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Invisible architecture, communicating space through sound models

For years now, the increasing development of virtual reality technologies and digitisation processes in architecture has been leading cultural heritage communication towards an increasingly sustainable and inclusive approach. In this sense, the accumulation of data and, consequently, of specific information that the models bring with them, offers the opportunity for numerous insights related to the conversion of parameters to achieve an even broader communication towards users with perceptual limitations. The topic of perception, although now intrinsic in the fundamental criteria of architectural design, may receive less public attention compared to more immediate issues like building accessibility.
From a practical point of view, the most innovative technologies to improve the quality of life of blind subjects come mainly from neuroscience laboratories, also and above all to assess the impact of so-called sensory substitutional devices on brain activity. What is presented in this study is therefore to extend what are the operating principles of the above-mentioned tools and contextualise them within the domain of the perception of valuable architectural space, for an understanding of geometry and proportion through sound.

Keywords:
Accessibility; Digitization; Inclusion; Museum-display; Algorithms

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INTRODUCTION AND OBJECTIVES

Constructing models has always been the synthetic tool to express the image of space. Whether we are talking about sixteenth-century perspectives or today's renderings, the returned image is always something that refers to something else, carrying forward peculiar characteristics of the whole from which it is derived (Migliari, 2004). In the Western World the word representation is often associated with an exclusively visual dimension, presumably for cultural reasons (Ingold, 2007). In the last decades, however, other elements of the sensory sphere have also gained an increasing consideration in the field of both design and communication in general (Bergamo, 2021). Within the domain of surveying, data acquisition methodologies have progressed to the point of conferring a level of information that makes it possible not only to return a graphic and interpretative image of the object, but also to produce actual model systems. Being able to make illustrations, virtual reality environments and physical models from the same source of information ensures a coherent reading of the whole in all its forms, increasing knowledge of the subject under investigation in different aspects of sensoriality.
The possibility of reproducing and communicating an object in different modalities has also enabled numerous steps forward in the field of inclusiveness and accessibility. While from a more immediate point of view virtualizing a space makes it potentially accessible in any spatial and physical condition, there are several other declinations, not necessarily pertaining to the sphere of the visible, that can be imagined when thinking about the issue of data conversion in favor of those with sensory limitations.
For several decades, in fact, the studies carried out on sensory substitution devices (SSDs) have achieved outstanding results, producing soundscapes that allow individuals without the use of sight to reconstruct the elements present in the figure in terms of position, size and color shades. This type of methodology is based on well-established conversion algorithms and is quite versatile since it can be used in different contexts such as face recognition experiments in blind subjects (Arbel, Heimler, Amedi, 2022), or to enhance perception in areas outside the visual field (Netzer et al, 2021).
This kind of device, however, is mainly dedicated to 2D images, and although they are scientifically accurate, they perform sound conversions related to purely quantitative values (Meijer, 1992).
If we wanted to extend this logic to the context of architecture and more specifically to cultural heritage, two fundamental issues would arise. The first is related to the transition from two dimensions to three and thus the consequent introduction of the depth parameter. The second is, if possible, even more complex and refers instead to those intrinsic values that characterize a valuable space and that must necessarily be communicated through form. Combining image and space, therefore, the attributes that make architecture the exceptional element in the context of works of art (Benjamin, 2020). In this, music remains the most appropriate tool, capable of returning a dynamic image without the need to share the same perceptual medium as the original object (Garroni, 2005).
To summarise, the aim of this study is to combine and contextualise the principles of sensory substitution devices in a three-dimensional setting, with a focus on their general validity in architectural spaces. This article focuses on the results obtained through the use of such principles to a specific case, the Tempietto of San Pietro in Montorio in Rome, outlined from a survey carried out in January 2024 (fig. 1).
This is an attempt to develop a methodology that can define through virtual reality an interactive sound model, extrapolating the geometries of the architectural layout and transposing their form in the most congruent way possible.

Fig. 1 - Tempietto of San Pietro in Montorio, view of the east entrance..

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Fig. 2 - Tempietto of San Pietro in Montorio, inner view of the dome.

