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## Ears of the past, an inquiry into the sonic memory of the acoustics of Notre-Dame before the fire of 2019

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## ABSTRACT

This interdisciplinary study brings together acousticians and anthropologists to examine the memory of the acoustics of Notre-Dame de Paris before the fire of April 2019, using a qualitative approach to collect the testimonies of 18 people involved in the sound usages of the cathedral. Testimonies were analyzed in light of research conducted in the anthropology of the senses, sensory perception, memory, and cultural heritage. Analysis highlights an apparent contradiction between the remarkable acoustics of the monument before the fire and the impression of musicians. These musicians reported a struggle to tame the cathedral's sound space, to hear each other well enough to craft their performances and to reach an acceptable level of clarity in their musical practice. These phenomena are examined with acoustic measurements and numerical simulations using a calibrated geometrical acoustics model of the cathedral before the fire, which allows for an objective exploration of the acoustic characteristics of Notre-Dame. This analysis concludes that the well-known reverberation of Notre-Dame, as well as the acoustic barrier of the transept and the poor acoustic return on the podium (the usual place for concert performers) negatively impact singers' comfort. This highlights the tension between the original architectural design of the cathedral and its modern religious and cultural usages. However, the regular occupants have developed a deep familiarity with these constraints during their ritual and musical practices, adjusting to the acoustics in a unique way. Such a tradition of adaptation must be considered as a part of cultural practice, not to be overlooked during the reconstruction.

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## 1. Introduction

The acoustics of heritage sites such as churches, ancient theaters, or concert halls are a valuable record of their physical state over the centuries because they are the result of their particular geometry, construction materials, decoration, and furnishings; they can be considered an audio snapshot in the same way that a photograph reflects the visual aspects of a room's appearance. As such, the acoustics change when the room is refurbished, renovated,

refurnished, or redecorated, but also when it suffers unexpected damage due to natural disasters or accidents, such as the fire that occurred at the cathedral Notre-Dame de Paris on April 15, 2019. With the recent adoption of UNESCO resolution "The importance of sound in today's world: promoting best practices", complementing the UNESCO Convention for the Safeguarding of the Intangible Cultural Heritage [28,29], the acoustic soundscape of places both existing and historical merit reflection, preservation, and scientific study [6,8]. Beyond the mere physical phenomenon, the subjective perception of the acoustics of a space constitutes a real heritage value that must be documented and archived: its importance is all the greater in places of worship where sound and music are part of the religious rite and constitute in this respect a key element of the experience of the faithful and visitors. Most academic writing approaches these material and immaterial dimensions sep-

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**Fig. 1.** View of the interior of the Cathedral Church of Notre Dame de Paris (circa 1760) Source: [catalogue.bnf.fr/ark:/12148/cb414229898](https://catalogue.bnf.fr/ark:/12148/cb414229898). Among the possible changes after the reconstruction phase, the re-installation of the *Mays* in the nave is mentioned, which could modify the pre-fire acoustics. The *Mays* are large paintings made between 1630 and 1707, donated by the Parisian goldsmiths' guild to the cathedral on May 1st of each year, which formed additional reflective walls in the nave. Note the absence of pews, installed later in the 20<sup>th</sup> century, which necessarily had an impact on the acoustics. Also absent is the rood screen of the 18<sup>th</sup> century, which disappeared during the French Revolution, and must have had an important impact on the diffusion of the sound in the cathedral, a situation unknown to the modern day musicians [5].

arately. We think however, as demonstrated by the collective work [9], that their combination is necessary to understand the evolving sonic environments of a heritage building like Notre-Dame de Paris.

As we write these lines, the cathedral has been closed for three years. After the shock that accompanied the fire, questions about its reconstruction followed. We now know that the roofing frame, the spire, the damaged elements, will be rebuilt “identically”<sup>2</sup>. Nevertheless, the question remains: “Will Notre-Dame recover?” Will it really be restored as it was before the fire? In other words, will we feel again the same emotions that were felt when experiencing the cathedral before the fire? This question especially concerns the acoustics, because the interior design is not necessarily subjected to the same requirement of historical authenticity<sup>3</sup> and we know that modifications over the course of history have had an impact on the interior’s acoustics [14,19]. For instance, consider the paintings that used to hang along the nave of the cathedral in Fig. 1. It will be possible, with the reopening, to compare the post-reconstruction acoustics with the pre-fire acoustics, thanks to measurements carried out in 1987 and 2015 [14,23]. These measurements were previously used in the creation of a geometrical acoustics model that reflects the physical reality of the acoustics of Notre-Dame at that time. While acoustic parameters are objective, the qualitative assessment of the buildings acoustics are, necessar-

<sup>2</sup> Faced with the controversies triggered by the announcement of the Head of State, the day after the fire, of “a contemporary architectural gesture” for the reconstruction of the cathedral, the National Commission of Heritage and Architecture (CNPA) finally ruled on a reconstruction of the building “exactly as it was” in its former state, bringing back the architecture of Viollet-le-Duc, roof and spire included, with the help of original materials.

