THE PAST HAS EARS: ACOUSTICS FOR CULTURAL HERITAGE

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When we think about great architectural achievements in European history, such as ancient amphitheatres or Gothic cathedrals, their importance is strongly tied to their acoustic environment, an intangible consequence of the building's tangible construction and furnishings.

Acoustic phenomena like reverberation, focusing, and whispering galleries have shaped political, religious, and symbolic spaces for centuries. With hearing central to human communication, advances in archaeoacoustics and computing now enable precise measurement and simulation of past soundscapes, significantly expanding cultural heritage research [1].

Preserving acoustics: Archaeoacoustics

Archaeoacoustics, a sub-field of archaeology and acoustics, can be defined as studies on the relationship between people and sound throughout history. The recent fires at *Notre-Dame* in Paris (2019) and *Teatro La Fenice* opera hall (1996) shined a light on the fragile nature of acoustic heritage. Acoustic measurements, numerical simulations, and digital reconstructions, offer the possibility to document the acoustics of important sites and allow for exploration and experiencing of lost acoustics by scientists (*e.g.* acousticians, archaeologists, historians, musicologists) and the general public. These efforts are exemplified by recent studies on the Cathédrale Notre-Dame de Paris and the Houses of Parliament in London.

Room acoustics

Architectural acoustics aims to provide optimal sound quality suited to a room's function. Indoors, sound • • •

••• reaches listeners both directly and via reflections off walls and surfaces. The lingering reflections form *reverberation*. Multiple paths between sound source and listener create complex interactions, forming the *room impulse response*.

Long before modern acoustics was theorised, the Greeks engineered open-air amphitheatres for optimal voice projection, avoiding the reverberation issues caused by enclosed spaces. Reverberation's impact depends on its duration, intensity, and the sound type. Now a key acoustic metric, reverberation time varies with space and positioning. In the late XIX[th] century, Wallace Clement Sabine formalised the study of room acoustics with a formula linking reverberation time to room volume and surface materials.

Optimal reverberation time depends on a room's function—shorter times suit speech-focused spaces like theatres, enhancing clarity. Excess reverberation can hinder intelligibility, requiring slower speech. Today, architects and acousticians use 3D modelling and material assumptions to predict and refine acoustic performance. These techniques also aid researchers in reconstructing the soundscapes of historical sites.

Acousticians describe a space's sound using standard metrics derived from room impulse responses. The most basic, Reverberation Time (T_{30}), measures how long sound takes to decay by 60 dB after the source stops, indicating how 'live' or 'dry' a space is.

Modelling acoustics

Physical and digital reconstruction methods have long been used in acoustics. Advances in computing have greatly enhanced acoustic simulations, allowing calibrated models to closely match real recordings [2]. These models enable exploration of architectural layouts, listener positions, and historical contexts, turning descriptive accounts into immersive, sensory experiences and offering powerful tools for historical research [3].

Accurate 3D models with material properties can simulate how changes in geometry or materials affect acoustics over time, reflecting structural evolution and cultural shifts. Most heritage acoustics studies use geometric acoustic models, tracing sound like light rays [4] (see Fig. 1). These methods approximate the room impulse response effectively, they lack low-frequency precision due to wave effects. Wave-based methods solve equations of motion directly for higher accuracy but demand greater computation, prompting research into hybrid models that blend geometric, wave-based, and statistical approaches [5].

Experiencing acoustics

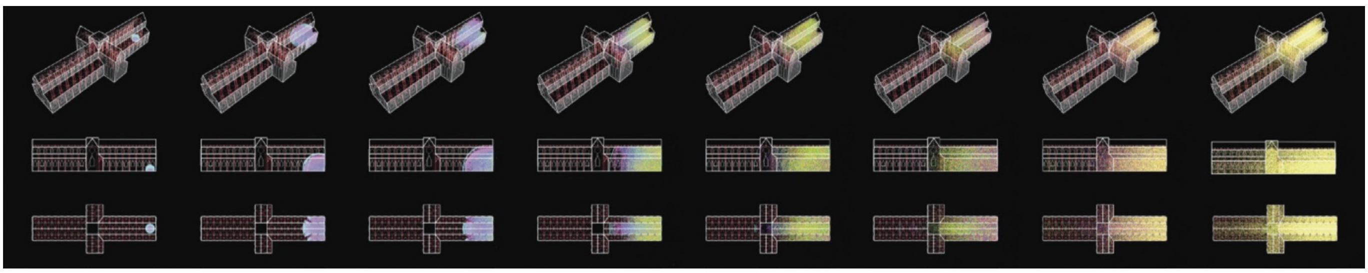
"Auralisation" is the auditory counterpart to visualization, allowing listeners to experience acoustic models via headphones or speaker arrays, simulating spatial properties as if present on site. Unlike vision's often external viewpoint (*e.g.*, bird's eye), auditory perception is inherently immersive and egocentric. Modern virtual reality (VR) renderings combine spatial audio with visual, as visuals influence auditory perception.

The Historic House of Commons Chamber, Palace of Westminster, London

The acoustics of the House of Commons Chamber, prior to its destruction by fire in 1834 and subsequent redesign and relocation within the Palace of Westminster, have been comprehensively studied through an interdisciplinary methodology, combining historical research with modern acoustic simulation techniques [6]. A poignant historical interest lies in exploring the acoustic properties of the ventilator space above the ceiling, where women gathered from the 1820s to listen to debates from which they were otherwise excluded. This research aims to understand how intelligible political speeches were to these women, revealing aspects of gender, privilege and space in 19[th]-century politics [7].

