The Past Has Ears at Notre-Dame Cathedral: An Interdisciplinary Project in Digital Archaeoacoustics

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The concept of a cathedral frequently suggests a static object where, once the final stones have been placed, the structure remains impervious to time. It is tempting to think of the great cathedrals as stoic white monuments filled with stone and, perhaps, the light of stained glass. However, the great cultural legacy of the medieval cathedrals is a legacy of change. Cathedrals continue to change long after the completion of their initial structure as their occupants discover new needs, new fashions, and new priorities. Combined with acts of humans, nature, and the passage of time, cathedrals are subject to constant evolution. The Cathédrale Notre-Dame de Paris is an excellent example of this.

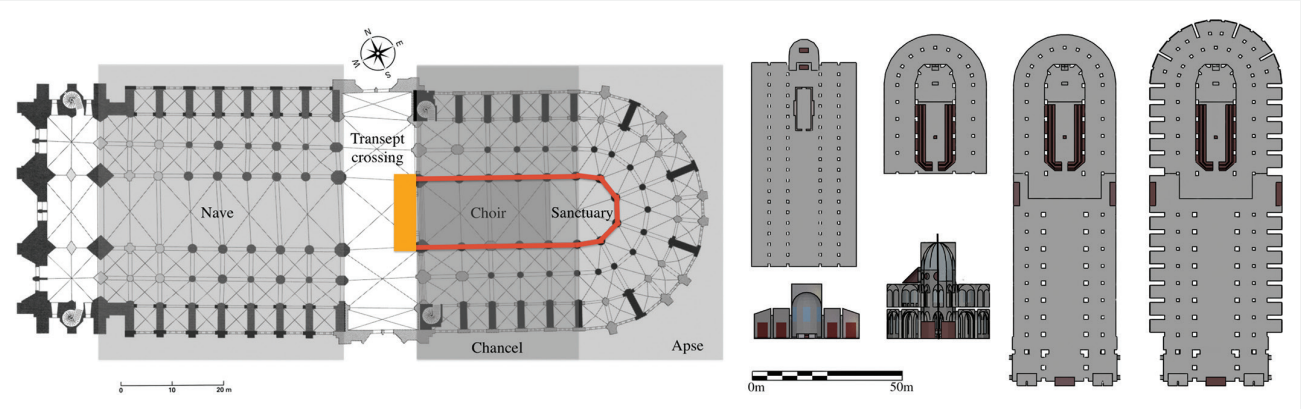
The recent fire at the cathedral (see youtu.be/jjPeEIgf0dw) has motivated a series of studies attempting to better understand the acoustics of Notre-Dame, its evolution over the centuries, and its influence on music, extending to predictions in the aid of its restoration. We present here an overview of the interdisciplinary work around the research into the acoustic history of the Cathédrale Notre-Dame de Paris. A light-hearted introduction to cathedral acoustics and our work can be watched in the popular science video (see youtu.be/aJvvkl3qrXM) made in collaboration with our team. But first, we present an overview of the cathedral and its long history.

Living Building

Anatomy of a Cathedral

In the following discussion, we use some technical terms to discuss locations within the cathedral. As seen in **Figure 1,** Notre-Dame de Paris is an approximately rectilinear building with an internal structure resembling a cross. The focus of ritual use is the *apse*, a semicircular termination of the cathedral in the east. The *nave* is an elongated area in the western portion of the Cathedral and is separated

Figure 1. ***Left****: floor plan of Notre-Dame with architectural terms, with the clôture (**red**) and jubé (**orange**).* ***Right:*** *acoustic model floor plans and elevations of cathedrals built on the Île-de-la-Cité.* ***Left to right:*** *the pre-Gothic basilica underneath Notre-Dame's parvis (before 1163); Notre-Dame at its consecration (1182); the termination of the nave (~1220); and the termination of the lateral chapels (~1350).* ***Right*** *reproduced from Mullins et al. (2022), with permission.*



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from the apse by a transversal aisle called the *transept*. The apse contains the *liturgical choir*, a consecrated area containing both the choir stalls for high-ranking church dignitaries and, historically, the grand altar and important relics within an area called the *sanctuary*. For most of Notre-Dame's history, the liturgical choir was separated from the rest of the apse by a tall stone wall called a *clôture (***Figure 1**, *red)* and access was limited by a large gate (*jubé*; **Figure 1**, *orange*) standing between the transept and the western end of the choir stalls. When considered vertically, the cathedral begins at the ground floor. The *triforium* level is located one floor above the ground (seen in the section drawing of Notre-Dame in **Figure 1**), and the stained glass windows are found in the *clerestory* level just below the vaulted ceiling. An online 360° image virtual tour is available that can help to better understand the space (see t.ly/J8on6).