<sup>3</sup> We note that some controversy broke out in Dec. 2021 concerning Notre-Dame’s interior redevelopment project proposed by the Diocese of Paris. The National Commission for Heritage and Architecture (CNPA) gave a generally favorable opinion of various elements of the proposition: “We stated that we had no opposition in principle to an ambitious redevelopment project desired by the diocese. But we also clearly rejected a number of points that were presented to us...”, said Alexandre Gady, historian, specialist of Notre-Dame, and member of the CNPA [18].

ily, in relation to the function and use of the space, which have clearly evolved over its long history.

## 2. Research aim

In collaboration with the project PHE (The Past Has Ears) [13] and the project PHEND (The Past Has Ears at Notre-Dame), a survey on the sound perceptions of the cathedral before the fire, was therefore commissioned by the working group on Acoustics of the *Chantier scientifique CNRS/Ministère de la Culture/Notre-Dame*<sup>4</sup> and carried out jointly with the working group *Émotions/Mobilisations*<sup>5</sup>, in order to collect testimonies. The result is an interdisciplinary study bringing together acousticians and social and historical anthropologists, that may further provide some guidance to the reconstruction team.

The study presented here outlines a first analysis from this collection, tending to show the heuristic value of the trans-disciplinary approach combining sciences of acoustics and anthropology. It allows us to consider the cathedral from the point of view – or rather from the point of listening – of its active participants, through an acoustic analysis of the various experiences resulting from the sonic uses of the cathedral before the fire.

Methodologies and tools employed in this study are presented in Section 3. Results are then presented and discussed in Section 4, following themes that emerged from the testimonies: the acoustic impressions of both early and late reverberation, the architectural particularities and spatial variations of the acoustics throughout Notre-Dame, and issues related to the amplification system.

<sup>4</sup> [notre-dame-de-paris.culture.gouv.fr/fr/acoustique-acoustic-task-force-notre-dame.dalembert.upmc.fr](https://notre-dame-de-paris.culture.gouv.fr/fr/acoustique-acoustic-task-force-notre-dame.dalembert.upmc.fr)

<sup>5</sup> [notre-dame-de-paris.../emotions-et-mobilisations](https://notre-dame-de-paris.../emotions-et-mobilisations)

### 3. Probing the sonic memory: when acoustics and anthropology join forces

#### 3.1. Deciphering the language of perceptions

“Blue... Light... Vibration...” So begins the list of words with which Aurélien P., stage manager of the cathedral in charge of the sound system since 2008, expresses his perception of the acoustics of the building. “Blue”, he explains, because “in Notre-Dame there were many stained glass windows with Mary surrounded by blue, symbolizing what it can symbolize, the sky, the sea... It is a color, indeed, that sends me immediately back to Mary.” How can we understand this association between the figure of the Virgin – patron saint of the cathedral –, a color and a sound experience? This example immediately brings us face to face with a problem that we were confronted with during our investigation: putting sound perceptions into words. “Any sound experience exceeds what can be said about it” so that one proceeds most often by analogies and various correspondences in order to report it [20]. Blue is a translation, explicit for Aurélien but hermetic for us, other than to understand that his perception of the acoustics of Notre-Dame is intimately linked to his perception of the building as a whole.

If the visual register is commonly called upon to express what one hears [20], it is possible that, here, its use is reinforced by the polysensorial dimension which characterizes the sensory experience in the cathedral. The polysensoriality is indeed one of the dominant themes which emerges from the survey of the general public previously realized [27,30]: Notre-Dame is a space that amplifies emotions by engaging multiple senses, so it is not surprising that some senses are expressed through others. Sets of lights, colors, musical vibrations, such are signs of the synesthetic experience which characterizes the perception of the ritual spaces, in particular for the Christian world, of Gothic cathedrals [1, p. 74]. Therefore, how do we untie the sonic perceptions of Notre-Dame from the other sensitive representations to which they refer? Is it possible to hear Notre-Dame without, at the same time, seeing and feeling it?

Added to this difficulty is the time that has passed since the building closed, the time that transforms experience into memories. We can only hear the acoustics, today, through the memories of those who have been there. But as writes the anthropologist Gediminas Lankauskas, one of the first to explore sensory memory, “the paradox of memory is that its main concern is the present” [15, p. 52]. In other words, memories are dependent on who we are at the moment we remember, shaped by our personal experiences as well as by our social and cultural affiliations. This last point has an impact on the memory of the cathedral. The intensity of the collective emotions, in reaction to the flames and the destruction, revealed, if not amplified, the importance of the attachment of the French and the international community to one of the emblems of world heritage. The sociologist Nathalie Heinich, a specialist in art and heritage, showed how heritage objects are invested with values on which emotions are anchored, such as the value of authenticity, “which is attached to the continuity of the link between the current state and the origin of the object”, and that of beauty, which in turn “is attached to the aesthetic quality of the object in question” [10, p. 202]. Thus, among other symbols, Notre-Dame is today unanimously considered as a “jewel” – “jewel of Gothic architecture” or “historical and cultural jewel”<sup>6</sup> whose acoustics, emanating from the building, are necessarily “magnificent”. Thus, when we asked Thaïs R.W., a singer of La Maîtrise<sup>7</sup>,

about the potential improvements that the reconstruction could bring, she was flabbergasted by the incongruity of the question: “In fact, for me”, she explains, “it was so perfect that I would have nothing to... For me, they are the best acoustics, it’s the best venue.” There is nothing to change, nothing to modify, on the contrary, “if it could remain the same, that would be incredible.” So, what was the sound like? What can we learn, with more precision, about the way in which the sounds propagated and, more importantly, were received there? How do we pass beyond the systems of representations in order to hear Notre-Dame, in all its complexity, as it was before the fire?

