Acoustics at the Intersection of Architecture and Music: The *Caveau Phonocamptique* of Noyon Cathedral

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In acoustical terms, the primary product of the combination of ecclesiastical music and architecture is *reverberation*, the dulcet swell that follows every sonic impulse made in an enclosed space. It is the sum of countless indistinguishable echoes, produced as this impulse is reflected with varying degrees of absorption from the walls and furniture in a combination unique to every building. Reverberation is a grand sonic blender, without which the music of a cathedral like Noyon seems lifeless. The church is as much an instrument as are the voices of cantors—the space, in no uncertain terms, sings along (Figure 1).[1]

Yet its voice is difficult to qualify at centuries-long remove. Although it is possible to learn something of the premodern musical repertory from manuscripts, much less is known about how it was performed, because practice was by nature intuitive and improvisatory and thus tended not to be noted.[2] Further, liturgical furnishings such as choir stalls, paintings, and tapestries, the ephemeral objects on which the sound quality of the space depends in proportion to their degree of absorption, tend not to survive the ravages of time, war, and changing fashion.

In a singular example, musicologist Craig Wright was able to document a direct relationship between the disposition of the liturgical furnishings of the choir enclosure at the Cathedral of Notre-Dame of Paris in the late Middle Ages and early Renaissance—with sound-deadening accoutrements deployed in proportion to the importance of the feast being celebrated—and the harmonic sophistication of the music performed over the course of a day.[3] The less reverberant the space, because of the absorptive properties of the textiles and paintings hung for the occasion, the greater the probability that complex contrapuntal music would be—or, rather, *could* be—performed.[4] As time went on, Wright notes, "the amount of sound-absorbent material placed in the choir [of Notre-Dame of Paris] increased. Its nature also changed as woolen tapestries and rugs became favored over silk drapes. . . . By the early sixteenth century there was scarcely an area of the chancel and sanctuary that was not covered with some sort of fabric on the principal feasts."[5]

An equally comprehensive musical and liturgical investigation unfortunately cannot be undertaken for the Cathedral of Noyon because many of the documentary resources have disappeared, but the surviving evidence suggests that the situation was similar.[6] For example, an entry dated 1231 in the medieval cartulary preserved in the departmental archives of the Oise in Amiens lists the duties of the various officers of the cathedral choir and indicates a similar deployment of liturgical materials according to the rank of the celebration; the *marguillers* (wardens) were expected to "help with the placement and removal of the ornaments of the cathedral" on high feast days.[7] An inventory of the cathedral treasury of 1419 indicates the impressive array of material that the chapter had at its disposal to deploy in the choir (and to wear).[8] A contract between the chapter and a certain Jean Brouardeau, dated 7 January 1572, required him to "hang the tapestries on feast days," among other duties.[9] And there is evidence that new tapestries continued to be commissioned. In 1648, for example, the cathedral treasurer paid 4,500 livres for a set of tapestries that represented the history of Noah; these remained in the possession of the chapter until the Revolution.[10]

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Figure 1 Noyon Cathedral, Noyon, France, begun ca. 1135, main vessel viewed from the choir tribunes, looking west (author's photo).

The changes produced by these sound-altering materials prompt Wright to ask a series of compelling questions:

> Did the growing acoustical clarity [at Notre-Dame of Paris] and at other churches contribute to the emergence in the late fifteenth century of four- and five-part writing for equal, independent voices? Because a shorter reverberation time usually engenders a faster tempo, was there a gradual increase in tempo for specific pieces that continued to be performed over the span of many decades? Since single voices would have found it difficult to fill the increasingly dampened choir, did the loss of resonance encourage the growth of choral polyphony, a mode of performance that came into being in Western church music in the early fifteenth century?[11]

Composers and performers at Notre-Dame of Paris were obliged to adapt to the variable and progressively "drier" acoustical environment of the choir, which was determined arbitrarily, not according to their needs as musicians, as a function of the sound-absorptive materials

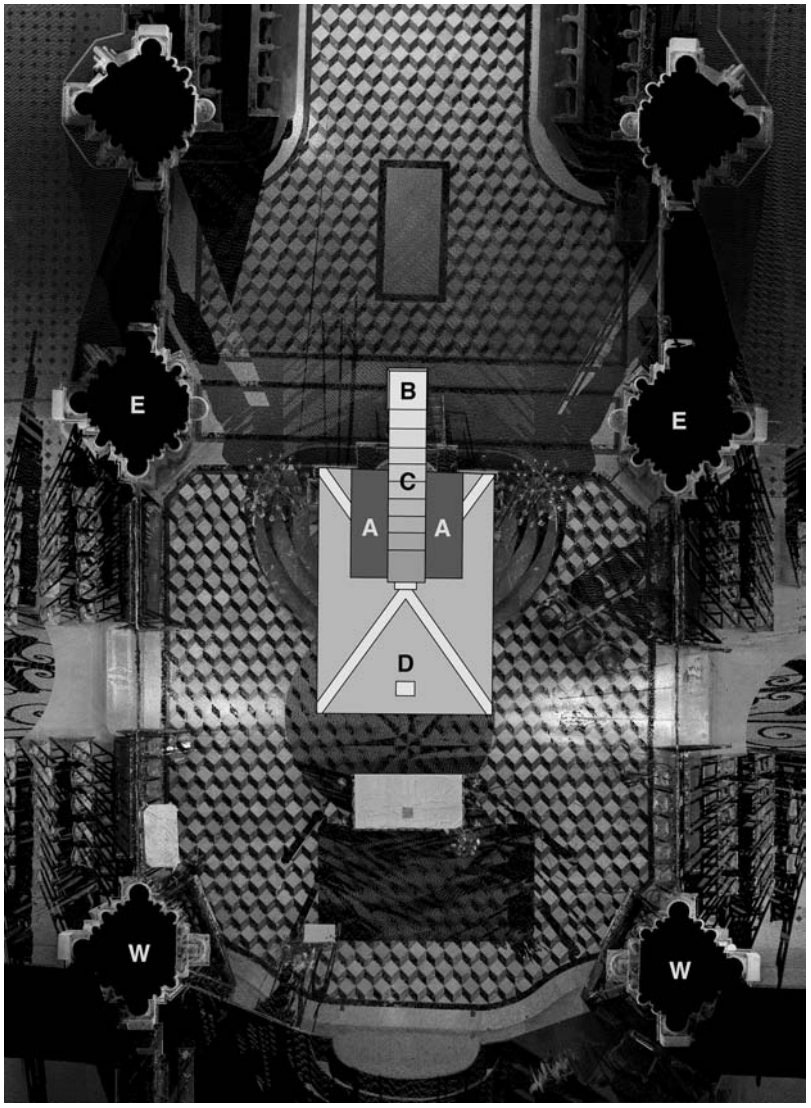

Figure 2 Noyon Cathedral, Noyon, France, begun ca. 1135, laser-generated plan of the choir and crossing with the plan of the *caveau phonocamptique* superimposed (image by author).

whose quantity and quality were imposed by festal rank. The musicians could not have done much to compensate, other than to increase their numbers, a solution that would have come at considerable expense given the additional prebends, salaries, and copies of choir books required.[12] In any case, they do not appear to have wished that the situation were otherwise.

At Noyon Cathedral, however, the canons, chaplains, vicars, and members of the *maîtrise*, the boy choristers, who sang the texts of the Divine Office and Mass in the rarefied liturgical zone that takes its name from their efforts, were apparently not content with what they heard and had a surprising idea for its improvement.[13] The chapter made the bold decision to modify the building fabric in service of the acoustics of the choir by installing one of the most extraordinary premodern sound reinforcement systems ever conceived and constructed, the *caveau phonocamptique*.

This vaulted chamber, designated *phonocamptique* (from the Greek: sound reflecting) by antiquarian C. A. Moët de la Forte-Maison in 1845, lies directly below the crossing, the point of intersection of the four "arms" of the church, and is approximately 3.5 by 4.5 meters in plan (Figures 2–4).[14] The quadripartite vault rises to a height of 3.5 meters; its limestone ribs are of simple profile, having been chamfered only, which suggests both a certain economy of means and that the space was not meant to be visited on a regular basis (Figure 5).

The walls of the chamber are replete with orifices: the mouths of sixty-four clay vases, whose pouring spouts indicate that they were created for another use, that of commonplace kitchenware (Figure 6).[15] The vases are mortared into quarter-circle panels of brick, each of which is fitted into the frame of its respective vaulting bay, delimited by the wall arches and by a brick column that bisects each bay (Figures 7 and 8).[16] The spouts have been placed

Figure 3 Noyon Cathedral, Noyon, France, begun ca. 1135, longitudinal section (image by author).

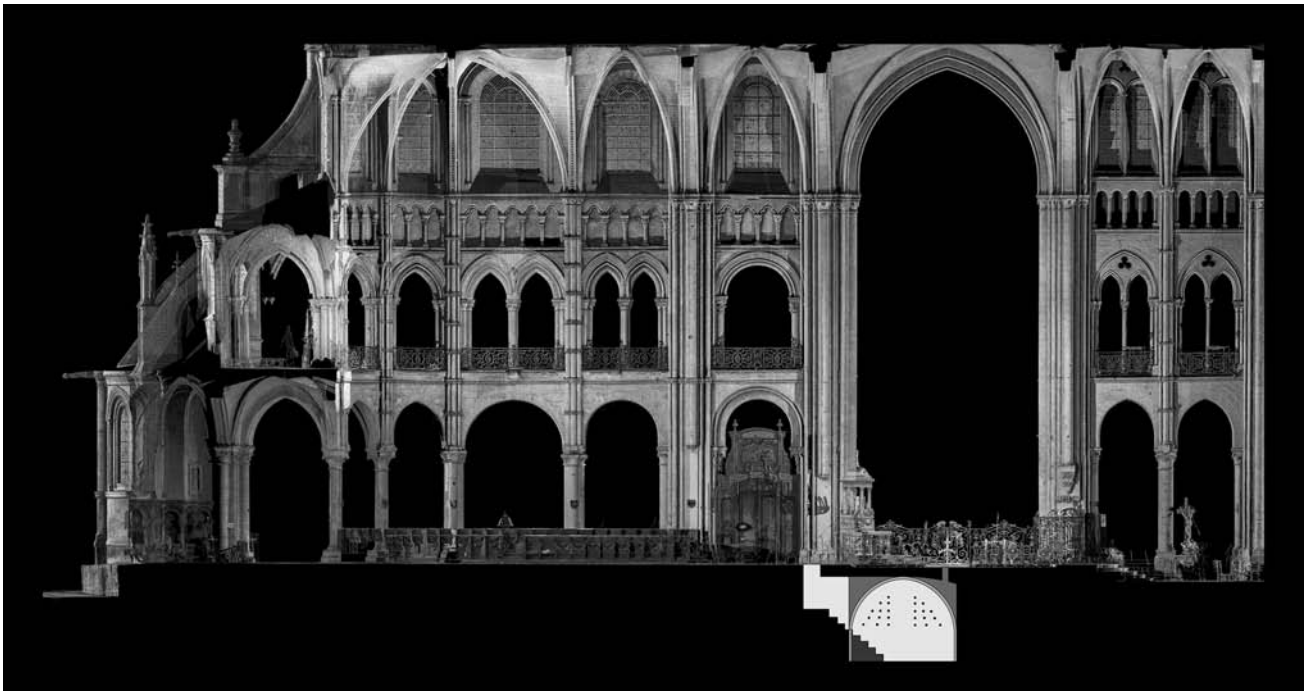

Figure 4 Noyon Cathedral, Noyon, France, begun ca. 1135, laser-generated longitudinal section through the choir and crossing (image by author).