Construction

Beginning its construction in the 1160s, Notre-Dame de Paris was not the first ecclesiastical building erected in Paris on the Île-de-la-Cité (see t.ly/9n0Do) nor was it the initial tribute to the Virgin Mary on the island. Rather, scholarly evidence suggests that the impetus behind Notre-Dame's construction lay in the endeavor to restore and rebuild the infrastructure of the *chapter* (a collective of priests, canons, and clerics affiliated with a specific church or cathedral) following the Viking Age. Notre-Dame emerged as one of the earliest manifestations in France of Gothic architecture (Hourihane, 2012). Spearheaded by Bishop Maurice de Sully (see t.ly/MyPHC), developmental efforts commenced on the apse in the spring of 1163 (Berger and Sandron, 2019) while existing church structures underwent demolition to clear the grounds for the burgeoning cathedral. These structures included a small chapel dedicated to Mary beneath the contemporary transept and a large basilica situated beneath the present-day *parvis* (churchyard, in front of the western entrance) of Notre-Dame (Viollet-le Duc, 1854/1868, §*Cathédrale*; Barbier et al., 2019). The inaugural phase of construction, culminating in the full completion of the apse, concluded in 1182 with the consecration of the grand altar (Sandron, 2021).

With this phase of construction, a significant retaining wall was erected to separate the consecrated choir from the on-going construction, allowing religious ceremonies to proceed without disruption. By the 1220s, the nave had been completed, and a new campaign began to expand the cathedral's perimeter with 35 chapels between the flying buttresses (see **Figure 1**). By the 1330s, work on the lateral chapels was completed, and the external structure remained largely unchanged until Viollet-le-Duc's nineteenth-century renovations. His excavations unveiled early design modifications, including circular attic openings below the stained glass windows near the ceiling. Originally smaller, the windows were enlarged after a fire in 1218 in an attempt to prevent future incidents.

Decoration

The chapter's presence within the cathedral quickly led to the decoration of the interior, including the choir stalls. A large stone jubé was constructed between the transept and the western choir entrance in 1135, and by 1350, the remaining sides were surrounded by highly ornamental stone walls (a clôture) (Gillerman, 1977), creating a ceremonial enclosure in the heart of the Cathedral. Church records contain inventories of tapestries, carpets, curtains, and hangings that decorated the interior of the consecrated space (Wright, 1989a). Over time, nobles and high clergymen were buried in the apse and choir and funerary monuments dotted the church. Statues, funded by Parisians, adorned the space, including one of King Philippe Le Bel placed in the transept after a victory in 1304. The highlight was a towering statue nearly 9 m tall of St. Christopher erected in 1413 in the nave (see t.ly/mFIY5) (Sandron and Tallon, 2020). Patrons enthusiastically adorned the lateral chapels. Over time, evolving tastes and trends influenced the style and character of these decorations, mirroring contemporary culture.

Living Heritage

The cultural heritage of Notre-Dame de Paris can be traced back to its initial occupancy, circa 1182. Next, we introduce a selection of the traditions housed within the cathedral for those with an interest in sound. **Figure 2** presents a companion timeline to this discussion, highlighting various historical, architectural, and musical events in the history of the cathedral.