#### 3.2. Fieldwork

For this research study we chose to interview only people familiar with the cathedral who have developed an auditory acuity associated with a rich vocabulary to translate their sound experiences. We wished to gather more precise information than would otherwise have been possible by interviewing a public that was charmed by the magnificence of the place. Thus, we targeted people who had worked at Notre-Dame and whose function required a particular attention to the acoustic response of the place. During the spring and summer of 2021, we met 18 people, including 3 musicians who exercised multiple functions. In all: 4 organists (3 titulars of the great organ and 1 of the choir organ), 7 singers, 2 choirmasters, 2 organ builders<sup>8</sup>, 2 stage managers, 1 chaplain, and 3 composers. Each of them was interviewed individually at least once, with the exception of two singers who were interviewed as part of a group (one of these singers was also interviewed individually). Excluding that of Jean-Loup B., interviews lasted from 1h23min to 3h5min (avg. 2h8min, standard deviation 33min). The interview techniques combined life stories and semi-structured interviews; several people were called back by phone to clarify certain aspects. This survey also benefited from previous studies and fieldwork conducted within La Maîtrise as part of the research conducted by the working group Émotions/Mobilisations, as well as on the organ and church musician communities [3].

By focusing on people involved in the vocal and musical productions within Notre-Dame, it was also intended to target a community sharing a set of identifiable codes and values, through which to decipher the verbalization of sonic perceptions. Accessing these *sensory worlds* requires culturally specific learning, “people inhabit different sensory universes” shaped by their experience and the various modalities of their socialization. As the anthropologist David Le Breton explains, “to come into the world means to acquire a style of seeing, touching, hearing, tasting and feeling specific to the community to which one belongs” [16, p. 46]. If he concludes from this observation that an anthropology of the senses opens new perspectives on the study of societies [17], we suppose that our knowledge of the community of Notre-Dame and, more generally, of the musicians’ universe enables us to properly decipher their statements on their common sensory experiences.

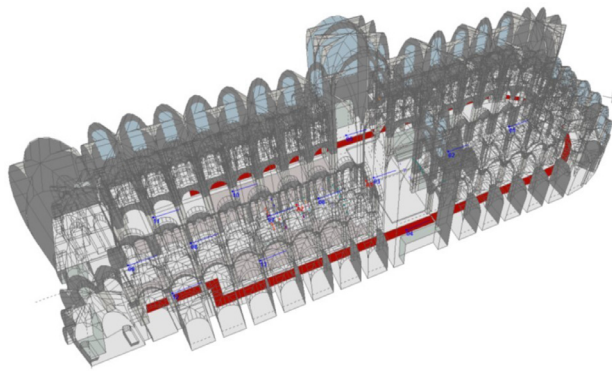
#### 3.3. Acoustic analysis: a revealer of perceptions

In an attempt to disentangle what, from the sensory perceptions, is more specifically related to the physics of acoustics, some of the comments reported by the interviewees were studied

<sup>8</sup> Jean-Loup B., participated in the restoration of the great organ in 1963, at which point he began to take care of the maintenance of the instrument which he continued until the beginning of the 2010s. He also directed the 1992 restoration, with his associate Bertrand C. (who took over the 2014 restoration), who was also interviewed. The interview with Jean-Loup B., in view of his knowledge of Notre-Dame de Paris over a long period of time, was conducted over 5 days, at his home, in the form of a life story.

<sup>6</sup> As regularly found in the media.

<sup>7</sup> La Maîtrise Notre-Dame de Paris is a singing school created in 1991 by the City of Paris, the Ministry of Culture and the Diocesan Association of Paris. It is also in charge of coordinating all music in the cathedral (concerts and liturgy).



(a) Global view.



(b) View from the great organ towards the choir. The galleries are visible on both sides of the nave.

**Fig. 2.** Visualization of the geometrical acoustics model of Notre-Dame de Paris.

through simulations via a calibrated geometrical acoustics model [21,22], or compared against acoustic measurements from Notre-Dame in 2015 [14] that also served for the calibration of the geometrical acoustics model (see Fig. 2). The model allowed us to simulate particular situations within the cathedral, for example with a number of singers in different spaces, such as on the podium or in the choir, and to analyze the acoustic parameters of the resulting sound field. A floor plan of Notre-Dame with a glossary of the various architectural spaces mentioned in this study is shown in Fig. 3.