Figure 5 Noyon Cathedral, Noyon, France, begun ca. 1135, *caveau phonocamptique*, quadripartite vault (author's photo).

Figure 6 Noyon Cathedral, Noyon, France, begun ca. 1135, *caveau phonocamptique*, vases of the southern wall (author's photo).

downward in all cases except for the bottom row on the western wall, where they are directed to the south (Figure 9); perhaps handles prevented these vases from being set as had the others.

Vitruvius's Theory of *Echea* and Its Relation to Medieval Acoustic Vase Arrays

As strange as this assemblage of clay pots recessed into the walls of a subterranean chamber might seem, it did not come out of nowhere. Antiquarian Alexandre Bouthors, in the first published mention of the chamber in 1838, attributed to its vases the ability to amplify sound, as he did to those found in another subterranean chamber at the Church of Saint-Germain in Laversines, near Beauvais, about 75 kilometers to the east.[17] "Many old churches," he wrote, "among them the Cathedral of Noyon, have earthenware devices in their vaults that were undoubtedly placed to increase sonority."[18] Bouthors supplied no justification for this acoustical attribution because none was expected; following a long tradition in print and a longer one in practice, he simply connected the clay pots in the chamber at Noyon with the *echea* (ηχεια), or resonating bronze vases, described by Marcus Vitruvius Pollio in his first-century BC treatise on architecture, *De architectura libri decem*.[19]

In book 5, chapter 4 of this work, Vitruvius introduces essential notions of scales, musical intervals, and harmony, the effect produced when two (or more) pitches are sounded simultaneously. "The harmonies that human nature can measure out," he states, "number six: *diatesseron* (fourth), *diapente* (fifth), *diapason* (octave), and *disdiatesseron* (octave + fourth), *disdiapente* (octave + fifth) and *disdiapason* (double octave)."[20] He insists that not just any two notes will produce a consonance. "For if sound is made by plucked strings or by vocal singing, it cannot make harmonies between [any] two intervals, nor with the third or sixth or seventh"; only "the harmonies of diatesseron and diapente and so on, up to disdiapason, have boundaries that coincide with the nature of the voice, and these create harmonies from the conjunction of the notes."[21] Vitruvius refers here, in abstruse terms, to the fundamental concepts

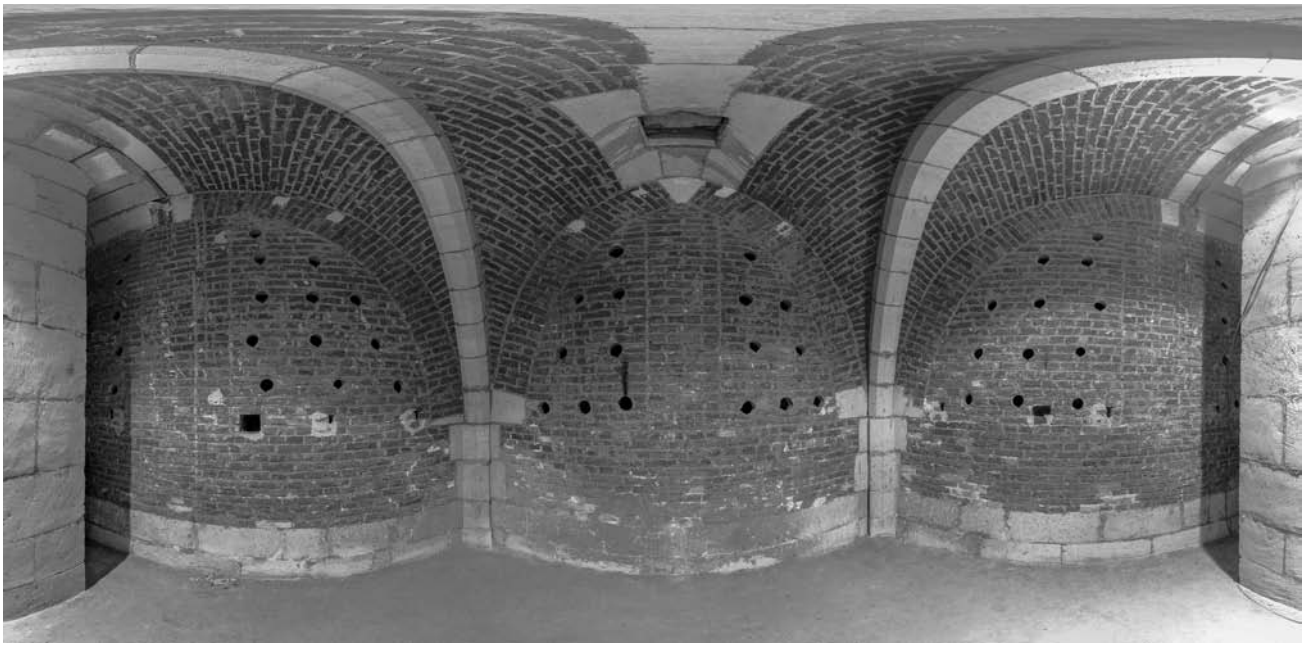

Figure 7 Noyon Cathedral, Noyon, France, begun ca. 1135, spherical photograph (occidented) of the *caveau phonocamptique* beneath the crossing (author's photo).

Figure 8 Noyon Cathedral, Noyon, France, begun ca. 1135, spherical photograph (oriented) of the *caveau phonocamptique* (author's photo).

of harmony traditionally attributed to Pythagoras (ca. 582–507 BC), who systematically documented the behavior of a vibrating string under constant tension using a monochord, a single-stringed instrument with a movable fret.[22] When divided in half, the string produced a sound nearly identical to that produced by the original length: the octave. Using the same technique, Pythagoras explored other proportions and concluded that the most pleasing, or consonant, of these were the simplest: the unison (1:1), the octave (2:1), the fifth (3:2), and the fourth (4:3).[23]

In the subsequent chapter, on theaters, Vitruvius adapts these concepts of consonance to a new purpose:

> Thus, as a result of these investigations, let bronze vessels be made on mathematical principles in keeping with the size of the theater, and have these vessels so made that when they are touched [by hand or voice], they can produce among themselves the diatesseron, diapente, and so on, up to disdiapason. Afterward place them in chambers set up for the purpose between the seats of the theater, and place them there according to the principles of music, so that they touch no walls and all around them they have an empty place and space above their heads.[24]

Figure 9 Noyon Cathedral, Noyon, France, begun ca. 1135, *caveau phonocamptique*, western wall (author's photo).

"By this contrivance," he concludes, "the voice onstage, poured forth from the stage—as it were, from the center of the theater—and circling outward, strikes the hollows of the individual vessels on contact, stirring up an increased [loudness] and a harmonic complement to its own tone."[25]

As Vitruvius presents it the idea is superabundant, because the intervallic permutations are spelled out at length—and remarkable. Vitruvius—or the authority from whom he appropriated it—appears to have wished to create a sort of harmonic grid system, a structure of pitch reference points distributed in space by means of resonant vases for performers singing in an open-air theater.[26] It is often difficult for a vocalist to hear the pitch that he or she produces in such an environment and thus challenging for the vocalist to know whether it has been set in the proper intervallic relationship with other pitches recently sung. "Indeed," writes Vitruvius, "we can observe this from performers who sing to the lyre," who "turn toward the stage doors and thus avail themselves of the harmonic support that these can provide for their voices."[27] This is why singers prefer reverberant spaces: they can hear, for a brief while, the sound they have just produced. A singer performing in an amphitheater equipped with this system could, in theory, keep him- or herself properly aligned with the harmonic mode used in the performance. Vitruvius maintains that "anyone who truly pays attention to his reasoning will be more easily capable of using the principles of Nature to design theaters that enhance the voice for the pleasure of the audience."[28]

Vitruvius offers a final point of particular utility to his postclassical students: "Many clever architects, moreover, who have designed theaters in towns of no great size, have achieved extremely serviceable results by taking clay jars tuned in the same fashion and assembling them according to the same set of principles."[29] This closing passage has invited generations of clerics and builders, like those of Noyon, to experiment—to take architectural acoustics into their own hands, even though the acoustical environment of a reverberant church is as antithetical to that of an open amphitheater as the freestanding installation of *echea* is at odds with the mortar-bound technique employed in the chamber at Noyon.

De architectura was available in Latin to potential practitioners through a long tradition of manuscript copies.[30] In France, the first vernacular translation was made in 1547 by Jean Martin—an event that may be connected to the creation of the chamber at Noyon.[31] Martin's rendering of the passage on the beneficial effects of the acoustic vase is particularly glowing: "If a worker or architect embraces this idea, there is no doubt that he will be more successful than others in perfecting [the acoustics] of such theaters, and will give as much resonance to the voice as it has of its own; moreover, he will produce a great contentment in the ears of the auditors."[32] Martin supplied no image, which surely assisted this imaginative translation of the open-air installation of vases prescribed by Vitruvius into the foreign, reverberant world of an enclosed stone space.[33]

One of the *Problemata*, a collection of questions attributed to Aristotle and translated into Latin in the High Middle Ages, may also have facilitated the conceptual conversion of the Vitruvian freestanding bronze vase into its enclosed postclassical counterpart:

> Why is it that if a large jar or empty earthenware vessels are buried in the ground and lids placed on them, the buildings in which they are have more resonance, and the same is true if there is a well or cistern in the house? . . . Anything which is hollow is particularly resonant [and] bronze vessels are particularly so. That resonance still continues when the vessels are buried need not surprise us; for the voice is carried downwards as much as in any other direction; indeed one conceives of it as being carried in a circle in every direction.[34]

The archaeological evidence for the adaptation of the Vitruvian vase prescription to ecclesiastical space is substantial. Most churches with acoustic vase arrays are located in France, where more than two hundred examples are known.[35] Vases are generally placed in the upper portions of walls and in vaults, as at the Cluniac priory church of Saint-Pierre-et-Saint-Paul in Souvigny, where they were inserted into a single vaulting bay over the choir soon after 1432, probably during construction (Figures 10 and 11).[36] Vase orifices are typically presented to the space, set flush with the wall or vault surface. They are found predominantly in the prime liturgical zones: the choir, the apse, and the eastern nave bays.[37] As in the chamber at Noyon, common household pots, often with pouring spouts, were standard (Figure 12).