The School of Notre-Dame and the Development of Written Polyphony

Notre-Dame de Paris boasts a rich musical legacy dating back to its inception. Spanning over 850 years, the cathedral has witnessed the evolution of music, with its most notable contribution being the establishment of the

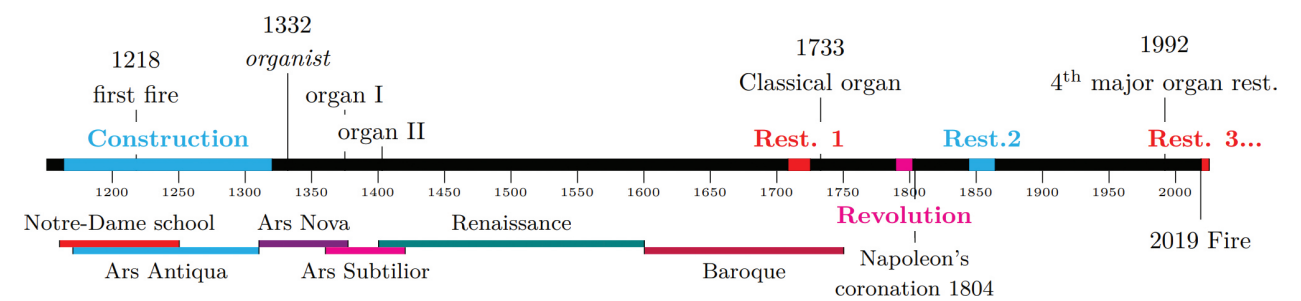


Figure 2. *Time line of relevant historical and construction events (**top**) and musical periods (**bottom**) of Notre-Dame for general reference. Rest, Restoration.*

Notre-Dame School of Music (see bit.ly/4bWjJdh). This group of composers and musicians introduced a virtuosic style of singing, enhancing single-melody plainchant (a type of liturgical song in which religious texts are sung on a single melodic line and in unison) with intricate ornamentation provided by multiple soloists. While polyphonic music (i.e., music with more than one melody) existed in Western Europe prior to the School of Notre-Dame, it was largely improvisational and confined to specific regions or time periods (Everist, 2011).

The Notre-Dame School is particularly associated with the musician Léonin (active 1160–1200; see t.ly/2JQRg) and his successor Pérotin (active 1180–1220; see t.ly/PCi3m), who expanded the music of Léonin into four-voice polyphonic arrangements. The historical record indicates that church authorities mandated the development of special musical arrangements to mark important dates in the church calendar (Everist, 2011). Thus, while a simple plainchant was performed daily for the mass and the intermittent prayer services of the church, the performance of Parisian polyphony was associated with the high feast days of the church calendar when the choir of Notre-Dame was richly decorated with velvets, tapestries, and other acoustically significant textiles (Wright, 1989b). Although Notre-Dame is not the only location to have a known relationship between composer and architecture, the fast pace of construction on the site in parallel with the rapid development of musical styles is suggestive. One wonders if the relationship between cathedral and musician influenced the development of the Notre-Dame School given the temporal correlation between cathedral occupancy and the active years of Léonin and Pérotin. Until recently, musicologists and historians could merely speculate about such a relationship, as later construction at the cathedral has entirely altered the acoustic characteristics of the twelfth and thirteenth centuries.

Medieval Organ

During the latter part of the fourteenth century, permanently installed pipe organs began to be installed in sizable churches and cathedrals, marking a significant evolution in their role within liturgical, devotional, and communal contexts (Ros, 2019). Notably, Notre-Dame housed at least two Gothic organs during this period: one dating back to the fourteenth century (referred to as Organ I) and another from the fifteenth century (referred to as Organ II). The earliest documented mentions of an organ within the records of Notre-Dame's chapter date even earlier, to 1332 where payment to an organist is noted, and to 1333-1334 when a bell was placed in the choir to complement the organ (Hardouin, 1973). These references likely allude to an earlier, more portable iteration of the instruments we call Organ I and Organ II.

In the fourteenth century, the organ's role was primarily reserved for 23 major feasts and special events. Although our understanding of the repertoire, both written and improvised, is limited today, glimpses of its nature are gleaned from subsequent written accounts. The transept in the Cathedral serves as a significant acoustic divider, creating two distinct zones due to its spaciousness and lack of partitioning walls. This acoustic division reflects the priorities of the original builders but no longer aligns with modern expectations of the Cathedral. Functionally, the instrument served two primary purposes, closely intertwined with the liturgical proceedings within the choir and the activities unfolding in the nave. First, it engaged

in dialogue with and potentially provided accompaniment to the choir ensconced within the apse. Second, it played pivotal roles in inaugurating and concluding the liturgy, supporting processions, and dignifying the arrivals of esteemed figures such as kings or visiting dignitaries (Wright, 1989b).