The model can also be modified by adding or removing architectural elements in order to simulate a past or future situation. This methodology was previously employed in a study showing that the addition of running carpets on the floor intended for the visitors in the ambulatory of Notre-Dame (visible in red in Fig. 2a) led to a decrease of the reverberation time observed between 1987 and 2015 [23]. In addition, the model simulations also allow the generation of the *room's impulse responses* which can be used for auralization purposes, *i.e.* to render the simulated acoustic characteristics of the space audible, as if the listener was there, during concerts [12] or through virtual reality experiences [19,24]. Simulations for this study were carried out using CATT-Acoustic v9.1f and TUCT v2.0f.

### 3.4. Acoustic metrics

In the present study, simulations carried out using the geometrical acoustics model or analysis of previous on-site measurements were used to ascertain some of the scenarios described by the interviewees, through the use of metrics commonly used in room acoustics. Typical room acoustic metrics and their measurement procedures are detailed in ISO 3382-1 [11]. To interpret the analytical results from a perceptual standpoint, we must take into account

the sensitivity of the human ear (*i.e.* the human auditory system as a whole) to variations of each metric. Our sensitivity to changes in an acoustic metric, quantified with respect to its lowest variation detectable by the human ear, is denoted just noticeable difference (JND) and is based on previous studies in the literature. The acoustic metrics selected as the most pertinent in this study are:

- Reverberation time (RT, measured in s) indicates the time it takes for an impulsive sound to decay by a factor of 1000 (*i.e.* 60dB) in a room. JND = 5%.
- Acoustic clarity ( $C_{80}$ , measured in dB) reflects the readability or “intelligibility” of a complex sound<sup>9</sup>. In the context of music, clarity represents the degree to which the individual sounds in a musical performance stand apart from one another [4]. In reverberant conditions, individual sounds tend to overlap with one another, resulting in reduced musical clarity. In this study, we have opted for the term “clarity” rather than “intelligibility” to assess the readability of the musical structure of the pieces interpreted by musicians, following the trend in use in the field of acoustics, although French musicians commonly use the expression “intelligibilité de la musique”. For music, clarity is generally calculated as the ratio between the early (*i.e.* arriving before 80ms) and late energy (arriving after 80ms) of a sound<sup>10</sup>. JND = 1dB.
- Early stage support ( $ST_{early}$ , measured in dB) reflects the quality of the room return between musicians from the same ensemble, by quantifying the acoustic energy received 1m away from the source during the time window 20ms to 100ms after the direct sound. JND = 1dB.

Room acoustic metrics are typically analyzed in octave band frequencies and this is the basic operating range of the simulation software. In this study, we report the metrics calculated throughout the space in the form of colormaps, depicting their variation across positions in the cathedral, or as direct values corresponding to discrete positions.

By comparing various simulations, we were able to identify situations that are more favorable than others – for example, a location in the cathedral that has a higher value of  $ST_{early}$  than another location is objectively more favorable for the musicians during their performance, while a higher value of  $C_{80}$  is more favorable for the audience – in order to corroborate certain aspects reported during the interviews. The geometrical acoustics model and associated measurements thus act here as a revealer of perceptions.

## 4. Results and discussion

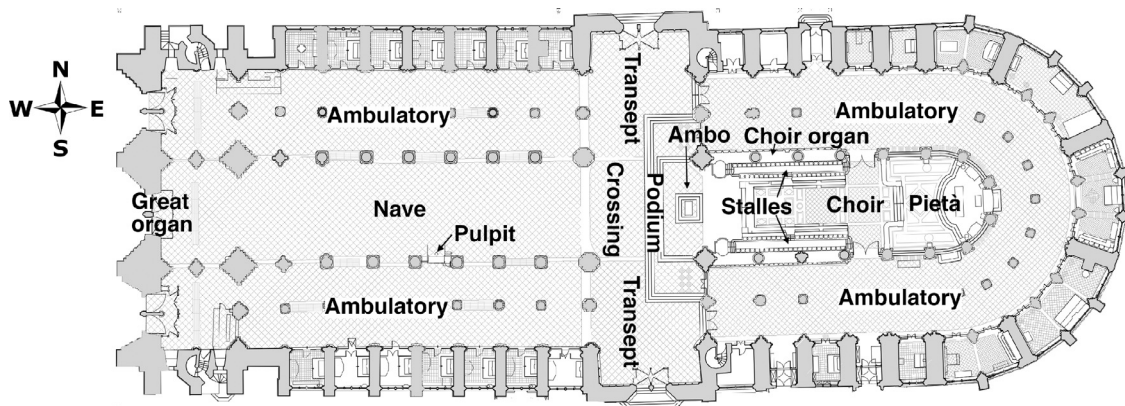
Although for a captivated public as well as for certain singers of La Maîtrise, the acoustics of Notre-Dame are a model of perfection, comments from other musicians, especially from choirmasters, induce more nuances. “Notre-Dame, it’s an acoustic that is absolutely unique”, notes a student of the adult choir<sup>11</sup>, but “I wouldn’t say that it’s a sound that I like very much. It’s a sound that’s great to hear from the audience, but for singing it’s pretty uncomfortable”.

