, section, and 3D Model of the Hoftheater.



(a) From [14]. (b) From [14].

Figure 3. Sound focusing in elliptical and circular shapes according to [14]

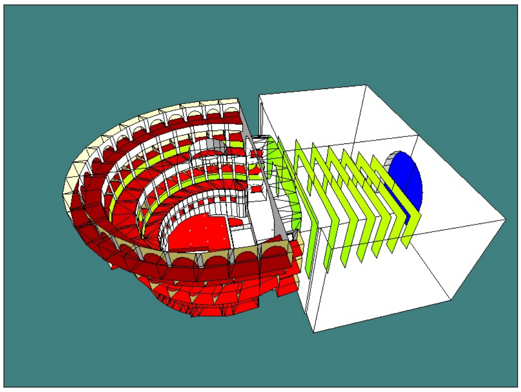


Figure 4. Catt-Acoustic model of the Hoftheater

most favorable circumstances, archived recorded Room Impulse Responses (RIRs) are accessible [23]. A step removed from direct measurements is the utilization of previously documented room acoustic parameters, constrained by potential disparities in analytical approaches and various uncertainties in measurement protocols [24].

In the current study, no acoustical parameters were available which could be employed in the GA model's calibration. As such, a broader approximate 'calibration' is employed, with informed estimations for reasonable ranges of values for different material's acoustic properties and an emphasis on relative differences between model configurations rather than absolute acoustic parameter results, as in [8]. 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.

When acoustic anomalies such as sound concentrations/focusing or echoes were observable in both conditions, it can be considered more than likely that such anomalies would have also occurred in the actual hall.

GA model creation and calibration were performed using CATT-Acoustic (v.9.1.g, TUCT v2), a software package capable of creating accurate and realistic room acoustic simulations [21]. The geometry of the Hoftheater model was determined from architectural plans, sections [17–19] and a 3D model provided (see Fig. 2). The model contained 1726 polygons with a volume of $\approx 10,500$ m^3 (see Fig. 4). Regarding calculation parameters, simulations were made using *algorithm 2* (longer calculation, detailed auralization), 2×10^5 rays, and an impulse response length of $4\,\mathrm{s}$ for parameter maps (grid step = $0.5\,\mathrm{m}$) and impulse response calculations. For the initial model, one source position was positioned at the center of the stage. As sound concentrations and echoes were most likely to occur in the parterre, parameter mapping was limited to this region and 9 receiver positions were distributed over the parterre audience.

4.1 Sound Absorption coefficients

In order to obtain the most realistic acoustic conditions, careful consideration was given to the material selection and calibration procedure. The books [9] and [25], as well as the original plans, sections and 3D model (see Fig. 2) and archival records [26], were reviewed for information concerning materials. Subsequently, the attribution of absorption coefficients was based on general published data sources [27–29]. The variation across data for comparable materials aided in defining a reasonable range of values for which simulations were made using the extents of likely absorption coefficients.

Information on specific materials is provided below, with a summary of attributed acoustic material properties given in Table 1.

- *1st floor audience wall*: According to [25] was constructed from granite.
- *2nd–4th floor audience wall, balcony & loge fronts and ceiling*: The material employed for these surfaces was assumed to be plaster on lathe as the plans seem to indicate this and as it seemed to be the contemporary material of choice [7].
- *Audience chairs*: The benches in the parterre and galleries were upholstered with padding made of horsehair (“Roshaar”) and covered in gray cloth (“graues Tuch”) [26].
- *Floor*: Sections show that the floor was boards positioned on joists, therefore similar materials were considered for the absorption coefficients.
- *Stage-house*: For these walls, the absorption ranged across data on brick walls.
- *Curtains*: The curtains in the princely loges were made of silk, adorned with tassels, pompoms, and trimmings [26]. The curtains on the second and third floors were modeled as flat against the wall. As no information was found on the fabric, the range was consciously kept broad.
- *Loges:* The grand ducal loges were covered with velvet and gobelin fabric. Other galleries/loges were covered with different types of cloth, some unspecified [26].