Revolution and Restoration

The French Revolution of 1789 significantly impacted Notre-Dame Cathedral, leading to damage and neglect as it became a target of revolutionary fervor. It was briefly transformed into a secular space during this time. However, post-Revolutionary efforts, including initiatives in the nineteenth century led by architect Eugène Viollet-le-Duc, helped restore the Cathedral's Gothic features. Despite the damage inflicted, the Revolution spurred endeavors to preserve and restore Notre-Dame, emphasizing its enduring significance as a symbol of French heritage.

The 2019 Fire and Acoustic Cultural Heritage

On April 15, 2019, a fire broke out in the attic of the Cathédrale Notre-Dame de Paris (for images, see t.ly/hXjDt). The damage caused by the incident destroyed the roof and created three significant holes in the vaulted ceiling as the spire and debris collapsed. Concerns arose about the building's structural stability, along with inquiries regarding the loss of Notre-Dame's historic acoustics. Despite erroneous reports from some international journalists suggesting the loss of these acoustics, documentation on Notre-Dame's acoustics had actually commenced several years before the incident.

Recent UNESCO (2017) resolutions and conventions underscore the importance of preserving, studying, and recreating the soundscapes and acoustics of historical sites. Advancements in computing power now facilitate detailed acoustic simulations for complex structures like theaters, concert halls, and cathedrals.

Living Acoustics

Acoustic Measurements

Despite the notoriety of the cathedral, there are few examples of published data on the acoustical parameters of this space. A few early twenty-first-century studies reported varying reverberation times for the modern cathedral (6.5-7.5 s at 500 Hz), where concert halls have a typical upper bound of 2.0 s. Our laboratory conducted two measurement campaigns prior to the 2019 fire, with additional measurements taken afterward to assess changes in the building's acoustics. The first campaign in 1987 utilized an impulsive source (balloon popping) retrieved from an acoustic study related to a potential organ installation. Although limited by incomplete stimuli details, such as anechoic signals and sweep stimuli parameters and despite not being omnidirectional sources, balloon pops provided valuable impulsive signals for certain applications (Pätynen et al., 2011).

Later, as part of a French research project on binaural listening (FUI BiLi), we made a series of acoustic measurements in 2015, almost four years to the day before the 2019 fire (Postma and Katz, 2016). These detailed measurements were made with the modern sine-sweep technique, with multiple receiver positions spread over a large portion of the floor area, including binaural and Ambisonic microphones at select positions.

As part of our role as coordinator of the Acoustics Working Group of Chantier Scientifique, the group organized by the French national science center and the Minister of

Figure 3. *Prefire measurement photos.* ***A:*** *setup for binaural room impulse response measurement and the miniature dodecahedron source. Postfire measurement photos.* ***B:*** *measurement team in protective gear in the safe zone;* ***C:*** *driving the remote vehicle that towed the microphone arrays; and* ***D:*** *view of the nave, off-limits to all persons, after the initial debris cleanup.* ***C*** *and* ***D*** *reproduced from acoustic-task-force-notre-dame.dalembert.upmc.fr, courtesy of Chantier CNRS Notre-Dame Groupe Acoustique.*