The perception of acoustic quality fluctuates greatly depending on one’s expectations, what one is looking for through a sound experience, as well as, more pragmatically, where one perceives it from: from the position of the musicians or that of the listeners in

<sup>9</sup> Clarity is different from aspects of language comprehension, quantified by other metrics such as the Speech Transmission Index (STI) [2].

<sup>10</sup> For comparison, a temporal division of 50ms is used for the clarity of speech, denoted as  $C_{50}$ .

<sup>11</sup> La Maîtrise is composed of three ensembles according to the age of the singers: the children’s choir, the young ensemble, and the adult choir.



**Fig. 3.** Floor plan of Notre-Dame de Paris with a labeling of architectural elements referenced in this study. The upper levels above the ambulatory on either side of the nave and the apse are called the galleries.

**Table 1**  
Reverberation Time of Notre-Dame de Paris as a function of octave bands, for an unoccupied cathedral. Results from the geometrical acoustics model and in-situ measurements from Katz and Weber [14].

Octave band (Hz)	RT (s) modelled	RT (s) measured
125	8.7	–
250	8.4	8.4
500	7.5	7.4
1k	6.4	6.1
2k	4.7	4.6
4k	3.0	3.0

the nave. For the singers, explains Sylvain D., a choirmaster specializing in Gregorian music, “Notre-Dame’s acoustics are difficult to tame”, which is particularly noticeable during concert rehearsals: “Even with singers who are really used to singing in Notre-Dame, in a dress rehearsal, it often takes half an hour, three-quarters of an hour, or even an hour, before they feel at ease.” For Henri C., director of La Maîtrise and also a choir director, this moment can be particularly distressing, “no matter how experienced you are, there are always, roughly, the first forty minutes when no one understands anything. You set up, you sing and it doesn’t set. It’s a weird thing, really, it doesn’t set... So we get stressed, we try to control everything but it doesn’t let you... And then, all of a sudden, the dough starts to set... then we start to breathe!” How can we understand, then, why it is so difficult for the singers to adapt to the acoustics, although they were used to performing several times a week in the cathedral during religious services and weekly concerts?

#### 4.1. A remarkable reverberation

“Notre-Dame, it is 8s of reverberation”, was told to us repeatedly, to the point that one can consider this persistence of the sound as the acoustic signature of the cathedral. According to the relation established by Wallace Clement Sabine [26], the reverberation time of a room is proportional to its volume, and inversely proportional to the surface area of its walls weighted by their absorption properties. Notre-Dame has a very significant reverberation time, on the order of 9s for the lowest frequency bands (see Table 1), in the absence of an audience<sup>12</sup>.

<sup>12</sup> The reverberation time of a room may decrease significantly with its occupancy rate, depending on the amount of absorbing material already present.

This reverberation, often considered as a “jeweled box” that “magnifies” the sound – especially by the organists of the great organ who are at pains to distinguish, in the beauty of the sound of the instrument, the contribution of the architecture from the product of the organ builders. The reverberation is, nevertheless, frequently pointed out by the singers as one of the parameters that disturb the execution of the singing: “Because the acoustics are quite reverberant, the sounds tend to mix together”, explains Carlos B.V. The singers, however, know how to control their voice to preserve the musical clarity in this type of acoustics, typical of cathedrals: “It is necessary to redouble precision, especially for the consonants, so that it does not become muddled from the third row on”, “one can articulate more, to have more presence on certain types of consonants, one can also exaggerate a little the natural rhythm of the text, the accents. We adapt”, they tell us, as do the choirmasters when they choose pieces from the repertoire and the composers when they write a piece for Notre-Dame. You make sure to slow down everything you conceive in your head”, explains Caroline M., “by telling yourself: you need that time to read the acoustics and situate your sound into the acoustics of the space.” Jean-Charles G., for his part, insists on the care to be given to the harmonic rhythm<sup>13</sup> in order to avoid the confusion that would arise from overlapping dissonant tonalities. However, this does not prevent each dress rehearsal from systematically beginning in a cacophony, which, curiously, does not seem to be the case for the religious services. Perhaps because the singers were used to singing the masses on site almost daily, while the concerts, less frequent, were prepared in a classroom with much drier acoustics: “In general, we prepare a lot of things, and once we get to the cathedral, we change a lot of things”, explains Matthieu W., “we change a lot of tempi, dynamics, because it doesn’t work.” However, the concerts were most often preceded by only one rehearsal in the cathedral, “as we were already occupying a lot of space and there is not only us, in general, it was a dress rehearsal-concert”; a condition that makes the question of mastering the acoustics particularly sensitive. All the more so since, in addition to the reverberation, another acoustic parameter is decisive for the singers: the early response of the cathedral.