HISTORICAL AND ARCHITECTURAL BACKGROUND

The Tempietto of San Pietro in Montorio can be defined as one of the most representative works of the Italian 16th century. Designed by the architect Donato Bramante in the early 1500s according to the wishes of the King of Spain, it is located within one of the courtyards of the convent of San Pietro in Montorio, on the slopes of the Gianicolo hill, at the base of which lies the Trastevere district, and where it is traditionally believed that the martyrdom of St. Peter took place (Lotz, 1997).
The building with a centric layout stands out from the christian tradition because of its shape: the round peripteral (Wittkower, Krautheimer, 2010). It consists of a Doric order colonnade that encloses the naos within it and is surmounted by the drum that culminates in the dome hemisphere (fig. 2). On the lower level there is a crypt, connected to the upper floor by two specular staircases.
The stylistic composition of the elements, as well as the proportional and geometric ratios, makes the Tempietto “The first classical building built in Rome” (Lotz, 1997). In fact, Bramante merges “in a single building several key themes of his age” (Attenni et al, 2019), starting with the use of a paradigm that in this case is the result of a comparison with the architecture of ancient Rome.
The complex is based on well-defined proportional relationships, but the original design conceived by Bramante was never brought to completion. In fact, the courtyard was originally conceived as a concentric structure surmounted by a trabeation, with the intention of bringing out the image of the temple as seen through the column shafts (Chastel, 1999) (fig. 3). The final result remains conditioned by the development of a context that differs from that envisioned by its architect, while maintaining its inestimable value.

THE SURVEY PROJECT: DATA ACQUISITION AND PROCESSING

As defined previously, the communication project based on an interactive sound model lays its foundation on a correct geometric reconstruction of the architectural space. In order to extrapolate the information that would be useful for the construction of the final model, it was necessary to critically process the data obtained in order to represent the elements that make up the space with the proper degree of uncertainty. This process is carried out from the collected data, identifying a number of significant points to be used as an interpretative basis (Bianchini, Fabbri, Borgogni, 2017). The goal is to produce two-dimensional and three-dimensional models that will be the reference used in the conversion method that originates the sound model.
Despite the abundance of elaborations and studies carried out on the subject of San Pietro in Montorio, this operation is also aimed at building a tool to verify existing data and previously formulated hypotheses. Thus, we started with the analysis of the available graphic documentation, and once the characteristics of the space were taken into consideration, on-site operations began.
Having decided to digitally reconstruct the interior space of the courtyard containing the Tempietto, there were no plans to process the information related to the context, both urban and architectural. The final result is a numerical model corresponding to the digital copy of the roman building, made with the systematization of data from the set of indirect (carried out by laser scanner and structure from motion) and direct survey operations and with the possibility of being inspected, decomposed and segmented in different ways (Ippolito et al, 2023) (fig. 4).
The scaling relationship between the numerical model obtained by laser scanner and the real object made it possible to maintain control and verifiability of the data in any state of the processing, including that of point management at the stage of aligning to data obtained from other sources.
The end result is a model integrated with information from different acquisition tools and systematized into a single object with the necessary features for the development of subsequent phases.

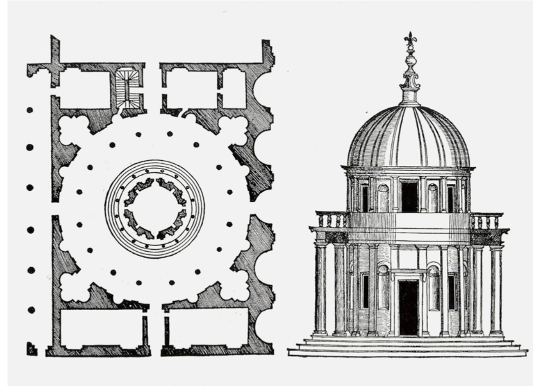

Fig. 3 - Graphic elaboration of Sebastiano Serlio’s drawing depicting the conformation of the courtyard according to Bramante’s original idea.

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Fig. 4 - Numerical model obtained by laser scanner. Starting from the top: image taken from the porch inside the courtyard, image taken near the colonnade, interior image of the naos environment.