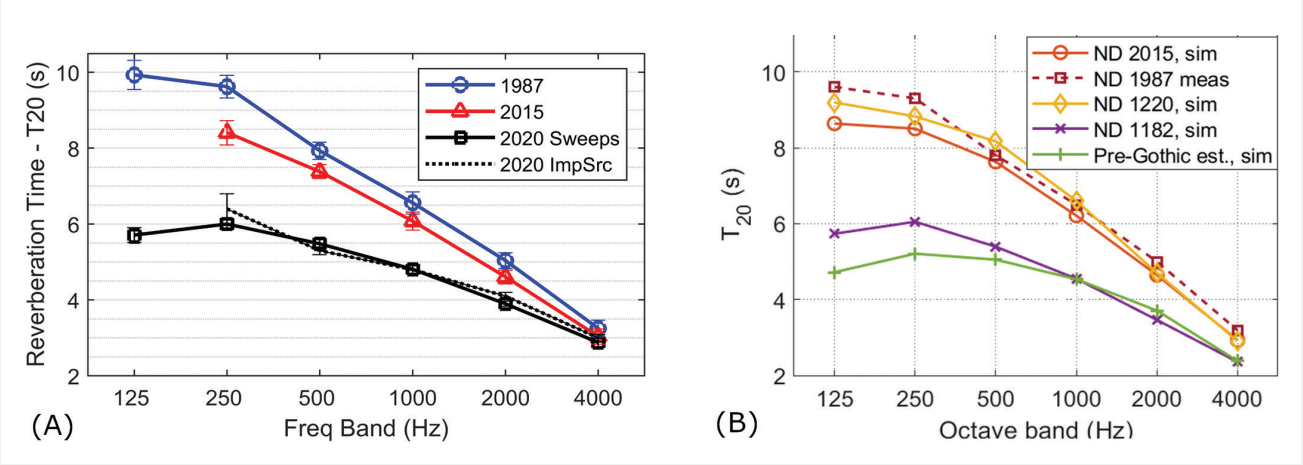


Figure 4. *Mean reverberation times (*T20*) over omnidirectional receivers for measured (meas; **A**) and simulated (sim; **B**) conditions for Notre-Dame (ND) and the speculative pre-Gothic church. Freq, frequency; ImpSrc, sweep and Impulsive type source stimuli.*

Culture to provide scientific support to the restoration team (Dillmann et al., 2024), we were granted access to the site for a third measurement campaign in June 2020 (Katz and Weber, 2020). The falling spire damaged the central part of the transept/altar marble floor, leading to restricted access to the central nave and transept due to the risk of falling debris and structural instability. The choir was also inaccessible due to debris. Side altars were used for storage, and scaffolding was installed for organ removal, along with a protection barrier enclosing the central nave. See the photos in **Figure 3** and a video documenting the measurement session (see youtu.be/YLi7ASosKvw, with English subtitles).

One can see the general decrease in reverberation times (**Figure 4A**) (Katz and Weber, 2020). We eagerly await assessing the Cathedral's acoustics in its updated state once the reconstruction is complete and the interior scaffolding is removed.

Historic Modeling/Acoustics

As a part of the 2015 measurement campaigns, a calibrated acoustic model of the twenty-first-century Cathedral was made (Postma and Katz, 2015). This was used as part of a research project on the use of binaural audio for media productions, where the aim was to create a virtual 360° re-creation of a concert in Notre-Dame where one travels around the Cathedral on a magic carpet (see bit.ly/3OZxf65; youtu.be/qcOPuIVpXxk), allowing for an appreciation of changes in acoustics with one's position in such a monumental space. Following the 2019 fire, it became evident that our model had broader applications. Through the Chantier Scientifique initiative, we have delved into detailed studies of the Cathedral's historical configurations and their cultural significance. Collaborating with experts in art history, architecture, and musicology, we have utilized the model to explore the acoustic impact of various elements such as draperies, organ placements and the enduring influence of paintings during Notre-Dame's early periods. Furthermore, we investigated the auditory experiences of significant events over the centuries, like the Festival of Reason, Napoleon's coronation, and the implications of Viollet-le-Duc's restoration efforts on the Cathedral.

A speculative model of the pre-Notre-Dame church was made following the archaeological traces found underneath the parvis, outlining a rectilinear building ≈35 m wide and ≈70 m long (Barbier et al., 2019), with two sets of side aisles flanking the main aisle. There is no record of the height of the ancient structure. To aid in the development of the speculative model of this building, a well-preserved, contemporaneous basilica-style church was identified and selected to stand in as a possible representation of the building. The church selected, the *Basilica of Santa Sabina all'Aventino* (see basilicasantasabina.it), is located on Aventine Hill in Rome, Italy. Originally built in the fifth century, the interior of the basilica has survived largely unmodified to the modern era, maintaining the

characteristic semicircular apse and flat, wood-paneled ceiling common to basilicas of the early Middle Ages. The acoustics of Santa Sabina were measured and reported in Cirillo and Martellotta (2005), and the base model was created and calibrated to the measurements following established procedures (Postma and Katz, 2015).

Because materials from the demolished preexisting church were reused for the construction of Notre-Dame, the same acoustical material properties were used to ensure continuity between the models. After verifying the Santa Sabina model calibration with measurements, the model was morphed to match the dimensions of the pre-Gothic church, maintaining the calibrated material properties as well as key design elements from Santa Sabina. Without knowing the height of the historic basilica, surviving contemporaneous basilicas of similar or larger size were consulted to maintain a consistent proportion of width and height for the center and side aisles, including *San Paolo fuori le Mura* (Rome), *Sant'Apollinare in Classe* (Ravenna, Italy), and the *Church of the Nativity* (Bethlehem, Israel).