#### 4.2. The early room response

In such a reverberant environment, the vocal emission must be precise enough to ensure a satisfactory clarity of the singing. To

<sup>13</sup> The speed at which the harmonies change. This is why Gregorian chant, which is modal, is particularly well adapted to long reverberation times, as is the French polyphony according to Yves C. who quotes the Great Motets by Campra.

achieve that, the connection between the members of the choir is indispensable to “form a block” in order to “craft the sound”.

But on the podium, *i.e.* at the crossing, which is the usual location of the singers during concerts whereas the services are sung from the choir, “we can’t hear each other.” At least, says Vincent P., “we can hear our neighbor, but the person who sings next to him, we have difficulty hearing him.” Moreover, some singers report that they feel that “the sound is lost” in the immensity of the nave, like Sylvain D.: “It is nevertheless an immense vessel [...], it is not a small Romanesque church where one makes *beuuu*, like that, and then immediately that sets and then one gets the acoustic return. When we sing, we like to have... Finally, when we get the return of the sound, it carries the energy and we can lean on it, whereas in Notre-Dame, it is more difficult to have it.”

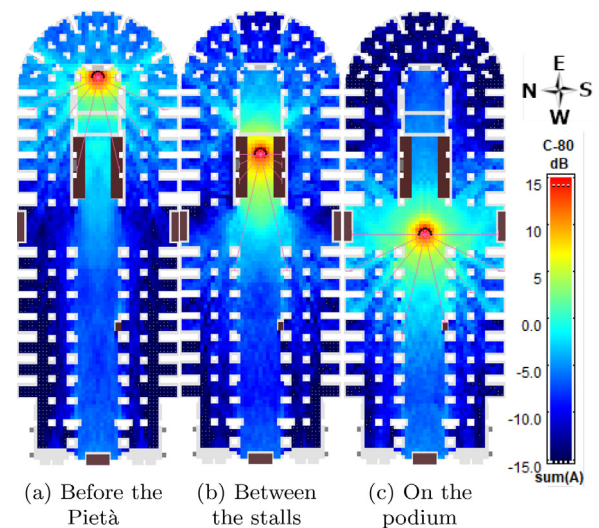
In the choir, however, the room return seems easier to perceive: “we can hear each other better”, report the singers. The anthropologist would like to see, here, the illustration of the social harmony that the training within the choir school shapes: a group welded together by the music and the time spent together; the choir being, for the singers, a “small bubble” protected from the crowd by the enclosure of the stalls, within which they feel, more than elsewhere, at home.

Although appealing, the hypothesis should not mask the physical reality. Some singers, like Matthieu W., have the feeling that if it is “comfortable” to sing between the stalls, it is “because there are these walls surrounding the choir that hold back the sound a little bit.” We ran the hypothesis through the geometrical acoustics model and calculated the acoustic index  $ST_{early}$ . The recommended threshold for this index, usually applied to concert halls, is  $-13\text{dB}$  [7]. Running the simulation for 8 receiver positions evenly distributed around a singer at 1m distance, we obtained the following values of  $ST_{early}$  for a position in the choir and on the podium:

- $ST_{early} = -14.8 \pm 0.5\text{dB}$ , choir
- $ST_{early} = -24.7 \pm 0.8\text{dB}$ , podium

In the choir, singers therefore enjoy an early stage support close to the recommended threshold for concert halls. On the other hand, the early stage support on the podium is almost 10dB lower than that of the stalls, a significant difference<sup>14</sup> that corroborates the hypothesis formulated by the singers correlating the cacophony experienced during the dress rehearsals to the low degree of room return on the podium.

Given these figures, one might be surprised by the choice of the podium as the preferred location for the concerts, yet the social criteria that led to this choice should not be overlooked. The podium is a recent construction that is appropriate, in the first place, to the requirements of the liturgy as defined in 1965 by the Second Vatican Council ordering the officiants to be closer to the congregation, which has continued to grow in number in the second half of the 20th century, as Laurent P., the cathedral’s stage manager, explains: “In 2021, we are no longer in a configuration of services such as the cathedral may have known them over the centuries. [...] After the Second Vatican Council and with the development of tourism, there has been a kind of reversal: the canons in the choir no longer say the services for themselves, but rather services are said daily for thousands of people.” The clerics thus left the choir to project towards the faithful and the tourists assembled in the nave, whereas the singers remained in the stalls since the singing for the ritual is not destined to be embodied contrary to what would be the case in a secular musical performance or concert. In this context, the podium becomes an ideal stage that favors proximity with the public: the singers are visually and sonically accessible, since their singing is perceived more distinctly in



**Fig. 4.**  $C_{80}$  maps (A-weighted sum of octave-band values, reflecting the non-uniform sensitivity of the human auditory system across frequencies, with higher sensitivity for the octave bands 1kHz to 4kHz) for several positions of a choir comprising 8 singers arranged in a semicircle around a conductor’s position at a distance of 1.5m (represented by black dots). The sound system has not been included in these simulations.

the nave than when they sing from the choir. This is a configuration in opposition to the original design and use of the cathedral, in which the singing of the choir did not have to be intelligible in the nave. On the contrary, just like some architectural elements – rood screen, wooden panels of the stalls, etc. – isolated the choir from the rest of the building, the acoustic sensation provided by the remoteness of the chant created a symbolic distance between the sacred and the people. [5,25].