Textual references to acoustic vase installation and practice, however, are extremely rare.[38] Those that have been

Figure 10 Priory church of Saint-Pierre-et-Saint-Paul, Souvigny, France, fifteenth-century vault over the monastic choir with acoustic vases (author's photo).

Figure 11 Priory church of Saint-Pierre-et-Saint-Paul, Souvigny, France, acoustic vase in the extrados of the choir vault (author's photo).

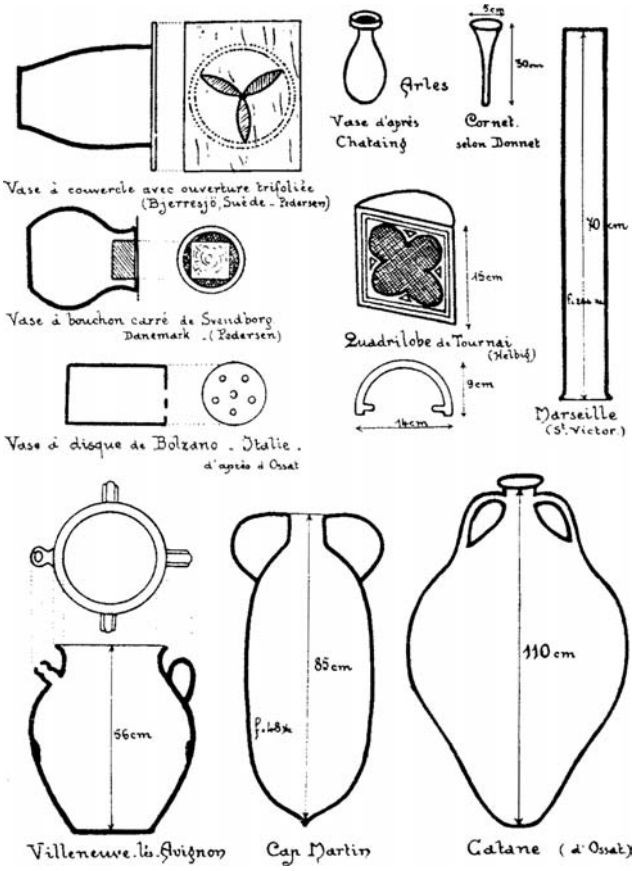

Figure 12 Varieties of acoustic vases (René Floriot, "Contribution à l'étude des vases acoustiques du Moyen Âge" [PhD thesis, Université d'Aix-Marseille, 1964], 21).

discovered share one important aspect: when function is mentioned it is invariably one of sound reinforcement or amplification. The earliest example is of particular interest because it evokes the acoustical benefits of vases in terms redolent of Vitruvius—and at the same time casts doubt on their efficacy. The author of the text recounts the return of Prior Ode le Roy to the monastery of the Celestines in Metz on 14 August 1432 after having attended a general chapter. Upon arriving, Prior Ode ordered that resonating pots be placed in the choir of the church—though he had never experienced such an installation himself—"thinking that they would improve singing and that the church would resonate more loudly." The vases were installed in a single day. "I am not sure," however, reported the author, "if one sings better than before. It is hard to believe that the walls of the church were seriously rent" for this purpose—an opinion, he tells us, that was apparently shared by many visitors, who "thought that it was done to please the foolish."[39] A note in the margin of the manuscript—*ecce risu digna* (for a laugh look at this!)—indicates a later commentator's sardonic accord.[40]

The association of Vitruvian *echea* with their church-bound ceramic counterparts—and the current of doubt as to their utility—goes back in print at least to the seventeenth century.[41] Jesuit theologian and music theorist Marin Mersenne, for example, in his *Livre de l'utilité de l'harmonie et d'autres parties des mathématiques*, the second volume of the *Harmonie universelle* of 1637, wrote that it was difficult for vases "to be loud enough to make their harmonies audible to

those listening when excited [only] by a single voice, as one can test with casks such as [Vitruvius] says are found in smaller towns instead of bronze vases in order to avoid the expense; whether of pottery or of wood, they will never produce the harmonies for which they were prepared when only the voice excites them."[42] The sense of Mersenne's comment is this: one cannot adequately predict the effect that pottery or wooden vases will have once installed based only on having sung into them beforehand. "In any case, the most they could do would be to reflect and render the voice stronger and more intelligible. . . . It is for this reason that one puts sparrow pots [*pots à moineaux*] or other hollow vases in vaults, or on the vaults of churches, in order to assist the voices of those who sing, and for this reason also that the voice is not as strong outside as it is in an enclosed space, whose walls reflect the voice and prevent it from being lost."[43] Despite having ascribed amplifying and clarifying properties to clay and wooden vases—it appears Mersenne expected more of them—he concludes that Vitruvius's proposal to use materials other than bronze was "unworkable; perhaps he had found a way to make it function, or else he simply had had the idea and was content to sketch it out."[44]

In the eighteenth century Louis Jaucourt, in Diderot and d'Alembert's *Encyclopédie*, wrote of the claim "that there are *echea* such as the ancients had used, present in the Cathedral of Milan, which is well suited to musical harmony." He added, however, that "many things are commonly claimed that, once examined, prove not to be true."[45] More reliable reports based on archaeology began to be published in the first decades of the nineteenth century. Aubin-Louis Millin, for example, in his 1806 *Dictionnaire des Beaux-arts*, cited evidence of earthenware pots installed in the walls of the thirteenth-century Temple-Neuf in Strasbourg. "It seems," he wrote, "that in the construction of Gothic churches such a means was employed occasionally to reinforce the voices of monks and canons."[46]

Moët de la Forte-Maison's 1845 description of the *caveau* at Noyon follows in the same vein. He asserted that it was "placed at the entrance to the choir to produce more echo in the church and to reinforce the voices of the cantors." The concave portion of the vases "forms a sort of vault that gathers sound, enlarges it, and then reflects it. This is at least the way it works according to the theory of the phenomenon of echo."[47] His positive estimation of the function of the *caveau* was followed in all but two antiquarian and scholarly publications through the turn of the second millennium.[48] Yet despite his confident and apparently scientific assertion that the *caveau* was designed to amplify, he intuited correctly that its vases in fact could not be effective. "I must admit that the abandonment of the procedure and the rarity of spaces which employed it suggest that it did not entirely respond to the hope that accompanied its creation."[49]

Acoustical Analysis of the *Caveau Phonocamptique* at Noyon Cathedral

The sixty-four vases in the *caveau phonocamptique* at Noyon are distributed as follows: the northern and southern walls each contain twenty-four in two symmetrical groups of twelve, and the western wall has sixteen in two symmetrical groups of eight (see Figure 7). Each vase has a resonant frequency, the pitch at which the mass of air in the vase begins to oscillate when excited acoustically. I determined these frequencies—expressed in the conventional unit of hertz (Hz; cycles per second) in Tables 1–3 and in musical notation, with pitches rounded to the nearest semitone (Figures 13–15)—first by striking the orifice of each vase with the palm of my hand and then by singing into it to confirm the resultant pitch.[50] Although other means of exciting the resonant frequencies of the vases exist, this simple method has the advantage of being that used in all probability by those who selected the vases originally.

Of the sixteen vases in the western wall, fourteen are clustered in the pitch range of B♭/A (see Figure 13). The remaining two, placed at the top of the wall, are approximately one-fourth higher in pitch. A similar arrangement is present in the northern wall (see Figure 14): two clusters of pitches, C/D♭/D (eleven vases) and B♭/A (thirteen vases), are in the approximate relationship of a fourth, and the higher pitches, with one exception, are once again placed above the lower.

Two points are important: first, the vases were chosen so that their resonant frequencies would correspond to the range of the male voice; second, they were arranged in groups related one to the other by the interval of one fourth, one of the consonances admitted by Pythagoras and Vitruvius. The fourth may also have been chosen because of its cosmogonic significance, as one of the Pythagorean ratios on which the universe itself is structured, as defined by Plato (ca. 427–347 BC) in the *Timaeus*.[51] In *De musica*, Saint Augustine of Hippo (AD 354–430) interpreted the Pythagorean ratios, which had been incorporated into Plato's account of the origins of the world's soul, for the Christian world.[52] For Augustine these ratios were the source of all beauty because they participated in a universal, divine harmony. Boethius (ca. AD 480–524), like Augustine, located the source of beauty in the Pythagorean ratios, but he articulated the relationship further by dividing music into three types: *musica mundana* (music of the cosmos), *musica humana* (the harmony of the soul), and *musica instrumentalis* (music produced by instruments, including the voice).[53] In the Boethian system, *musica instrumentalis* is completely subject to the imperceptible *musica mundana*, its beauty due solely to its emulation of the cosmic prototype.[54] Conversely, *musica instrumentalis*, as the indicator of the celestial music, becomes a powerful means of emulating the perfection of God on earth.

Whether strictly Pythagorean and Vitruvian or with the added import of Augustine and Boethius and their theorist

Table 1. Noyon Cathedral, *Caveau Phonocamptique*, Western Wall Vase Resonant Frequencies (Hz)

		153.6	137.8		
	106.0	120.3	106.3	114.1	
	114.2	110.0	111.7	108.0	
111.9	112.3	114.5	111.0	114.5	108.0

Table 2. Noyon Cathedral, *Caveau Phonocamptique*, Northern Wall Vase Resonant Frequencies (Hz)

		138.0	142.2		
	148.8	138.2	141.8	147.5	
133.0	144.9	136.9	133.3	109.3	141.0
110.0	115.5	101.9	111.7	111.7	110.5
111.7	110.0	115.1	111.5	111.3	112.4

Table 3. Noyon Cathedral, *Caveau Phonocamptique*, Southern Wall Vase Resonant Frequencies (Hz)

		143.4	135.9		
	116.9	92.9	147.8	133.2	
137.8	145.8	149.4	144.1	144.3	145.7
148.5	153.2	145.1	153.3	137.3	159.5
109.2	114.9	144.5	139.1	94.1	140.6

successors, the ratio of the fourth is purposefully present in the *caveau*. By attempting to create resonance along this key musical axis, the creators of the vase system reveal their desire to reinforce one of the simplest—but also most significant—harmonic structures.