The methodology involved creating a detailed acoustic model. Historical evidence, including architectural plans, minutes of meetings, engravings, and paintings (*e.g.*, Sir George Hayter's "The House of Commons, 1833"), provided critical information on layout, fabric, and use. Features such as seating arrangements, galleries, the Speaker's chair, carved

▼ FIG. 1: Geometric acoustic numerical simulation showing a graphical representation of the propagation and build-up of sound from an impulse-like source at the west end of a 3D model of the now ruined St Mary's Abbey Church in Museum Gardens (www.york.ac.uk/research/themes/sixteenth-century-acoustics), York, UK. This image sequence shows the first 400ms of sound diffusion through the Abbey, with the full simulation indicating it takes nearly 6s for sound energy to decay beyond audibility. At the west end of the nave, reverberation dominates over direct sound, reducing intelligibility compared to locations nearer the source.



decorations, windows, and the unique ventilation system with metal grilles were incorporated, attributing appropriate acoustic properties. Results were calibrated against acoustic measurements from similar, existing contemporary spaces.

Acoustic simulation software was used to analyse propagation for a simulated male voice to predict speech intelligibility, considering background noise from external (*e.g.*, coal barges, paddle steamers) and internal (*e.g.*, smoking room chatter) sources.

Important results showed a fully-occupied house was less reverberant (T30: 0.70s to 0.90s) and objectively more suitable for speech than a half-occupied house (T30: 0.92s to 1.27s). Speech intelligibility was uneven, highly dependent on both speaker position and orientation. Galleries and under-gallery areas generally had poor intelligibility, aligning with historical accounts. A half-occupied house resulted in poorer overall intelligibility, supporting the observation that, "the fewer persons the worse the hearing" [7].

For those women listening from the ventilator space above the ceiling speech intelligibility varied from poor to fair. Under certain conditions (*e.g.*, half-full house, specific speaker positions), it is hypothesized that women in the ventilator would experience more intelligible speech than many Members of Parliament within the main chamber. This finding, contradicting some historical reports, supports others like Lady Frances Shelley's view that "the sound ascends so perfectly that, with attention, not a word is lost", [7].

The research highlighted that 19th-century architects, while identifying acoustic challenges, lacked a full scientific understanding of sound propagation, misattributing issues to the "elasticity" air instead of modern principles like direct line-of-sight. This work offers valuable, scientifically plausible reconstructions for parliamentary historians, providing insights into political culture, seating dynamics, and oratorical strategies within the pre-1834 House of Commons.

Cathédrale Notre-Dame de Paris

Research into the acoustics of Notre-Dame has been undertaken as part of interdisciplinary endeavour bringing together acousticians, musicologists, and historians to explore the cathedral's soundscape before the 2019 fire and its evolution through the centuries.

The methodology centred on creating a digital acoustic twin of the cathedral, reflecting its acoustic properties and enabling reconstruction of historical or future states. Based on calibrated geometrical acoustic models validated against 1987 and 2015 on-site acoustic measurements, it incorporates historical architectural changes such as the lateral chapels, choir stalls, and the jubé (rood screen), along with decorative elements like tapestries and paintings, and organ positions. Interviews with musicians and choirmasters added qualitative insights into perceived acoustics [8]. Real-time auralisation systems allowed professional choirs to perform in simulated historical acoustic environments, observing their adaptive behaviours as a function of musical genre [9].

The importance of the results is multi-faceted. While Notre-Dame's acoustics were "remarkable," musicians reported them as "difficult to tame," particularly during rehearsals. The model confirmed T30 was significant (up to 9s for low frequencies in an unoccupied state) and that poor early-stage support on the podium negatively • • •

▲ **FIG. 2:** The House of Commons 1692–1707, remodelled as part of the "Virtual St Stephen's Chapel Westminster Project" (www.virtualststephens.org.uk). This 3D graphical model provided part of the foundation for the 1800 acoustic model as developed and tested in [6, 7] impacted singers' ability to hear each other and maintain clarity. Despite these challenges, occupants developed adaptive strategies, adjusting their vocal delivery and repertoire.

The transept was identified as an acoustic barrier, reducing musical clarity between the choir and nave, consistent with historical observations. Organ placement and elevation significantly affected sound propagation and clarity within different parts of the cathedral [10].

The research demonstrated the perceptible acoustic evolution of the cathedral over centuries from its early Gothic construction (1160-1230), to addition of lateral chapels (1225-1320), and later decorative additions. The research also recreated historical soundscapes of construction sites and urban environments.

Beyond scholarly inquiry, a key aspect of the project is translating research into freely available public experiences, including an immersive radio-fiction (Looking for Notre-Dame, http://lookingfornotredame.pasthasears.eu/), a geo-localised audio-guide (Notre-Dame Whispers, http://ndwhispers.pasthasears.eu/), and a virtual concert (Vaulted Harmonies, http://vaultedharmonies.pasthasears.eu), utilising the digital twin and binaural audio to immerse listeners in the cathedral's sonic history [11].

Concluding remarks

Acoustic reconstruction enriches historical research and public engagement, offering immersive insights into past soundscapes. Yet, auralisations remain interpretative, shaped by modelling choices, technological limits, and contemporary listening perspectives. Like all reconstructions, they reflect both historical evidence and the present-day lens of their creators.

Digital reconstructions offer a tangible form for hypotheses drawn from history, architecture, and acoustics – but should not be mistaken for absolute representations of the past. Even the most rigorous models remain informed approximations. ■

▼ FIG. 3: Photos from acoustical measurement sessions at Notre-Dame, before the fire of 2019, during the restoration work, and after reopening in 2025.

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