REFERENCE MODELS

From these starting conditions, then, the necessary steps to achieve the set goals were defined. The objectives related to this phase are mainly related to the production and systematization of the models to be used as reference for subsequent operations, which were the tools employed both as the basis for the form investigation and to realize the final virtual space.
From the numerical model, several vertical and horizontal sections were produced to generate the two-dimensional 1:50 scale drawings created using CAD (fig. 5a, 5b). Then, a parametric 3D model cut approximately at the section height of the 2D plan was made. This choice is motivated by the fact that at the current stage of the research the sound model will only refer to the planimetric layout of the spaces as it does not require information about the upper portion of the temple.
From the parametric model, finally, 3D-printed models in PLA material were produced to test the level of understanding of space that the blind subjects could get through touch.
This process was especially useful in figuring out how to proceed in the later stages of extrapolating the basic geometries of the temple architecture and also to define the physical model to be included in the training phase of associating sounds with space. The first printing attempt was in fact a model built in relief on a square base, basically a bas-relief of the plan. From this model, however, it was difficult for users to define the structure of the Tempietto, so it was decided to move on to the actual printing of the parametric 3D model (fig. 6). This turned out to be much more useful than the previous one, making it clear which shapes were more intuitively deducible and which were less so. From these objects, it was possible to identify the main environments that characterize the space of the Tempietto in order to successively extrapolate the geometries underlying their compositional structure. Considering that the crypt is not part of this experimental phase, it is possible to divide the building into three parts: the crepidoma (the outer space), the ambulatory (the intermediate space)

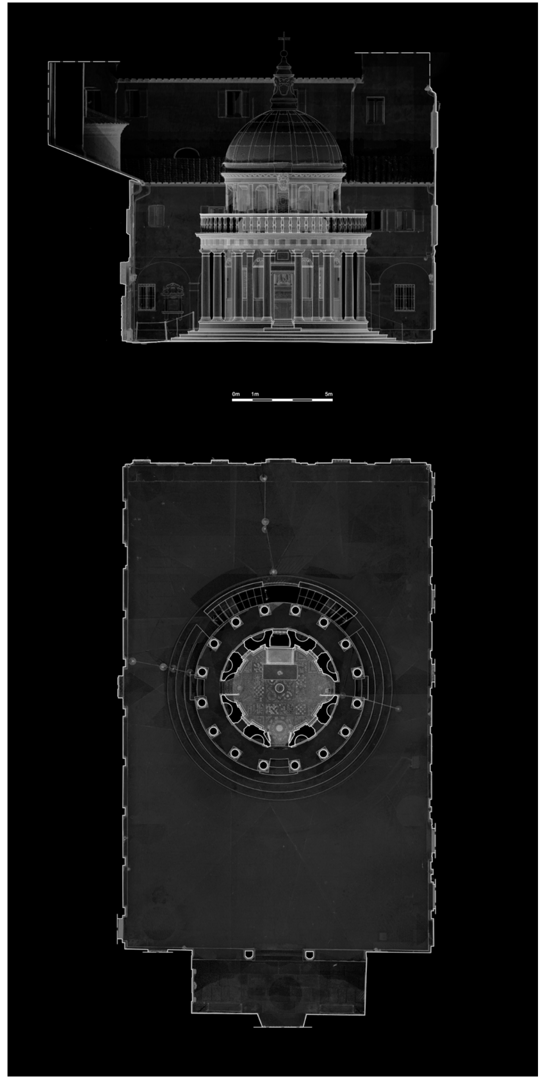

Fig. 5a - 2D elaborations obtained from the numerical model. From top to bottom: elevation and plan of the Tempietto.

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and the naos (the inner space).
The structure of these spaces can be reconstructed in highly simplified manners through the use of concentric circumferences and polygons of different sizes as shown in figure 6. On the innermost of the circumferences is grafted the rectangle of the altar, while the one that corresponds to the limit of the ambulatory accommodates within it the peristasis, simplified into a set of circles inscribed in squares.
Internal and external pilasters were not included in the geometrization of this space. This choice was dictated both by a subsequent study regarding the individual architectural elements and by the need to simplify the wall surface, found directly in the feedback obtained from users who tested the PLA models.
The same principle was not followed for the columns for two basic reasons: the first is that they are an integral part of the boundary that defines the peristasis environment, and the second is that they were intuitively recognized by the users who tested the models.
The shapes shown in the C section of figure 6 will then be the actual images on which to build the sounds to be included in the virtual model, defined by a conversion method linked to the cross-modal associations of certain peculiar characteristics of both elements, as we will see later. This statement is based on studies that investigate the association of different types of phenomena, in this case visual and acoustic, and establish the possible causes of the relationships between them. Wanting to give an example: a sound waveform that has more ridges is generally associated with images of angular solids by those tested, while flatter waveforms are associated with less angular solids (Liew et al, 2018).
Once the basic geometries were extrapolated, it was decided to make a final version of the model in PLA totally resembling the simplified 2D geometric scheme and divided into three blocks corresponding to the three environments thematized earlier, as shown in section D of figure 6.
The development of these models thus shows a consequentiality in the construction of the tools