The southern wall of the *caveau* presents a different scheme (see Figure 15). Nineteen of the twenty-four vases are clustered in a heterogeneous pitch zone, roughly similar to that of the upper northern wall: C/D♭/D/E♭/E. The placement of the remaining five vases appears haphazard, with an approximate pitch relationship to the major cluster of one-fourth to one-fifth.

As indicated earlier, the vases were chosen from existing pottery; had they been made especially for the *caveau* they probably would not have been fitted with pouring spouts. Given the frequency variability of the pitch clusters, one could simply conclude that finding harmonically attuned ready-made pots was difficult. More interesting, however, is that the creators of the *caveau* were willing to accept the results: the tonal discord among vases suggests that the builders were not particularly concerned with the sort of pitch homogeneity that Vitruvius prescribes.[55]

Yet there is a larger issue against which this troubling pitch divergence pales in comparison; it is the fundamental paradox of the acoustic vase and the *caveau phonocamptique* at Noyon. An acoustic vase does not—in fact cannot—amplify sound, according to the law of conservation of energy (the first law of thermodynamics); to do so it would have to be able to create new energy in addition to that imparted by the voice. The vase simply *appears* to amplify because it absorbs less energy at its resonant frequency than it does at neighboring frequencies.[56] The *caveau phonocamptique* was thus incapable of functioning as a sound amplifier. If anything, it diminished whatever little sound energy managed to enter from the choir space above, given the small size of the aperture through which it had to pass (see D in Figure 2, as well as Figures 5 and 7).

The foundational studies of acoustic vases in churches, both in situ and in the laboratory, were undertaken by René Floriot in the early 1960s and by Jean-Marc Fontaine a decade later. Despite his equivocal experimental results, Floriot was unwilling to accept that those who had employed vases had been mistaken; he suggested that the vases of certain churches had been placed with mastery of their acoustical consequences according to a secret, guild-based tradition.[57] Fontaine was more conservative in his interpretation. He pointed out that although the church on which his study was primarily based—Saint-Herlé of Ploaré-Douarnenez in Brittany, built around the turn of the seventeenth century—had an unusually large number of vases (110), these had relatively minimal influence on the acoustics of the church; the results, furthermore, could not be generalized.[58] Although the acoustical instruments that Floriot and Fontaine used were

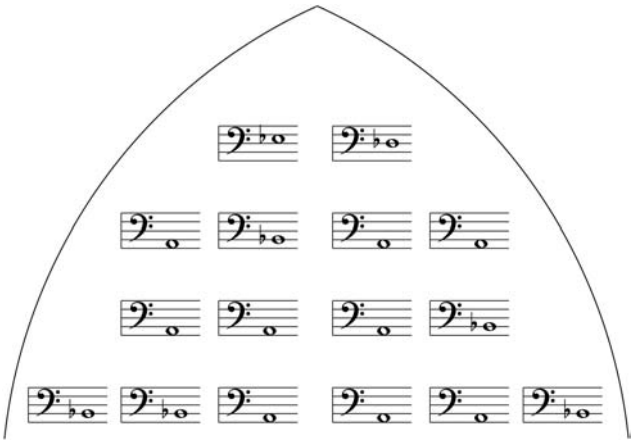

Figure 13 Noyon Cathedral, Noyon, France, begun ca. 1135, *caveau phonocamptique*, western wall vase resonant frequencies in musical notation, rounded to the nearest semitone (image by author).

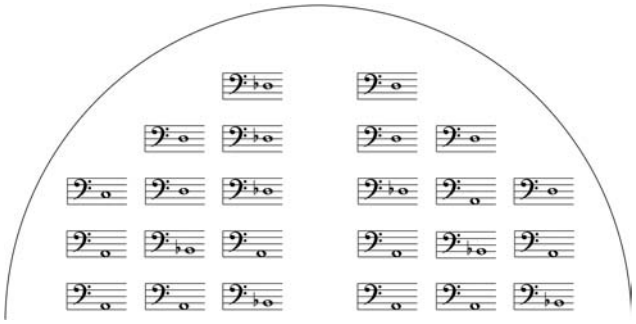

Figure 14 Noyon Cathedral, Noyon, France, begun ca. 1135, *caveau phonocamptique*, northern wall vase resonant frequencies in musical notation, rounded to the nearest semitone (image by author).

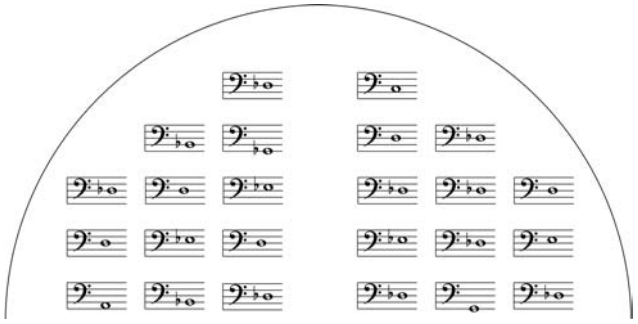

Figure 15 Noyon Cathedral, Noyon, France, begun ca. 1135, *caveau phonocamptique*, southern wall vase resonant frequencies in musical notation, rounded to the nearest semitone (image by author).

capable of registering a difference in acoustical energy when all vases were plugged and then reopened, the difference was subtle at best—and it was not clear how the effect, in performative and musical terms, could be construed as calculated.[59]

In the face of such empirical ambiguity, a common response has been to attribute an exceptional aural sensitivity to those who employed acoustic vases—one sufficiently fine as to be inaccessible to modern scientific instruments and the scholars who wield them. "It is certain that contemporary ears," wrote Yves-Pierre Castel, for example, "afflicted with brutally distributed decibels, have trouble properly appreciating the modifications made to churches by ancient acoustical vase systems."[60] Yet it is difficult to accept such reasoning, especially when confronted with the tonal imperfection of acoustic vase arrays such as that at Noyon. For centuries musicians had been performing compositions that were both sophisticated and harmonically coherent; the vases at Noyon are only approximately so.[61] The attribution of extraordinary acoustical prowess to those responsible for the installation of these vases—given such clear lack of control—is ill considered.

Construction

As far as I have been able to determine, there is no documentary evidence for the construction—or the existence—of the *caveau* in the cathedral chapter documents, rendered sparse by a fire set by revolutionaries in August 1793.[62] Neither of the two assiduous modern documentarians, archdeacon (1607–16) then dean (1616–38) of the chapter Jacques Le Vasseur (d. 1638) and canon Claude Sézille (1707–75), both of whom had access to a much more complete range of sources, mentions the *caveau*.[63] It can nonetheless be dated to the sixteenth century on the basis of architectural details.[64]

The vault webs and walls in which the vases were inserted during construction are red brick with thick mortar beds (see Figure 8). Although there are isolated examples of Picard brickwork in the late Middle Ages—one being the castle of Rambures, built around 1450—only in the later fifteenth century and particularly in the sixteenth is there clear evidence of the regular association of brickwork walls and vaults and cut stone framing elements such as are present in the *caveau*.[65] That brick, rather than more conventional stone, was used for the walls and vaults indicates that this relatively new material was in ready supply. The bricks of the *caveau* may in fact have been produced at a factory at the Place du Marché Franc, just one kilometer to the southwest of the cathedral.[66] The brickwork in the *caveau* was laid using simple alternation, sometimes called the *chaine anglaise* (English chain). As Pierre Patte wrote in Jean-François Blondel's *Cours d'architecture*, the technique involves "rows of bricks placed flat and with alternating long and short sides, without leaving a void in the interior."[67] It was the most common mode of bricklaying in Picardy in the sixteenth and seventeenth centuries.[68]

Additional corroboration for this putative construction date is supplied by a discovery published in 2015 by art historian Charlotte Stanford: a similar Vitruvian resonating chamber with forty clay vases built in the early sixteenth century below the floor of the chapel of Saint John the Baptist in the

Savoy Hospital in London.[69] An entry titled "Erthyn potts" from the building records for the pay period spanning 27 February to 12 March 1514 reads as follows: "paid For 40 potts of Erthe For to lay under the deske [the pulpit] in the church *For to mende the sound*, price le pece 3d, in toto: 10s."[70] The church, today known as the Queen's Chapel of the Savoy, suffered a fire in 1864 and was heavily rebuilt; whatever survived below the floor level—including the subterranean acoustic chamber—was removed at that time by order of architect Sydney Smirke.

Although the pots might have been had for a pittance—according to the British National Archives, ten shillings in 1514 would be roughly equivalent to three hundred dollars today—building a chamber to contain them below floor level, whether at the Savoy Hospital or at the Cathedral of Noyon, could only have been a costly and troublesome affair.[71] At Noyon the pavement of the crossing had to be torn up, the earth and foundations of older buildings had to be excavated to a depth of at least 5 meters, and the stalls had to be partially dismantled or removed. All of this would have necessitated a displacement of the liturgy—the primary activity of the cathedral—perhaps to the nave or to another building entirely. There are two moments in particular that suggest themselves as possibilities for this major intervention.

During the Wars of Religion the city of Noyon was sacked and set ablaze on more than one occasion.[72] Jacques Le Vasseur reports, for example, that a major fire broke out in the cathedral after it was despoiled in 1552 following an attack; the canons were forced to abandon the building to Spanish occupiers.[73] In 1557 the city was invaded again; this time the canons fled 30 kilometers south to the parish church of Pierrefonds in the diocese of Soissons, and the cathedral was vacated once more.[74] The *caveau* may have been created following this period of extraordinary adversity as part of a larger reconstruction project, perhaps in anticipation of the visit of King Charles IX, who attended vespers in the cathedral on 14 August 1567.[75] Or perhaps in celebration of Bishop Jean de Hangest, who died on 4 February 1577 after having served fifty-two years as bishop, and who left one hundred gold écus to the cathedral *fabrique*, the building maintenance corporation.[76] Or, for another possibility, the *caveau* may have been created at the behest, or at least with the collaboration, of Nicolas de Marle, whose career as a composer is sufficiently well documented that we may suppose his active presence at the Cathedral of Noyon beginning in the second half of the sixteenth century.[77]

Whenever the moment—one that cannot be located with any precision without the missing or destroyed capitular documents—the *caveau* was subjected to a major modification fairly soon after its construction. A pair of massive piers was somewhat crudely inserted into the vault (Figures 16 and 17; see A in Figure 2 and Figure 8), perhaps to support

Figure 16 Noyon Cathedral, Noyon, France, begun ca. 1135, *caveau phonocamptique*, juncture between the rib vault and the piers (author's photo).