#### 4.3. The transept barrier

The  $C_{80}$  maps in Fig. 4 clearly show the impact of the location of the singers on the clarity of the music when perceived from the nave. Positive values of  $C_{80}$  indicate better clarity while negative values indicate poorer clarity<sup>15</sup>. When music is generated from different positions in the choir (Fig. 4a and b), clarity is already low when it reaches the nave, whereas when it is emitted from the podium, clarity is better preserved in the first rows of the nave before decreasing in the second half of the nave, *i.e.* on the west side of the pulpit (Fig. 4c). Overall, the clarity in the nave of Notre-Dame is inversely proportional to the distance between the singers and the nave. However, in some other churches this relation does not necessarily hold true, as testified by Caroline M.: “There are some acoustics where [the sound] passes over the altar before reaching the public quite closely.” To illustrate her statement, she mentioned the church of Saint-Roch in Paris, where she feels that the sound propagated to the nave is better preserved when sung from the choir than from the podium (the choir being further away from the nave than the podium). This difference with Notre-Dame is probably due to some architectural specificity of the church of Saint-Roch compared to Notre-Dame, which remains to be studied.

In Notre-Dame, the reduction in clarity with distance is exacerbated by the presence of a wide and tall transept in between the choir and the nave, and the presence of side galleries along the choir and the nave, and open to the transept, as illustrated by the drop of  $C_{80}$  observed in that region (Fig. 4a and b). The

<sup>14</sup> Equivalent to 10 times the JND of  $ST_{early}$ .

<sup>15</sup>  $C_{80}$  does not depend on the sound level: for a fixed room and fixed source and receiver positions,  $C_{80}$  doesn’t change when the source level changes.

transept thereby acts as a barrier for the clarity of music. The strong decrease in clarity is likely due to the sudden expansion of the transept in both height and width, reducing constraints on the acoustic propagation to occupied areas. The choir is a relatively narrow area, bordered by the wooden backs of the stalls, which is in stark comparison to the transept, open across the full width of the cathedral and roughly 4 times wider than the space between the stalls. The stalls surrounding the sources act as reflective sidewalls, producing primary early reflections reinforcing the direct sound, thus preserving the early energy level. On the contrary, the absence of close reflective surfaces in the transept has the opposite effect: the energy radiated to the sides travels much farther before encountering a reflective surface, with the subsequent reflections no longer contributing to the early sound energy. This, combined with the loss of early energy which enters the upper gallery levels and only returns to listeners as very late energy, results in a notable decrease in  $C_{80}$  as the sound passes through the transept.

Although the level of clarity in the first half of the nave, *i.e.* on the east side of the pulpit, depends on the location of the singers in the church, the clarity in the second half of the nave, *i.e.* on the west side of the pulpit, remains significantly poorer ( $C_{80}$  consistently lower or equal to  $-2.5\text{dB}$ ) regardless of the singers position, as Henri C. notes: “It is a very big cathedral, even if it is not the biggest cathedral, it remains a big vessel<sup>16</sup> and it’s true that when you’re at the back, without help, you have a very messy sound.”

#### 4.4. On the amplification of singing and speech

In order to adapt its acoustics to its new sound usage, the cathedral was equipped with a very sophisticated sound system aiming at preserving “the greatest clarity and intelligibility” of the singing in the entire nave, which in addition allows the words of the priests to be heard by all. “It was really done with great finesse” recalls a singer, so much so that even expert ears were misled. Sylvain D. likes to tell the revealing anecdote of the Australian composer who was amazed to learn that the concert he had just heard was amplified, “you don’t notice it!” The sound system was designed to be “discreet and efficient”, almost unnoticeable. The stage managers are careful to create the impression of a natural sound within the cathedral.

Another benefit of the sound system is reported by the chaplain Henry V.: “The particularity of Notre-Dame was its immediacy. It didn’t feel like the sound had to take long to get to the other end. What I wanted to say was fully present. In many places, other churches or conference rooms, I always feel that there is a loss. At Notre-Dame you could expect to be heard by everyone, at the same time. It’s not that common.” The fact that the acoustic experience of the priest is clearly influenced by the use of the sound system led us to analyze more finely some of the singers testimonies that seemed contradictory at first sight. For example, Carlos B.V. explains that at the podium, when singing with the rest of the vocal ensemble during the concerts, “you really couldn’t feel what you were producing”, whereas he “could hear the room return very clearly” when singing from the *ambo*<sup>17</sup> (see Fig. 3) as a soloist during the religious services.