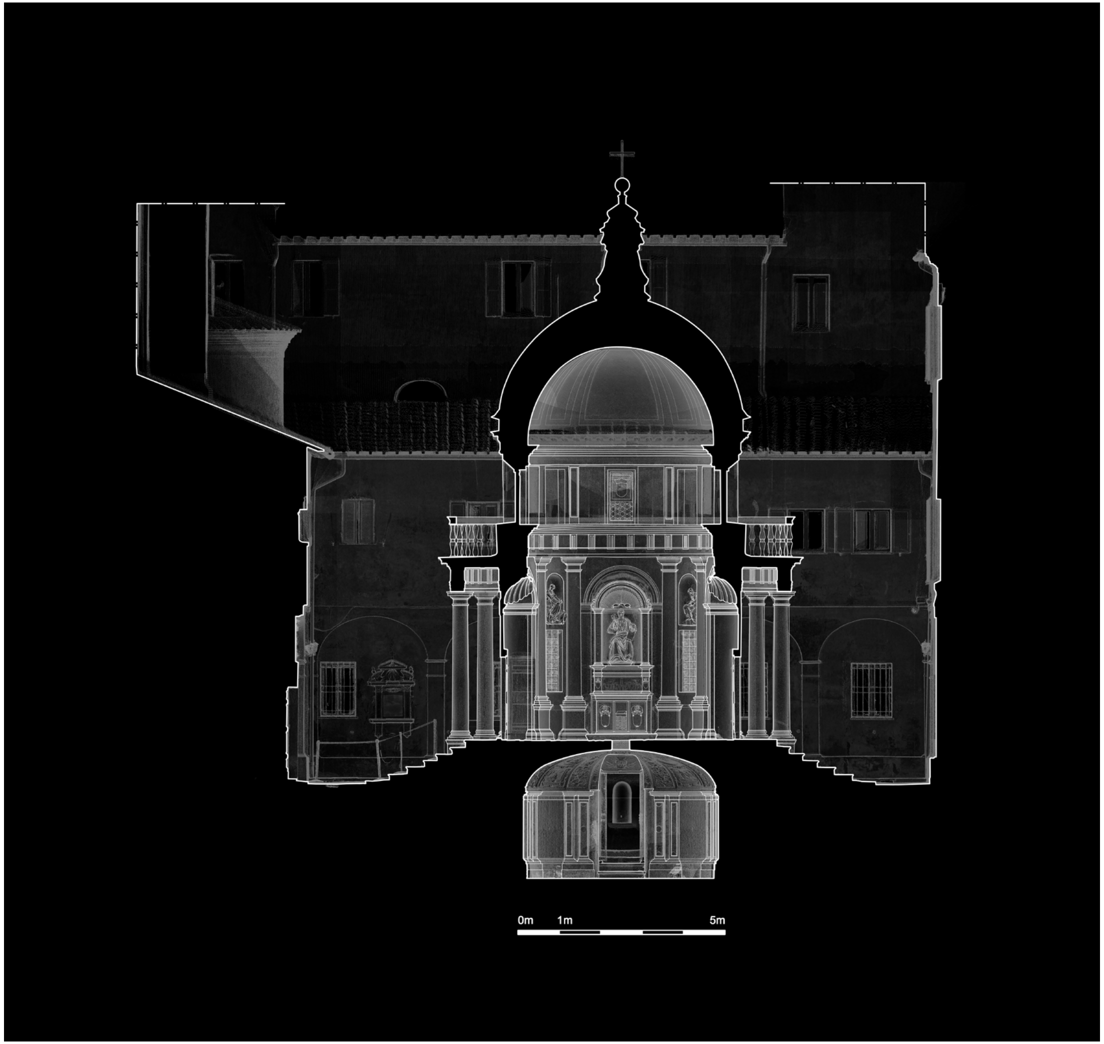

Fig. 5b - 2D elaborations obtained from the numerical model: section.