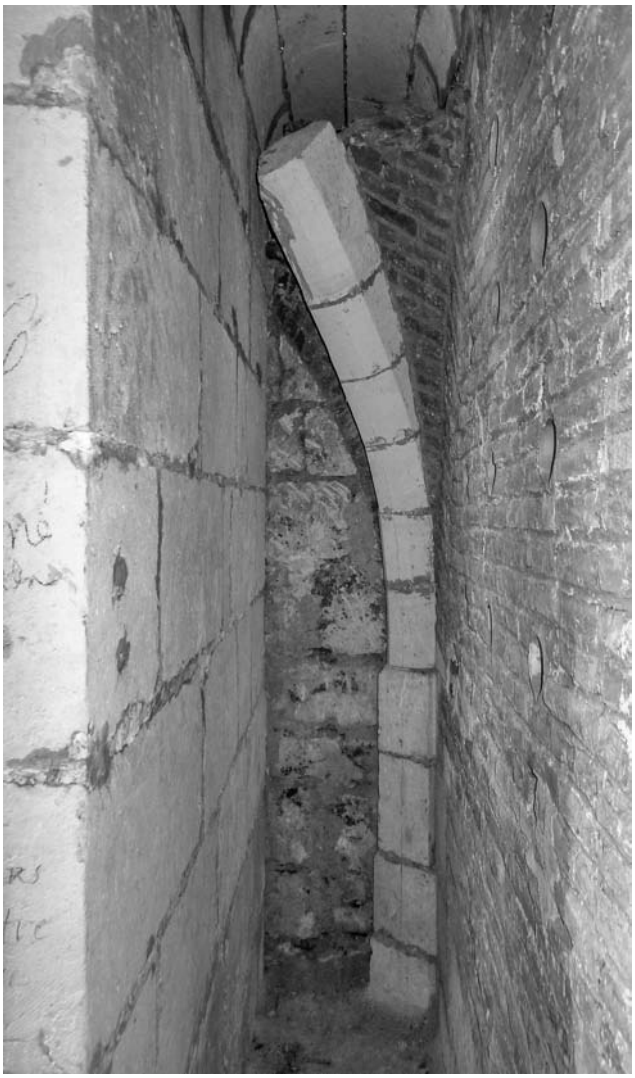

Figure 17 Noyon Cathedral, Noyon, France, begun ca. 1135, *caveau phonocamptique*, truncation of the rib vault to accommodate the southern pier (author's photo).

Figure 18 Noyon Cathedral, Noyon, France, begun ca. 1135, eighteenth-century high altar, viewed from the east, with access shaft to the *caveau phonocamptique* with marble cover to the east (author's photo).

Figure 19 Noyon Cathedral, Noyon, France, begun ca. 1135, *caveau phonocamptique*, access shaft with marble cover removed (author's photo).

a new altar planned for the crossing above but never completed, and an arch with stereotomy characteristic of this period was sprung between them (see Figures 5 and 16). Scholar Eloi Delbecque has proposed that these changes were motivated by a desire to use an underground space that had fallen into disuse as a mortuary chamber for Bishop Charles de Balsac (d. 1625), in a perpetuation of a long-standing tradition of episcopal burial in the choir.[78] Although this possibility is compelling, there is no evidence, whether documentary or archaeological, that the *caveau* was employed in this way. The work in any case cannot have taken place later than 8 May 1633, a date supplied by a graffito inscribed on the northern pier by a certain Charles François Graux.[79]

The *caveau* is accessed with some difficulty. First, one must remove a heavy marble slab fitted with hoist rings, installed when the choir floor was repaved in 1743 (Figures 18 and 19).[80] Beneath the slab lies a 2-meter-deep shaft (see B in Figure 2) that requires the use of a ladder to access the staircase below (C in Figure 2). The archaeological investigations undertaken by architects André Collin and Alfred Révillon from 1921 to 1923 revealed no evidence of an entrance other than this one, although the excavations carried out in the area of the high altar were not systematic enough to rule out the possibility.[81] The most important consequence of the 1743 choir repaving for the *caveau* was that its acoustical connection to the space above—the small square conduit located between the western vault severies—was permanently sealed (D in Figure 2; Figure 5).

The aperture once opened into the liturgical choir above, at the very center of the crossing (see Figures 2–4). In the sixteenth century, during the probable time of construction of the *caveau*, the disposition of the choir was unlike that of today in three key ways. First, the canons and their stalls were not confined to the bays east of the eastern crossing piers (see E in Figure 2); the choir extended through the crossing and was terminated to the west by a great rood screen (demolished in 1757) that stretched between the westernmost crossing piers (W in Figure 2).[82] Second, evidence from the Cathedrals of Notre-Dame of Paris and Notre-Dame of Laon suggests that there would have been a lectern at Noyon *in medio chori*, at the center of the choir—and thus just above the *caveau* aperture—to be used in the performance of polyphonic settings of the texts for the Divine Office and the Mass.[83] This zone is occupied today by a high altar erected in 1779, following several decades of deliberation (see Figures 18 and 19).[84]

Finally, as I argued earlier, the choir space, at least on high feast days, would have been filled with sound-absorptive materials such as tapestries.

Conclusion

The *caveau phonocamptique*, true to the name coined for it by Moët de la Forte-Maison, appears to have been intended as a monumental sound amplifier. It was conceived in a such a way that the vocal production of a cleric or group of singers, situated perhaps at the center of the crossing, could have entered the chamber through the aperture in the floor, been treated by the array of vases, and been returned by the same route. It may well have been intended as a clever scheme—if an illusory one—to increase choral output without having to engage a greater number of cantors and choristers, at significant cost.[85]

Whatever the specific motivation for its construction, the existence of the *caveau* can be attributed to the authority of Vitruvius and to his confident assurance of improved singing with the acoustic vase. A contemporary reader of Jean Martin's newly published translation of Vitruvius would have had little reason to doubt the accuracy of his assured prediction.[86] Even had some doubt managed to linger, it would have been swept away in the moment of truth, the real-world test. All one had to do was sing into it, as Marin Mersenne instructs us to do; the vase will not disappoint.[87] If one of the frequencies traversed during a vocal pitch sweep, or portamento, were to coincide with the vase's resonant frequency, the vase would suddenly—and dramatically—resound.[88] It is this strong association of an attractive theory posited by an eminent authority, Vitruvius, and the apparently irrefutable evidence supplied by the clay pots themselves that must have rendered the technique of acoustic vase "amplification" so seductive.

Yet it is not as if the use of vases at Noyon was entirely naive, as the placement of the *caveau* makes manifest. Vases might indeed sing back at close range, but if placed some 22 meters above, in the high vaults, as was conventionally done—for example, as at Souvigny (see Figure 10)—would they have an effect? Surely not. Better to concentrate a large number in proximity to the sound source in need of reinforcement, in a space that must have seemed like a large resonator of its own. It was a solution as ingenious as it was improbable.

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Notes

1. This article is dedicated to my parents. I am grateful to Jean-Yves Bonnard, Laurent Cessin, Jonathan Chenette, Lindsay Cook, Stéphanie Diane Daussy, Eloi Delbecque, Hélène Dulauroy-Lynch, Aurélie Dupont, David Fiala, David Gadanho, Nicole Griggs, Patricia Morton, Bénédicte Palazzo-Bertholon, Judy Selhorst, Mary E. Tallon, Arnaud Timbert, and Jean-Christophe Valière. My thanks also to Marc Crunelle, who introduced me to the *caveau phonocamptique* in 1991.

2. See Craig Wright, "Performance Practices at the Cathedral of Cambrai 1475–1550," *Musical Quarterly* 64, no. 3 (1978), 295.

3. Craig Wright, *Music and Ceremony at Notre Dame of Paris 500–1550* (Cambridge: Cambridge University Press, 1989), 1–18.

4. I recently explored a similar relationship of space and sound at the abbey church of Saint-Germain-des-Prés in Paris. See Andrew Tallon, "L'espace acoustique de l'abbatiale de Saint-Germain-des-Prés," in *Saint-Germain-des-Prés: Mille ans d'une abbaye à Paris*, ed. Roland Recht and Michel Zink (Paris: Académie des Inscriptions et Belles-Lettres, 2015), 77–90. Acousticians Brian Katz and Bart Postma were further able to propose an acoustical reconstruction—an "auralization"—of the space and its changing conditions over time. Brian Katz, Bart Postma, and Andrew Tallon, "Calibrated Auralization Simulation of the Abbey of Saint-Germain-des-Prés for Historical Study," in *Proceedings of the Ninth International Conference on Auditorium Acoustics, Paris, 29–31 October 2015* (St. Albans, England: Institute of Acoustics, 2015), 190–97. For an investigation of another cathedral performance space, that of Beauvais, from an acoustical point of view, see Andrew Tallon, "The Play of Daniel in the Cathedral of Beauvais," in *Resounding Images: Medieval Intersections of Art, Music, and Sound*, ed. Susan Boynton and Diane J. Reilly, *Studies in the Visual Cultures of the Middle Ages* (Turnhout, Belgium: Brepols, 2015), 214–17.

5. Wright, *Music and Ceremony*, 17.

6. The little information that survives concerning liturgical music and its performance at the Cathedral of Noyon can be found in David Fiala, "La musique à la cathédrale de Noyon," in *La musique en Picardie du XIV^e^ au XVII^e^ siècle*, ed. Camilla Cavicchi, Marie-Alexis Colin, and Philippe Vendrix (Turnhout, Belgium: Brepols, 2012), 153–69.

7. Archives départementales de l'Oise, G 1984, f. 228. See Armand Rendu, *Inventaire du cartulaire du chapitre cathédral de Noyon* (Beauvais: C. Moisand, 1875), 10. It is possible, although unlikely, that further information could be gleaned from rubrics in the two-part incunable breviary from Noyon, dated 1515–25, held in the Bibliothèque Nationale de France in Paris (vellums 1614 and 1615). See canon E. Morel, "Les livres liturgiques imprimés avant le XVII^e^ siècle à l'usage des diocèses de Beauvais, Noyon et Senlis," *Bulletin historique et philologique du Comité des travaux historiques et scientifiques* 1902 (1903), 191–94.

8. Aléxandre de la Fons, *Une cité picarde au Moyen-Age, ou Noyon et le Noyonnais aux XIV^e^ et XV^e^ siècles* (Noyon: Soulas-Amoudry, 1841), 151–64.

9. Archives départementales de l'Oise, G 1362. See also Eugène Lefèvre-Pontalis, "Histoire de la cathédrale de Noyon (II)," *Bibliothèque de l'Ecole des chartes* 61 (1900), 149, 151.