4.2 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 Eq. (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.

$$scatt_{coef}(f)\Big|_{\geq 0.10}^{\leq 0.99} = 0.5\sqrt{\frac{char_{depth}}{\lambda}} \tag{1}$$

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.

5. RESULTS

The reverberation times of the Iffland Theater and the Hoftheater are compared to each other as well as to the ‘optimal’ reverberation times from a modern design perspective. According to [30, p.30] the optimal reverberation time for occupied drama theaters in the mid frequencies lies between 0.7 and 1.0 s. As the difference in reverberation time between occupied and unoccupied conditions in a drama theater typically ranges between 0.2 and 0.5 s seconds [30], the optimal range for the unoccupied Hoftheater was 0.9 and 1.5 s. Additionally, [30, p.22–23] emphasizes the importance of achieving uniform sound distribution and maintaining speech intelligibility, which can be compromised by architectural features like concave surfaces that cause sound focusing. Finally, in order to study whether architects learned lessons from the Iffland Theater, the occurrence of echoes was studied employing the echo criterion (*EKgrad*). However, where echoes in the Iffland theater were probably present no echoes were observed for the Hoftheater.

Table 2 presents the *T20* results for both theaters with maximum and minimum absorption coefficients. The results suggest that the reverberation time in the Hoftheater was most likely significantly shorter than in the Iffland theater. However, while the reverberation time in the Hoftheater may have fallen within the contemporary optimum range, it is more likely that it was excessively long, as most of the simulated values exceed the optimal range for drama theaters.

Table 1. Absorption coefficients, $char_{depth}$ (mm) as the single value using Eq. (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
1st floor	min.	0.01	0.01	0.01	0.02	0.02	0.02	20	85
audience wall	max.	0.10	0.05	0.06	0.07	0.09	0.10	20	85
Panel	min.	0.14	0.05	0.04	0.03	0.03	0.02	80	1319
	max.	0.42	0.25	0.22	0.15	0.10	0.08	80	1319
Audience chairs	min.	0.32	0.48	0.66	0.73	0.77	0.74	†	716
	max.	0.72	0.82	0.91	0.96	0.94	0.90	†	716
Floor	min.	0.10	0.07	0.06	0.06	0.06	0.06	20	588
	max.	0.15	0.11	0.10	0.07	0.06	0.07	20	588
Stage-house	min.	0.01	0.01	0.01	0.02	0.02	0.02	20	638
	max.	0.10	0.05	0.06	0.07	0.09	0.10	20	638
Curtains	min.	0.04	0.05	0.11	0.18	0.30	0.35	20	711
	max.	0.10	0.38	0.63	0.63	0.70	0.73	20	711
Glass	min.	0.06	0.04	0.03	0.02	0.02	0.02	20	70
	max.	0.28	0.20	0.11	0.06	0.03	0.02	20	70
Loges	min.	0.14	0.05	0.04	0.12	0.19	0.30	20	938
	max.	0.42	0.25	0.22	0.22	0.29	0.40	20	938

Table 2. *T20* results for the unoccupied Hoftheater and Iffland Theater with maximum and minimum absorption coefficients.

	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Iff_{min}	4.29	5.82	5.41	4.83	4.09	2.64
Hof_{min}	3.53	4.87	4.19	3.41	2.44	1.65
Iff_{max}	1.66	2.44	2.34	2.53	2.52	1.85
Hof_{max}	1.26	1.38	1.13	1.27	1.18	0.91

Fig. 5 presents A-weighted sound pressure level maps for maximum and minimum absorption coefficients for both the Iffland Theater and the Hoftheater. For the Iffland Theater, sound focusing effects were observed on the order of approx. 4 dB(A). The appearance of sound focusing effects mirrors the predictions of [14] (see Fig. 3(a)). For the Hoftheater, sound focusing effects of approx. 7 dB(A) along a curved, arc-like shape that follows the contour of the audience seating area were observed. This shape mirrors the predictions from [14] (see Fig. 3(b)).