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that lead to the realization of the final goals, starting from more abstract and geometric references up to the scaled, tangible and real physical object.

THE COMMUNICATION PROJECT

BUILDING A RELATIONSHIP BETWEEN SOUND AND IMAGE

Once the images to be converted had been clearly defined, and in order to construct sounds that were in some way related to them, it was necessary to resort to the already well-known perceptually structured associations between sound and image, and more specifically between sound and space. Indeed, auditory experience is not relegated exclusively to hearing. Just as in the other cases, the perception of music is defined by a set of interconnected factors that justify the activation of images or other non-auditory experiences through sound (Macedo, 2015). In several experiments where participants were asked to express sound perception in modalities other than auditory, many of the verbal expressions used were based on visual-spatial modalities, a finding that was surprisingly valid for both sighted and blind subjects (Antovic et al, 2013).
In fact, it is not difficult to imagine an association between certain spatial or dimensional features of an object and a hypothetical difference in the pitch or gravity of a sound, since these kinds of correspondences pertain to long known themes in perception (Gibson, 1966). In general, some associations might depend on everyday experience (Evans, Treisman, 2010) but, as mentioned earlier, the goal is to communicate intrinsic features of the form that make the architectural space unique and place it in a specific context, whether historical or artistic. This kind of metaphorical relationship between sound and image could be based on a code that does not derive from an intuitive association, let alone with words representing objects (Otzurk, Krehm, Vouloumanos, 2013).
For example, the Tempietto is a building with a centered layout whose reference geometry in terms of plan is comparable to a circumference, the circle being the basis of Bramante's design. This criterion is immediately deductible through sight and, as we have seen above, forms the basis for setting up a geometric simplification in order to constitute a reference scheme of the plan.
At this point if we imagine placing a sound source in space in relation to the considerations outlined, we could easily define what parameters are to be converted in terms of placement and size. The change in note height can be a good indicator of the position of the object in relation to the Z-axis and its size in general, while intensity can be considered a reference to the X- and Y-axis. If we add that this is a three-dimensional and virtual environment, we can also define the direction in which a sound source expands.
Regarding the geometric shape from a phenomenological point of view we have already mentioned the correspondence between the sound waveform and the continuity or discontinuity of the visible surface of the object (Liew, 2018), as well as dynamics and timing of sound emission (in a nutshell, rhythm), can be diversifying factors in the development of associations towards objects more or less oriented towards roundness.
Finally, as a last consideration it should be taken into account that at a timbral and rhythmic level using unfamiliar samples could be distracting for the user of the model (Athanasopoulos, Moran, 2013).
From this analysis, six sound samples inspired by the geometric shapes previously extracted from the temple plan were produced.
Through an online survey at this point, the tracks were played to a group of thirty-one anonymous participants whose task was to match the sounds to geometric shapes in a picture (fig. 7). The option of not answering or associating a figure with several different sounds and vice versa was also given.
This operation was planned with the aim of choosing which of the proposed sounds was most evocative of the simplified geometries of the temple plan.
The six geometric shapes were divided into three groups: the quadrilaterals (the square and the