10. Lefèvre-Pontalis, "Histoire de la cathédrale de Noyon (II)," 152; M. Berquët, "Inventaire du mobilier de l'église cathédrale de Noyon (1790)," *Comptes rendus et mémoires de la Société archéologique, historique et scientifique de Noyon* 7 (1885), 133–42; Eugène Lefèvre-Pontalis, "Histoire de la cathédrale de Noyon (III)," *Bibliothèque de l'Ecole des chartes* 61 (1900), 288. It is possible that the 420-page *Rituel du diocèse de Noyon* compiled in the mid-eighteenth century by cathedral canon Périn, held in the French Archives Nationales, Paris (L738, folder 3), may record similar evidence for textile use on feast days.

11. Wright, *Music and Ceremony*, 18.

12. On the cost of maintaining such a performing ensemble, see Rob C. Wegman, *The Crisis of Music in Early Modern Europe, 1470–1530* (New York: Routledge, 2005), 39.

13. On the roles played by the various members of the cathedral choir, see David Fiala and Etienne Anheim, "Les maîtrises capitulaires et l'art du contrepoint du XIV^{e} au XVI^{e} siècle," *Analyse Musicale* 69 (2012), 13–20.

14. The asymmetry of the eastern wall visible in Figure 2 is due to the presence of an earlier building on the site during the construction of the present cathedral; the eastern wall probably abuts a foundation raft adjoining the easternmost crossing piers (E in Figure 2). See Charles Seymour, *Notre-Dame of Noyon in the Twelfth Century: A Study in the Early Development of Gothic Architecture* (New York: W. W. Norton, 1968), 33–40. My laser scan of Noyon Cathedral, used to produce Figures 2–4, was funded by the Andrew W. Mellon Foundation as part of the Mapping Gothic project (http://mappinggothic.org), a five-year collaboration between myself and Stephen Murray at Columbia University. I am grateful to Nicole Griggs and Benjamin Outrey for their assistance.

15. An additional set of rectangular openings was left in the brickwork of the north and south walls, perhaps for use as putlog holes during construction (see Figures 7 and 8).

16. For an interactive 360-degree projection of Figures 7 and 8, see http://faculty.vassar.edu/antallon/noyon/caveau.

17. Alexandre Bouthors, "Cryptes de Picardie: Recherches sur l'origine des souterrains refuges qui existent en grand nombre dans les départements de la Somme, du Pas-de-Calais, de l'Oise et du Nord," *Mémoires de la Société des Antiquaires de Picardie* 1 (1838), 427. On the chamber at Laversines, discovered around 1810, see Etienne Bourgevin-Vialard, comte de Saint-Morys, "Note sur un souterrain découvert dans la commune de Laversines," *Mémoires et dissertations sur les antiquités nationales et étrangères* 1 (1817), 339; "Souterrains de Laversines," in *Dictionnaire des découvertes en France de 1789 à la fin de 1820* (Paris: Louis Colas, 1823), 10:256–59; Louis Graves, *Précis statistique sur le canton de Nivillers, arrondissement de Beauvais (Oise)* (Beauvais: Louis Graves, 1830), 60–61; Louis Graves, ed., *Notice archéologique sur le département de l'Oise* (Beauvais: Achille Desjardins, 1839), 16–17; Baruch Weil, "Description des cryptes du département de l'Oise," *Mémoires de la Société academique d'archéologie, sciences et arts du département de l'Oise* 1 (1847), 182–90.

18. Bouthors, "Cryptes de Picardie," 427. Translations are mine unless otherwise noted.

19. Marcus Vitruvius Pollio, *Ten Books on Architecture*, ed. Ingrid D. Rowland and Thomas Noble Howe, trans. Ingrid D. Rowland (Cambridge: Cambridge University Press, 1999), 5.5.

20. Ibid., 5.4.7.

21. Ibid., 5.4.9.

22. Willi Apel, "Mathematics and Music in the Middle Ages," in *Medieval Music: Collected Articles and Reviews* (Stuttgart: Steiner Verlag Wiesbaden, 1986), 122–56; Hermann von Helmholtz, *On the Sensations of Tone as a Physiological Basis for the Theory of Music*, 2nd ed., trans. and ed. Alexander Ellis (New York: Dover, 1954), 262–66.

23. Apel, "Mathematics and Music," 125; Leonid Zhmud, *Pythagoras and the Early Pythagoreans*, trans. Kevin White and Rosh Ireland (Oxford: Oxford University Press, 2012), 306–7.

24. Vitruvius, *Ten Books on Architecture*, 5.5.1. For further discussion of the Vitruvian prescription for the use of vases, see Robert G. Arns and Bret E. Crawford, "Resonant Cavities in the History of Architectural Acoustics," *Technology and Culture* 36, no. 1 (1995), 105–12; Umberto Pappalardo and Daniela Borrelli, *Teatri greci e romani* (San Giovanni Lupatoto, Italy: Arsenale, 2007), 28–30.

25. Vitruvius, *Ten Books on Architecture*, 5.5.3. The original passage reads: "Ita hac ratiocinatione vox a scaena uti ab centro profusa se circumagens tactuque feriens singulorum vasorum cava excitaverit auctam claritatem et concentu convenientem sibi consonantiam." Marcus Vitruvius Pollio, *Vitruvius: On Architecture*, trans. Frank Stephen Granger (London: William Heinemann, 1931), 1:278. I have substituted "loudness," another sense of *claritas*, for "clarity" as given in Rowland's translation.

26. Claude Perrault proposed a clarification of the idea in a note to his 1673 translation of Vitruvius: the vases "were tuned according to the sounds distributed in the range of two octaves that the voice could sing, so that there would be no sound from an actor that would not meet its match in one of the vases, which would respond by resonating and thus augment and fortify it." Claude Perrault, translator's note in Marcus Vitruvius Pollio, *Les dix livres de Vitruve, corrigez et traduits nouvellement en François, avec des notes et des figures*, 2nd ed., trans. Claude Perrault (Paris: Jean-Baptiste Coignard, 1673), 168n8. See also Pierre Perrault, *Essais de physique ou recueil de plusieurs traitez touchant les choses naturelles* (Leyden: Pierre van der Aa, 1721), 2:216.

27. Vitruvius, *Ten Books on Architecture*, 5.5.7.

28. Ibid., 5.5.6. The original passage reads: "si qui ratiocinationibus his attenderit, ad naturas vocis et audientium delectationes facilius valuerit theatrorum efficere perfectiones." Vitruvius, *On Architecture*, 1:280.

29. Vitruvius, *Ten Books on Architecture*, 5.5.8.

30. Carol Krinsky, "Seventy-Eight Vitruvius Manuscripts," *Journal of the Warburg and Courtauld Institutes* 30 (1967), 36–70.

31. On Martin's translation, see Frédérique Lemerle, "Jean Martin et le vocabulaire d'architecture," in *Jean Martin: Un traducteur au temps de François Ier et de Henri II*, ed. Marie-Madeleine Fontaine (Paris: Presses de l'Ecole Normale Supérieure, 1999), 113–26; Frédérique Lemerle, "*L'Architecture, ou Art de bien bastir* de Vitruve, traduit par Jean Martin à Paris chez Jacques Gazeau Françoys, en 1547," in *Sebastiano Serlio à Lyon: Architecture et imprimerie*, ed. Sylvie Deswarte-Rosa (Lyon: Mémoire Active, 2004), 418–19.

32. Marcus Vitruvius Pollio, *Architecture, ou Art de bien bastir de Marc Vitruve Pollion*, trans. Jean Martin (Paris: Jacques Gazeau, 1547), fol. 74r.

33. Martin included an image of an amphitheater with bronze vessels in his 1553 translation of Leon Battista Alberti's *De re aedificatoria* (*L'architecture et art de bien bastir*, published in Paris by Jacques Kerver); the image was copied from Cosimo Bartoldi's 1550 Florentine edition of the same work. See Mario Carpo, "Le *De re aedificatoria* de Leon Battista Alberti et sa traduction française par Jean Martin, à Paris chez Jacques Kerver en 1553," in Deswarte-Rosa, *Sebastiano Serlio à Lyon*, 371–72.

34. Aristotle, *Problemata*, ed. W. D. Ross, trans. E. S. Forster, in *The Works of Aristotle* (Oxford: Clarendon Press, 1927), 9.8. In the mid-fifteenth century Leon Battista Alberti made an explicit link between Vitruvian acoustic vase practice and the *Problemata*. Leon Battista Alberti, *On the Art of Building in Ten Books*, trans. Joseph Rykwert, Neil Leach, and Robert Tavernor (Cambridge, Mass.: MIT Press, 1988), 8.7.276.

35. Andrew Tallon, "Acoustique de l'architecture médiévale: Enquête sur quelques aspects des rapports entre la musique religieuse et l'architecture médiévale en France" (master's thesis, Université de Paris–Sorbonne, 1992), 50–73, 96–107; Bénédicte Palazzo-Bertholon and Jean-Christophe Valière, "Pour un recensement des pots acoustiques: État de la question," in *Archéologie du son: Les dispositifs des pots acoustiques dans les édifices anciens*, ed. Bénédicte Palazzo-Bertholon and Jean-Christophe Valière (Paris: Société Française d'Archéologie, 2012), 85–97. See in particular the inventory maintained at the Laboratory of Sound Archaeology at the University of Poitiers: http://archeoacoustique.labo.univ-poitiers.fr/inventaire (accessed 21 Mar. 2016).

36. Jean-Marc Fontaine, "Un système historique de correction sonore: Les vases acoustiques," in *L'orgue français classique: Actes du colloque de Souvigny (3 août 1983)*, ed. Henri Delorme (Souvigny: Association Saint-Marc, 1985), 82. The Abbey of Cluny possessed a copy of *De architectura*. See Krinsky, "Seventy-Eight Vitruvius Manuscripts," 37.

37. See Yves-Pierre Castel, "Les systèmes de vases acoustiques anciens dans les églises du Finistère (XIV^{e}–XVII^{e} siècle)," *Bulletin de la société archéologique du Finistère* 104 (1976), 331–47.

38. Bénédicte Palazzo-Bertholon, "Les sources médiévales et modernes," in Palazzo-Bertholon and Valière, *Archéologie du son*, 27–31.

39. Ernest de Bouteiller, "Notice sur le couvent des Célestins de Metz," *Mémoires de l'Académie impériale de Metz* 43 (1861–62), 528.