The models of the Cathedral, representing the 1182, 1220, and 1225 states, were based on the 2015 calibrated model of Notre-Dame. The interior geometry of the calibrated model was altered to reflect the commonly held view of the construction timeline, with attention paid to changes in furnishings and decorations. Additional models were selected to examine the closing and completion of the nave, spanning approximately 1225 to 1320. These states include the "finished" state of the building when the nave was completed in 1220, several intermediate states as the chapels were built, and the state in 1320 after all the side chapels were completed. The results of some of these models in comparison with the acoustic states from the twentieth and twenty-first centuries can be seen in **Figure 4B**.

To accurately re-create the historical states of the church, it was important to verify the acoustic properties of textile and decorative materials present. Various historical materials were measured to assess their absorptive qualities. These included carpets from the liturgical choir, tapestries from workshops supplying the cathedral, and velvet hangings used for special occasions. Additionally, absorption coefficients were measured for loose straw and woven jute because it was common practice in the Middle Ages to use these materials for flooring in high-traffic areas.

These measurements enabled us to establish the appropriate material properties for inclusion in the acoustic models, although some uncertainties persist. For example, the impact of medieval clothing on audience absorption remains unknown because modern audience absorption coefficients are based on contemporary clothing. Similarly, the application of layers of whitewash to Notre-Dame's stone walls during its seventeenth-century renovation raises questions about the long-term effects on the characteristics of the Lutecian limestone. Despite these uncertainties, efforts have been made to acoustically represent the decoration and materials of the time in the historical models.

The Organs

We used the models to investigate the origins of the first medieval organs. The location of the fourteenth-century organ is uncertain, but it's believed to have been built in the second half of that century during renovations. Organ I is poorly documented, with limited information found in the Cathedral's chapter registers from 1426. These records mention that the organ blocked a window on an exterior wall. Six assistants operated the bellows using a wheeled blowing engine, and it was referred to as a "large organ" by a visitor in 1414 (Wright, 1989b).

We examined the acoustic effects of the organ's position and mounting height. Evidence from various sources suggests that the organ likely protruded from the triforium level, referred to as a "swallow's nest" (see bit.ly/3ST6PUw), somewhere in the nave of the Cathedral. Although the exact position within the nave remains uncertain, the southern wall is considered the most probable due to better climatic conditions because the wall does not receive direct sunlight. Comparing locations between the two nave positions reveals that although sound pressure levels are relatively high and uniform throughout the nave, an organ positioned in the second bay (closest to the nave) would be more beneficial to the choir due to its proximity to the apse. Additionally, positioning Organ I in the second bay above the chapel dedicated to St. Augustine aligns with the theological significance of music in his teachings (Canfield-Dafilou et al., 2023). **Figure 5** shows the results of the room acoustic parameter *center time* (i.e., the center of gravity of energy in the room impulse response) analysis