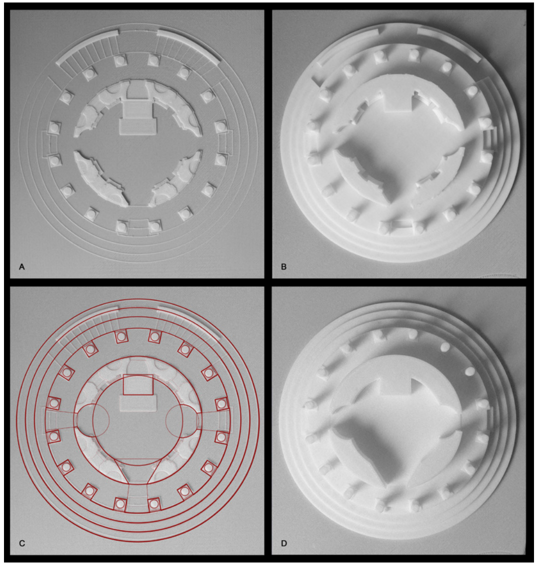

Fig. 6 - Section A: Bas-relief made in 3D printing of the plan of the Tempietto of San Pietro in Montorio. Section B: Plastic model made in 3D printing of the Tempietto of San Pietro in Montorio up to a height of about 2 meters. Section C: Geometric simplification overlayed on the bas-relief present in Section A. The purpose of the operation is to extrapolate the geometries underlying the conformation of the Tempietto. Section D: Model made in 3D printing based on the simplifications made in section C.

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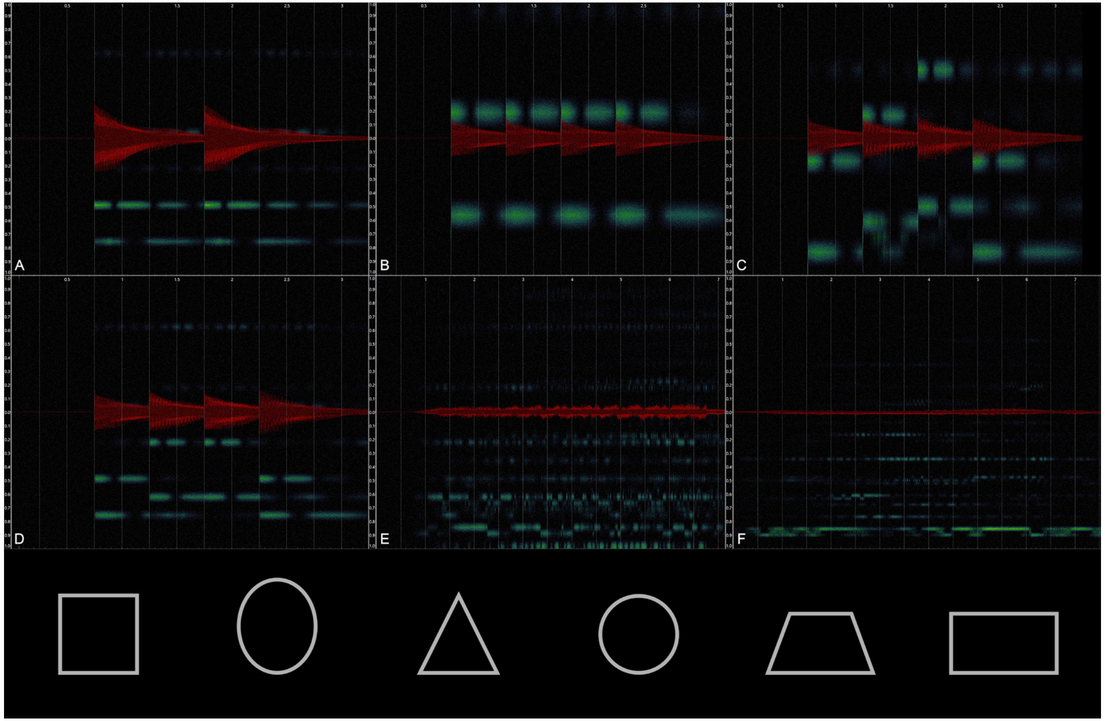

Fig. 7 - Graphical representation of the sounds composed for the survey. In red is the sound waveform while in green is the frequency of the emitted sound. To simplify: the red shape represents the dynamics and intensity of the sound, while the green shape represents the pitch. Below are the geometric shapes to be paired with the sounds in the survey.