40. Ibid. In 1898 a canon named Bourbon wrote of the vases in the church of Syens, in Switzerland, in similar terms: "The monks and the chapter redoubled their efforts to harmoniously sing the praises of God. They even wished to have the vaults echo the sacred chant. To this end, they equipped them with resonating pots which were, for a time, very successful. However, the principles of acoustics did not cooperate; experience soon showed that these resonating pots were but useless furniture [*meubles inutiles*]." Cited by Adolphe Decollogny, *Cent églises vaudoises* (Lausanne: Adolphe Decollogny, 1971), 178.

41. Arns and Crawford suggest that the earliest connection between Vitruvian *echea* and postclassical clay vases is found in the commentary on Vitruvius by Cesare Cesariano, *Di Lucio Vitruvio Pollione De architectura libri dece traducti de latino in vulgare affigurati: Commentati & con mirando ordine insigniti* (Como: Gottardo da Ponte, 1521), fol. 79v: "Introclusi intra le Theatrale sedie con queste ratione che de tuti quasi perscribe et etiam potrano fare tale harmonia per la dispositione che Vitruvio qua discribe: quisto sono concordanti: ut puta per [?] exemplo quelle rote che si soleno collocare in le Ecclesie per sonare a le messe: nel tempo che il sacerdote dimonstra la sacrata hostia et calice del nostro Signore Iesu Christo: et de queste rote cosi fabricate in la Francia: et Germania aptissimamente se ne usa et altroe." See Arns and Crawford, "Resonant Cavities," 116. The passage, however, does not refer to clay vases at all; rather, it discusses the use of a "rota," or wheel, probably a bell mounted to a disk much like those still found adjacent to the sacristy doors of certain European churches. The "rota" seems to have been used to signal the elevation of the Host during the sacrament of the Eucharist—a practice that would be codified several decades later during the Council of Trent. Cesariano appears to have been unaware that there was an active tradition of acoustic vase usage in northern Europe; the resonance of the Vitruvian *echea* is connected to what seemed to him the most probable equivalent, the resonance of a bell made of bronze. I am grateful to Nicholas Adams, John Ahern, and Lorenzo D'Anselmi for their assistance with this passage.

42. Marin Mersenne, *Harmonie universelle, contenant la théorie et la pratique de la musique*, vol. 2, *Livre de l'utilité de l'harmonie et d'autres parties des mathématiques* (Paris: Sebastien Cramoisy, 1637), 35, corollary 3.

43. Ibid.

44. Ibid., 36, corollary 3.

45. Louis Jaucourt, "Vases de théatre," in *Encyclopédie, ou Dictionnaire raisonné des sciences, des arts et des métiers, par une société de gens de lettres*, ed. Denis Diderot and Jean le Rond d'Alembert (Neuchâtel, Switzerland: Samuel Faulche et Compagnie, 1765), 16:854.

46. Aubin-Louis Millin, "Echea," in *Dictionnaire des Beaux-arts*, ed. Aubin-Louis Millin (Paris: Desray, 1806), 1:477–78.

47. C. A. Moët de la Forte-Maison, *Antiquités de Noyon, ou Étude historique et géographique, archéologique et philologique des documents que fournit cette ville à l'histoire des cités gallo-romaines et féodales de France* (Rennes: Anciennes Libraries Vatar et Jausions, 1845), 319–22.

48. First, the exceptions: Geoffroy Asselin, then director of the Académie in Amiens, injected a healthy dose of common sense in a little-known talk given on the *caveau* in 1986; see Geoffroy Asselin, "Installations destinées a préserver ou à améliorer l'acoustique," *Comptes rendus et mémoires de la Société archéologique, historique et scientifique de Noyon* 37 (2000), 265–75. And Jean-Christophe Valière and Bénédicte Palazzo-Bertholon reserve judgment in "Le dispositif acoustique du caveau de la cathédrale de Noyon (Oise)" (paper presented at the Twelfth French Congress of Acoustics, Poitiers, 22–25 Apr. 2014). The others are as follows: M. l'Abbé Laffineur, *Une visite à Notre-Dame de Noyon, ou déscription sommaire de la cathédrale de Noyon et ses dépendances* (Noyon: Andrieux-Letellier, 1858), 45; Emile Coët, *Ephémérides du Noyonnais* (Noyon: J. Tugaut, 1887), 114; L. Pihan, *Esquisse descriptive des monuments historiques dans l'Oise* (Beauvais: Père, 1889), 1:342–43; Alphonse Béchet, "A travers Noyon," *Notes d'art et d'archéologie* 4 (1892), 245–49; Robert de Guyencourt, "Mémoire sur l'ancienne église des Cordeliers d'Amiens et sur les fouilles qui suivirent sa démolition," *Mémoires de la Société des Antiquaires de Picardie*, 4th ser., 2 (1894), 19–20 (Guyencourt makes reference to the *caveau* in the context of a similar space discovered in the church of the Cordeliers in Amiens, which was destroyed in the Revolution); Louis Cloquet, "Notes d'art et d'archéologie," *Revue de l'art chrétien*, 4th ser., 4 (1893), 71; Louis Cloquet, "Vases acoustiques," *Revue de l'art chrétien*, 4th ser., 8 (1897), 518–19; Louis Cloquet, *Traité d'architecture* (Paris: Charles Béranger, 1901), 5:249. Cloquet popularized Béchet's version of Moët de la Forte-Maison's account—as well as Béchet's misspelling of *phonocamptique*, from which he had omitted the *t*. Lefèvre-Pontalis, who might have been expected to say more, given his archaeological bent, refers to the chamber only twice: Lefèvre-Pontalis, "Histoire de la cathédrale de Noyon (III)," 286; Eugène Lefèvre-Pontalis, "Le jubé de Noyon," *Bulletin monumental* 82 (1923), 442. His brief mentions are taken up by Seymour, *Notre-Dame of Noyon*, 83. Ludovic Vitet, surprisingly, was unaware of the *caveau*. "Beneath the Cathedral of Noyon," he wrote, "there exists neither crypt, confessional, nor basement whatsoever." Ludovic Vitet, *Monographie de l'église de Noyon* (Paris: Imprimerie Royale, 1845), 168–69.

49. Moët de la Forte-Maison, *Antiquités de Noyon*, 322.

50. I sampled the *caveau* vase resonant frequencies on 13 December 2012 with the assistance of Nicole Griggs. A recording made of these tests was then subjected to detailed frequency analysis.

51. Plato, *Timaeus*, trans. and ed. Donald J. Zeyl (Indianapolis: Hackett, 2000), 34b10–36d7. It was through the commentary made on the *Timaeus* by Chalcidius in the early fourth century and the work of Neoplatonists such as Plotinus (AD 204–69) that the views of Plato were promulgated. Albert Seay, *Music in the Medieval World* (Englewood Cliffs, N.J.: Prentice Hall, 1965), 18.

52. Saint Augustine of Hippo, *De musica*, in Jacques-Paul Migne, *Patrologia Latina* Database (ProQuest Information and Learning Company), 32: 1079–1194, http://pld.chadwyck.com (accessed 21 Mar. 2016); Saint Augustine of Hippo, "On Music (*De musica*)," trans. Robert Catesby Taliaferro, in *Writings of Saint Augustine*, ed. Roy J. Deferrari (Washington, D.C.: Catholic University of America Press, 1947), 153–379.

53. Anicius Manlius Severinus Boethius, *Fundamentals of Music*, trans. Calvin M. Bower (New Haven, Conn.: Yale University Press, 1989), 1.2; Anicius Manlius Severinus Boethius, *De musica*, in Migne, *Patrologia Latina* Database, 63: 1167–1300. See Nan Cooke Carpenter, *Music in the Medieval and Renaissance Universities* (Norman: University of Oklahoma Press, 1958), 3–31, 46–69, 115–27.

54. Manfred F. Bukofzer, "Speculative Thinking in Medieval Music," *Speculum* 17, no. 2 (1942), 167; Leo Spitzer, *Classical and Christian Ideas of World Harmony* (Baltimore: Johns Hopkins University Press, 1963), 36.

55. For an alternative analysis of the vase frequencies, see Valière and Palazzo-Bertholon, "Le dispositif acoustique." Acoustician Valière uses statistical analysis to isolate two primary pitches. The approach is problematic, however, because it obscures the relatively wide frequency variability among vases, an essential index for evaluating the skill of those who created the system.

56. On the physical properties of the acoustic vase, see Helmholtz, *On the Sensations of Tone*, 43–44; Uno Ingard, "On the Theory and Design of Acoustic Resonators," *Journal of the Acoustical Society of America* 26, no. 6 (1953), 1052; Arns and Crawford, "Resonant Cavities," 122–23, 130; Per Brüel, "Models of Ancient Sound Vases," *Journal of the Acoustical Society of America* 112, no. 5 (2002), 2233; Tilemachos Zakinthinos and Dimitris Skarlatos, "The Effect of Ceramic Vases on the Acoustics of Old Greek Orthodox Churches," *Applied Acoustics* 68, nos. 11–12 (2007), 1307–22. I am grateful to David Bradley for his insight on acoustic vase function.

57. René Floriot, "Contribution à l'étude des vases acoustiques du Moyen Age" (PhD thesis, Université d'Aix-Marseille, 1964), 128; René Floriot, "Les

vases acoustiques du Moyen-Age," *Bulletin du Groupe d'Acoustique Musicale* 98 (1978), 6; René Floriot, interview by author, January 1992, Avignon.

58. Jean-Marc Fontaine, "Contribution à l'étude des vases acoustiques disposés dans les églises (XI–XVIII^{e} siècles)" (master's thesis, Conservatoire National d'Arts et Métiers, 1979), 92–98, summarized in Jean-Marc Fontaine, "Un système historique de correction sonore: Les vases acoustiques," *Qualité acoustique des lieux d'écoute (Université Pierre et Marie Curie, Paris, 13–16 October 1981)* (Paris: CNRS, 1981), 93–117; see also Jean-Marc Fontaine and Jean-Christophe Valière, "L'exemple de Ploaré-Douarnenez (France)," in Palazzo-Bertholon and Valière, *Archéologie du son*, 175–81.

59. Floriot's and Fontaine's conclusions were problematic, moreover, because they were framed in terms of the intelligibility of the spoken word—a consideration of negligible importance for a liturgy that was nearly entirely sung. This fundamental misconception persists today. For example, Jean-Christophe Valière and his colleagues undertook an acoustical survey of twenty-five French churches containing acoustic vases, and they conclude that their "measurements and observations . . . are consistent with an acoustical purpose of the pots to decrease the reverberation time at frequencies strongly excited by the spoken voice." Jean-Christophe Valière, Bénédicte Palazzo-Bertholon, Jean-Dominique Polack, and Pauline Carvalho, "Acoustic Pots in Ancient and Medieval Buildings: Literary Analysis of Ancient Texts and Comparison with Recent Observations in French Churches," *Acta Acustica* 99, no. 1 (2013), 70.