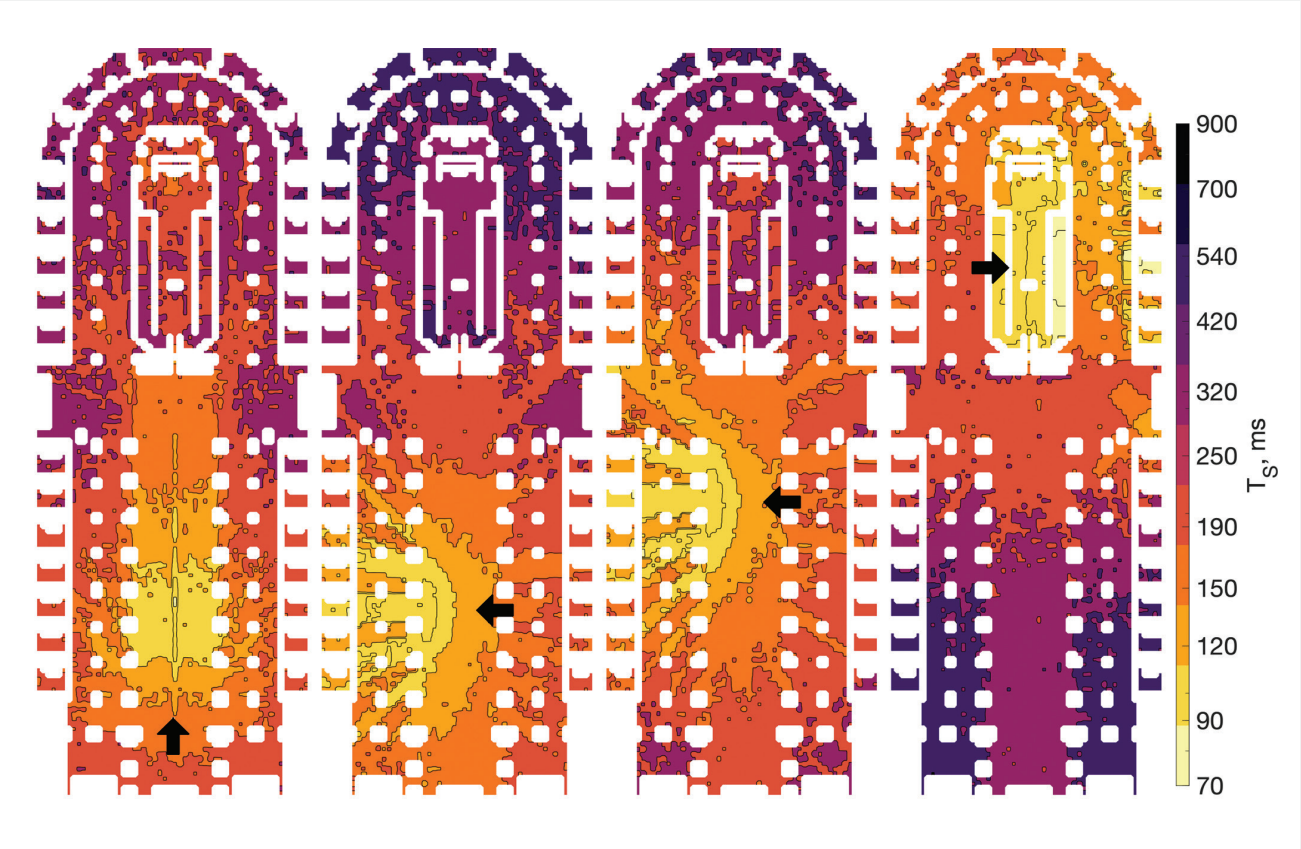
of the various locations considered. We opted for the use of center time as a more general notion of musical clarity compared with other parameters because it provides for a better interpretation of the energy distribution and is not limited in musical style in its interpretation (e.g., liturgical music found within Notre-Dame).

Acoustics of Gothic Columns

In large ancient structures like Notre-Dame, various columns and piers with distinct shapes scatter sound waves in all directions, termed volumetric diffusers. Unlike modern acoustic surface diffusers that diffuse sound at wall reflections, cylindrical obstacles like those found in buildings like Notre-Dame disperse waves in all directions. Examples include reflector canopies above concert hall stages and hanging panels in reverberation chambers. Although these objects typically have less impact on longer wavelengths, considerations for their curvature at lower frequencies are necessary. The rows of columns surrounding the nave in Notre-Dame act as lateral reflectors, reflecting Gothic architectural styles over centuries. Although columns produce limited reflections due to their finite size, these reflections arrive considerably earlier than most wall reflections.

We also investigated the sound scattering of various designs using physical scale models and numerical simulations. Both methods demonstrated strong agreement, validating the results. The scattered field showed audible reflections in all directions, with temporal spreading influenced by the shape of the scatter (Weber and Katz, 2022). Piers with smaller features can produce diffuse reflections similar to surface diffusers. Spectral differences between piers suggest the possibility of distinguishing between their reflections, indicating the need for further perceptual evaluations in realistic settings.