6. DISCUSSION

The analysis of the Hoftheater's acoustics has highlighted several critical issues, despite the theoretical principles that informed its design. These issues have also been compared to the acoustics of the Iffland Theater:

- **Sound focusing:** The curved layout caused focal points, resulting in uneven sound distribution across the auditorium, as anticipated by Langhans Jr. Sound focusing was also observed in the Iffland Theater, though with a different pattern.

- **Extended Reverberation Time:** Simulations suggest that the Hoftheater's reverberation time was significantly shorter than the Iffland Theater's, however, the Hoftheater's reverberation time still most likely exceeded optimal values for its function.

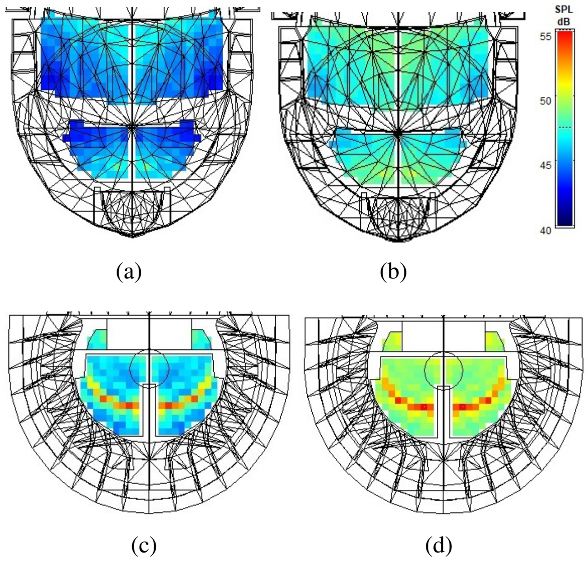


Figure 5. Sound Pressure Level (A-weighted) maps for (a) the Iffland Theater with max., (b) the Hoftheater with min., (c) the Iffland Theater with max., and (d) the Hoftheater with min. absorption coefficients. All figures use the same provided colormap.

- **Echoes:** Contrary to the Iffland Theater, echoes were avoided in the Hoftheater through strategic ceiling and proscenium design.

7. CONCLUSION

We presented a study of the room-acoustics of the Hoftheater's (Karlsruhe, 1808–1847) original configuration, contextualized through comparisons with the earlier Iffland Theater (Berlin, 1802-1817). Lessons from the Iffland's elliptical layout informed the Hoftheater's design, notably the elimination of echoes through improved stage geometry and reduced reverberation through the application of additional sound absorbing material. Nonetheless, the Hoftheater had other acoustic problems, particularly sound focusing (which also occurred in the Iffland Theater but in a different pattern) and, eventhough less pronounced than in the Iffland Theater, excessive reverberation. These findings underscore the empirical nature of early acoustic theory and the limitations of curved audience layouts, which have since been largely abandoned in German theater design.

By revisiting both theaters, we confirmed key aspects of Langhans Jr.'s 1810 critique, showing how practical experience and theoretical speculation began to converge through emerging methods of acoustic analysis. This study reinforces three central insights:

- Pre-Sabine acoustic theories, though grounded in experiment, often failed in practice.
- Curved audience shapes posed challenges in sound distribution and were not repeated in later designs.
- Langhans Jr.'s work marked an early move toward systematic acoustic modeling.

The Hoftheater's central role in Langhans Jr.'s treatise highlights its importance in the evolution of room acoustic design. Like the elliptical form after the Iffland Theater, the three-quarter circular layout was, to the authors' knowledge, not used again in German theaters. The evolutionary principles guiding architecture result in poor performing halls being destroyed, with only well performing halls remaining. Study of these "pruned" halls is important in furthering our understanding of acoustic design in history. Future studies will examine the acoustic impact of the 1830–1831 renovation and the proposals by Langhans Jr., further tracing the evolution of empirical and theoretical approaches to room acoustics.

8. ACKNOWLEDGMENTS

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