60. Castel, "Systèmes de vases acoustiques," 347. J. G. Landels takes a similar stance concerning the vases thought to have been used in the ancient world. See J. G. Landels, "Assisted Resonance in Ancient Theatres," *Greece & Rome* 14, no. 1 (1967), 91.

61. On the late medieval and early modern music performed at the Cathedral of Noyon, see Fiala, "Musique à la cathédrale de Noyon," 153–70.

62. Lefèvre-Pontalis, "Histoire de la cathédrale de Noyon (III)," 289. Those I was able to examine were G1338, *gros oeuvre*; G1358, *reliques*; G1362, *tapisserie*; G1380 and G1380/2, *comptes*; G1390, *sous-trésorerie*; G1390 bis (or G1390/2), *maîtrise des enfants de choeur*; G2616, *écolatre*; G2621, *mélanges* (sixteenth–eighteenth centuries); and G2622, *trésorerie* (sixteenth–eighteenth centuries). I am grateful to Lindsay Cook for sharing her photographs of these documents with me. See the careful (but selective) review of these and other documents by Eugène Lefèvre-Pontalis, "Histoire de la cathédrale de Noyon (I)," *Bibliothèque de l'Ecole des chartes* 60 (1899), 457–90; Lefèvre-Pontalis, "Histoire de la cathédrale de Noyon (II)," 125–72; Lefèvre-Pontalis, "Histoire de la cathédrale de Noyon (III)," 457–90; and the bibliographical note in Seymour, *Notre-Dame of Noyon*, 179–87.

63. Jacques Le Vasseur, *Annales de l'église cathédrale de Noyon* (Paris: Robert Sara, 1633); Claude Sézille, "Nouvelles annales, ou Mémoires chronologiques pour servir à l'histoire de la ville et de l'église de Noyon," Bibliothèque Nationale de France, manuscrits français 12032, ca. 1750; Claude Sézille, *Nouvelles annales, ou Mémoires chronologiques pour servir a` l'histoire de la ville et de l'église de Noyon*, ed. Eloi Delbecque (Noyon: Société Historique, Archéologique et Scientifique de Noyon, 2012).

64. Lefèvre-Pontalis also dates the *caveau* to the sixteenth century, although without specific justification. See Lefèvre-Pontalis, "Le jubé de Noyon," 442. I hope that the archaeological analysis of the *caveau* currently being undertaken by the Service Archéologique de Noyon, Univ'archéo (the archaeology unit of the University of Amiens), and Bénédicte Palazzo-Bertholon (University of Poitiers) will shed new light on this question.

65. Josiane Sartre, *Châteaux "brique et pierre" en France* (Paris: Nouvelles Editions Latines, 1981), 32–38; Bernard Marrey and Marie-Jeanne Dumont, *La brique à Paris* (Paris: Editions du Pavillon de l'Arsenal, 1991), 20–21, 32–33; Josiane Sartre, *Châteaux "brique et pierre" en Picardie: Quatre siècles d'architecture*, 2nd ed. (Paris: Nouvelles Editions Latines, 2012), 91–94, 107–9. See also Pierre Chabat and Félix Montmory, *La brique et la terre cuite* (Paris: Morel, 1881), 70; Auguste Choisy, *Histoire de l'architecture* (Paris: Gauthier-Villars, 1899), 2:703; Camille Enlart, *Manuel d'archéologie française depuis les temps mérovingiens jusqu'à la Renaissance*, pt. 1, *Architecture religieuse*, 3rd ed. (Paris: Picard, 1927), 1:7.

66. A document of 1629 from the archives of the parish church of Saint-Maurice in Noyon attests to the existence of the brick factory. See "Une briqueterie du XVII^{e} siècle Place du Marché Franc," Noyon Ville Sensations, http://www.ville-noyon.fr/Une-briqueterie-du-XVIIe-siecle.html (accessed 1 Jan. 2016).

67. Jacques-François Blondel and Pierre Patte, *Cours d'architecture, ou Traité de la décoration, distribution et construction des bâtiments* (Paris: Desaint, 1777), 5:297.

68. Sartre, *Châteaux "brique et pierre" en France*, 34–35; Sartre, *Châteaux "brique et pierre" en Picardie*, 89–90.

69. Charlotte A. Stanford, ed., *The Building Accounts of the Savoy Hospital, London, 1512–1520* (London: Boydell & Brewer, 2015), 16, 308. I am grateful to Dr. Stanford for having brought this information to my attention.

70. Westminster Abbey Muniments MS 63509, fol. 203v, emphasis added.

71. National Archives (United Kingdom), "Currency Converter," http://www.nationalarchives.gov.uk/currency (accessed 1 Jan. 2016).

72. Le Vasseur, *Annales de l'église cathédrale de Noyon*, 1187–97; Lefèvre-Pontalis, "Histoire de la cathédrale de Noyon (II)," 147–49.

73. Le Vasseur, *Annales de l'église cathédrale de Noyon*, 1189.

74. Ibid., 1193–94.

75. Lefèvre-Pontalis, "Histoire de la cathédrale de Noyon (II)," 148.

76. Le Vasseur, *Annales de l'église cathédrale de Noyon*, 1198, 1202.

77. Fiala, "Musique à la cathédrale de Noyon," 158–59.

78. Eloi Delbecque, "La vue de la pompe funèbre de Charles de Broglie et l'espace liturgique de Noyon: Les oeuvres de Pierre-François Godot et de Jacques Gondouin," *Bulletin monumental* 165, no. 3 (2007), 279–80n68. On the episcopal (and other) burials in the choir, see Alphonse Boulongne, *Inscriptions tumulaires de l'église Notre-Dame de Noyon* (Noyon: Andrieux, 1876); Lefèvre-Pontalis, "Histoire de la cathédrale de Noyon (II)," 166–67; André Collin and Alfred Révillon, "Fouilles entreprises en la cathédrale Notre-Dame de Noyon (1920–1923)," *Comptes rendus et mémoires de la Société archéologique, historique et scientifique de Noyon* 36 (1990), 189; Arnaud Timbert and Hélène Dulauroy-Lynch, "Les fouilles archéologiques de la cathédrale Notre-Dame de Noyon: État de la question," in *La cathédrale Notre-Dame de Noyon, cinq années de recherches*, ed. Arnaud Timbert and Stéphanie Daussy (Noyon: Société Historique, Archéologique et Scientifique de Noyon, 2011), 62.

79. A cursory list of the graffiti in the *caveau* was published in Martine Plouvier, "La nouvelle décoration du choeur," in *La ville de Noyon: Catalogue de l'exposition "Noyon, mille ans d'art et d'architecture": Musée du Noyonnais, 20 juin au 5 octobre 1987*, ed. Martine Plouvier, *Cahiers de l'inventaire* (Amiens: Association pour la Généralisation de l'Inventaire Régional en Picardie, 1987), 124n8. In June 2013, Bénédicte Palazzo-Bertholon undertook a complete documentation, which to date remains unpublished.

80. Lefèvre-Pontalis, "Histoire de la cathédrale de Noyon (II)," 166–67.

81. On the excavations, see Lefèvre-Pontalis, "Le jubé de Noyon," 442–45; Seymour, *Notre-Dame of Noyon*, 35; Collin and Révillon, "Fouilles," 183–99; Timbert and Dulauroy-Lynch, "Fouilles archéologiques," 29–104.

82. Stéphanie Diane Daussy, "L'aménagement liturgique du chevet de la cathédrale de Noyon," *Viator* 42 (2011), 169–201. The decision to dismantle the screen was made in 1753, although not without protest; only in 1757, after arbitration by the Conseil du Roi, was demolition finally undertaken. Sophie Cloart-Pawlak, "Le jubé de la cathédrale Notre-Dame de Noyon: Précision sur sa datation," in Timbert and Daussy, *La cathédrale Notre-Dame de Noyon*, 276–88.

83. On the disposition of the *pulpitum* and the *aquilam* (the eagle-shaped lectern) at the Cathedral of Paris, see Wright, *Music and Ceremony*, 98–101. On the Cathedral of Laon, see Alexander J. Sturgis, "The Liturgy and Its Relation to Gothic Cathedral Design and Ornamentations in Late Twelfth and Early Thirteenth Century France" (PhD thesis, London University,

1990), 151–60. On the performance of polyphony at the Cathedral of Noyon, see Fiala, "Musique à la cathédrale de Noyon," 156–57.

84. On the prolonged dispute over the construction of the high altar in the eighteenth century, see Lefèvre-Pontalis, "Histoire de la cathédrale de Noyon (II)," 169–72; Seymour, *Notre-Dame of Noyon*, 82–83; Jacques Foucart-Borville, "Les projets de Charles de Wailly pour la gloire de la cathédrale d'Amiens et de Victor Louis pour le maître-autel de la cathédrale de Noyon," *Bulletin de la Société de l'Histoire de l'Art Français* (1974), 131–43; Plouvier, "Nouvelle décoration du choeur," 122–23; Christian Baulez, "Les marbriers Dropsy et leurs immeubles," in *Le Faubourg Saint-Germain*, *rue de l'université*, ed. Françoise Magny (Paris: Délégation à l'Action Artistique, 1987), 171–81; Jacques Foucart-Borville, *Nouveaux aperçus sur le maître autel néoclassique de la cathédrale de Noyon* (Amiens: Bibliothèque Municipale d'Amiens, 1999), 138–43; Delbecque, "La vue de la pompe funèbre de Charles de Broglie," 263–80, 324–25; Mathieu Lours, *L'autre temps des cathédrales: Du concile de Trente à la Révolution française* (Paris: Picard, 2010), 195–207; Mathieu Lours, "Le choeur en bataille: Débats et polémiques sur les choeurs dans les cathédrales françaises au XVIII^{e} siècle," in *La place du choeur: Architecture et liturgie du Moyen Âge aux temps modernes*, ed. Sabine Frommel and Laurent Lecomte (Paris: Picard, 2012), 227–36.

85. For a sense, based on limited documentation, of the cost of maintaining a group of *chantres* (cantors) and choirboys in the fifteenth and sixteenth centuries, see Fiala, "Musique à la cathédrale de Noyon," 157.

86. Vitruvius, *Architecture*, *ou Art de bien bastir*.

87. Mersenne, *Harmonie universelle*, 36, corollary 3; Arns and Crawford, "Resonant Cavities," 132–33.

88. Vitruvius describes an effect like portamento, in contradistinction to a series of fixed pitches. Vitruvius, *Ten Books on Architecture*, 5.4.2–3.