The difference between those two situations comes from that two sound systems co-existed in Notre-Dame, each of them being used for a specific purpose: while in the first situation the singing of the ensemble was amplified by the sound system specifically used for the concerts – the “Maîtrise circuit” –, in the second situation Carlos’ voice was amplified by the sound system used for

the religious services – the “speech circuit”. The speech circuit is made of “a whole bunch of loudspeakers scattered throughout the cathedral, in the galleries, in the ambulatory, in the choir, in the nave, really everywhere” explains Laurent P., whereas “La Maîtrise circuit”, as it was used for the concerts, “took over from the fifteenth row and covered the whole back of the nave.”<sup>18</sup> This example shows that the acoustic return as reported by some interviewees does not necessarily originate from the room acoustics themselves but sometimes from the presence of loudspeakers in their vicinity, especially when singers were at the *ambo*. We note that we have always taken this parameter into account when analyzing the testimonies<sup>19</sup>.

## 5. Conclusion and future works

The acoustic image of the cathedral Notre-Dame de Paris, which has gradually emerged through the collected memories of people involved in its sound usage, is evidence of the complex relationship between the building’s architecture and contemporary musical and liturgical demands. Faced with this situation, it may seem surprising that none of the interviewees mentioned the possibility of modifications to the interior architectural design in order to improve the acoustics for the singers, whereas other actors, such as the Diocese of Paris, took advantage of the restoration to conform the interior design of the cathedral to new liturgical and touristic usages. We hypothesized that the heritage values associated with Notre-Dame contribute to the perception of the quality of the acoustics as well as to the wish expressed by many musicians to find them unchanged after the restoration. The testimonies invite us to consider this attachment as the outcome of the time spent taming the sound space, by collectively elaborating specific know-how through mobilizing a diversity of experiences and creative solutions. As one singer put it, the acoustic challenges of Notre-Dame “make us want to go beyond them”, and consequently “we propose things in the cathedral that are more interesting than the frontal concert.”<sup>20</sup> “It’s such an exciting place to inhabit musically and especially to explore sonically. That, for us, is exciting”, explains another. For the singers, difficulty can also be a source of pleasure. By challenging their skills and pushing them to excel, the cathedral itself gives value to their performance. The magnificence of the sound becomes a goal to be reached that engages the singers intensely. It is partly through this quest that they shape their skills, to become Notre-Dame musicians. Therefore, a restoration of the building that seeks to improve the comfort of the musicians – the singers in our example – should not ignore the physical, social, and symbolic relationships between the communities involved and the building. From the singers’ perspective, this means considering the richness and diversity of the acoustics of Notre-Dame.

At this preliminary stage of our research, we focused on the most frequently mentioned scenarios, the analysis of which was made possible by a sufficient number of collected testimonies, thereby excluding the range of artistic devices imagined by choral conductors and composers to shape, through alterations of the spatial settings of the music, a sensory universe that favors wonderment. Having now laid the foundations of this research and com-

<sup>18</sup> “La Maîtrise circuit” is made up of two directional loudspeakers installed at the back of the first pillar on both sides of the nave and pointing towards the back of the cathedral. The first fifteen rows therefore receive mainly natural sound while the following rows benefit from the support of the sound system.

<sup>19</sup> All acoustic scenarios simulated in this study assume that the sound system was off.

<sup>20</sup> Many singers mentioned the processions introducing services or other ambulatory singing as part of “spatialized concerts”, an expression that covers a multitude of configurations: alternating or simultaneous singing between several choirs or soloists at different positions – including in upper gallery levels – singing all around the public, alternating with choir organ and great organ, etc.

<sup>16</sup> The length of the nave is 60m, the transept is 14m long and the choir 36m long. The total length of the cathedral is 128m, with a volume of  $\approx 82700\text{m}^3$ .

<sup>17</sup> In the Christian liturgy, the *ambo* is a kind of small pulpit (raised by a few steps at Notre-Dame), used for certain public or liturgical readings as well as preaching.



bined our methods of investigation, it could be of interest to explore these various configurations in order to report not on a singular acoustic of Notre-Dame, but on its multiple acoustics, explored not only as a function of use, but also across history.

As an example, some participants reported the propagation of higher pitched notes being favored over that of lower pitched notes (especially when listening from a distance), a phenomenon that could not be investigated through analysis of the acoustics of Notre-Dame alone, requiring more comparative studies. The acoustic data of Notre-Dame should be compared with other cathedrals where such a phenomenon is not observed, in order to ascertain its possible origin beyond simple conjecture. Such a study could for example lead to examination of the influence of the specific shapes of columns on their sound diffraction properties as a function of frequency and position in the nave.

Another important point reported in the interviews was the reference to the soundscape of Notre-Dame as a component of the acoustics as a whole. Almost all the musicians, as well as the religious personnel, mentioned the presence of background noise due to the uninterrupted flow of tourist visits, to the urban environment surrounding Notre-Dame on the Île de la Cité, and to the multiple machines and electronic circuitry present inside the cathedral. The impact of this sound environment on acoustic perceptions is such that it is inextricably linked to the acoustic object as a whole. This observation invites us to consider the overall soundscape of the environment in the past as part of the study of the historical acoustics of Notre-Dame, as initiated within the PHEND project. As such, it is hoped that this interdisciplinary study on the appreciation of the acoustics by its previous and recent users, along with research on the evolution of the acoustics of Notre-Dame over the centuries, will provide valuable information for the reconstruction team.

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