Figure 5. *Center time (T_S) for unoccupied condition, comparing organ position/orientations (**black arrows**). **Left to right:** location of the contemporary grand organ in the tribune; two positions in the nave; and the location of the contemporary choir organ. Lower values indicate earlier arriving energy and hence more musical clarity. Reproduced from Canfield-Dafilou et al. (2023), with permission.*



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Living Culture

The historical and culturally significant practices at Notre-Dame can be categorized into two groups. The first comprises singular events such as the Cathedral's conversion to the Worship of Reason during the French Revolution. This provides context but is not acoustically focused. The second includes long-term developments like the Notre-Dame School, preaching practices, and funerary traditions. Of particular interest is the Notre-Dame School, which emerged alongside the Cathedral's construction and had international influence. The historical state acoustic models were used to explore the relationship between architecture and music during this period. Two hypotheses were formed. The development of the Notre-Dame School was influenced by the Cathedral's acoustics and the new style was well-received by clergy members. We carried out two experiments designed to test these hypotheses based on research into musical performance and room acoustics.

Experiments

In the first experiment, a real-time auralization system was set up in an anechoic chamber to simulate different acoustic environments. The system rendered convolutions of binaural room impulse responses derived from acoustic models, modified to remove direct sound and floor reflections. Medieval music specialists were asked to sing three musical excerpts from different periods within the Notre-Dame School's timeline. These performances were recorded in various virtual acoustics, including those of the pre-Gothic cathedral, Notre-Dame from 1182, 1225, and 1320, as well as in an anechoic condition. Each choir performed the three songs three times each, repeating the procedure in the five acoustic conditions, resulting in 180 audio and video recordings per session. This setup allowed for testing the impact of changing acoustics on musical styles. If the hypothesis holds true, cleaner and more synchronized performances would be expected in the 1182 acoustics during the Notre-Dame School's pieces. Alternatively, if the null hypothesis is confirmed, no significant interaction between acoustic and performance parameters or even a negative impact on synchrony and performance metrics would be observed.

The ongoing analysis of audio and video data has revealed several intriguing trends. Similar to observations in solo vocalists (Luizard et al., 2020), the two choirs exhibit different adaptive behaviors. For instance, one ensemble's performance speed varies significantly across tested acoustics, whereas the other ensemble shows no statistically significant change.

The second experiment aims to understand how the high clergy may have perceived new musical styles in the cathedral. Singing experiments were recreated for offline listeners to assess three music genres across the acoustic conditions from the first experiment, listening from the perspective of the bishop. This test was presented to an international participant pool of 19 medieval and early-music specialists who were asked to separately score the amount of reverberation as well as its suitability of the acoustics for each genre. Although opinions on reverberation were consistent with earlier experiments, assessments of acoustic suitability varied widely. Another round of the experiment is planned to gather more participant data for further analysis.

The methods of auralization hold great promise for this kind of interdisciplinary research where scientists and sociologists, historians, or musicologists collaborate. When asked to provide oral feedback on their experience, members of the ensembles commented on the plausibility of the interactive system, noting that they had similar issues performing within the re-created cathedral acoustics as they do within physical cathedrals. However, the early results also underline another key point: no matter how sophisticated the experiments, they are nevertheless conducted with the cooperation of modern participants. This introduces a new research question at the

heart of the ongoing experiments surrounding the School of Notre-Dame: as musical styles and expectations change around us, what effect will they have on our taste and expectation for the acoustics we experience them in?

Public Mediation

Our research on Notre-Dame Cathedral's acoustics has spurred innovative projects aimed at highlighting its cultural significance. Virtual tours and audio productions like *Ghost Orchestra* offer immersive experiences of Notre-Dame's acoustic environment, showcasing its spatial variability (Katz et al., 2016; Postma et al., 2016). An extended audio-only version, offering an entire concert from several fixed positions, was produced during the Covid lockdown (see lavierge2020.pasthasears.eu) (Katz et al., 2021). Additionally, *Looking for Notre-Dame*, a radio fiction series, provides a three-dimensional (3D) sound experience, transporting listeners to explore the Cathedral's medieval essence through the mind of Victor Hugo (see bit.ly/49rKwwr; audio teaser: on.soundcloud.com/3HsPz) (Cros et al., 2022). The *Notre-Dame Whispers* audio-guide mobile app offers an immersive experience using binaural 3D audio narratives, covering various aspects of the cathedral's sonic history for visitors in multiple languages (see t.ly/QqN55 [Android]; t.ly/Abwfr [iOS]) (Muynke and Peichert, 2023).

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