rectangle) the oblique shapes (the trapezoid and the triangle) and the curved shapes (the circle and the ellipse). The final objective of the test was to understand whether through cross-modal association, i.e. the co-ordination of sensory inputs involving different brain regions, the characteristic elements of geometry such as the orthogonality of lines or their curvature, could in some way be communicated through sound, following in the footsteps of experiments carried out in the field of psychological and neuroscientific studies (Parise, Spence, 2012).
The six audio tracks were composed according to different variations in frequency, intensity, rhythm and timbre, identifying these four characteristics as the main categorisation indices of a sound.
The first audio track found an association rate of 21.74% with the trapezoid and 30.43% with the triangle, while track two found 39.13% with the square and 26.09% with the rectangle. Track three showed an affinity of 34.78% with the trapezoid and 17.39% with the triangle.
Tracks five and six, i.e. those without variations in rhythm and composed of continuous notes, had a 43.48% and 34.78% association with the circle respectively, while they had a 30.43% and 34.78% association with the ellipse.
The criteria that were most taken into account were therefore the variation in note dynamics and timbre. Audio tracks that presented a set of continuous notes with a softer timbre were almost unanimously assigned to shapes with curved lines, while audio tracks composed of notes with a cadenced rhythm and low frequency variation were associated with the more orthogonal geometries. The sounds were then associated with the shapes previously extrapolated from the temple plan following these criteria

TRAINING

The basis of the communication project is the definition of the elements that make up the set of sounds, images, and objects. Once a correspondence between sound and image has been established and all models, both physical and virtual, have been prepared for the experimentation phase, it is possible to delve into the first preparatory steps prior to using the virtual model, where the user must learn to associate sounds with shapes.
The goal remains to develop a functional model for initial experimentation. In fact, if as mentioned above many of the sensory substitution devices rely primarily on real-time conversion of visual parameters, the approach illustrated in this study involves a sound-object relationship defined beforehand, allowing the user to become familiar with the model before experiencing it in virtual reality.
The final product will thus be a virtual space with the features of the Tempietto di San Pietro in Montorio on a 1:1 scale in which sound sources will be placed in such a way that through them both the

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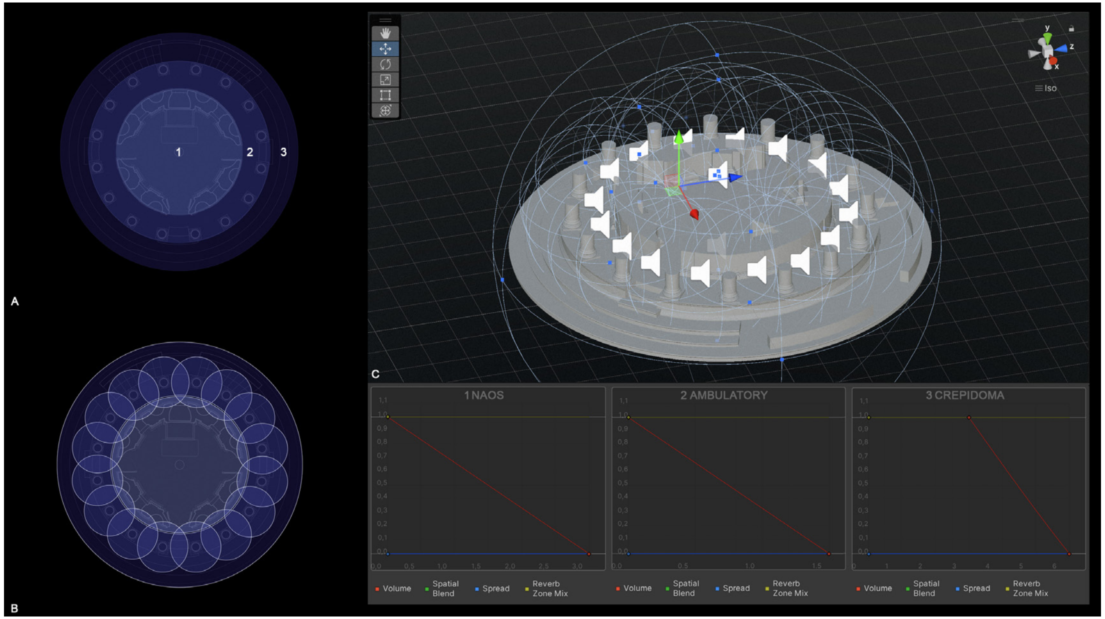

Fig. 8 - Section A: thematic subdivision in plan of the environments according to the criterion used previously for 3D printing, namely naos, ambulatory and crepidoma. Section B: graphical representation in plan of the areas of influence of the sound sources placed on Unity. Section C: Unity interface where is loaded the parametric 3D model on which the sound sources are placed. Below are graphs representing the volume trend versus distance from the source origin.

boundaries of the space and the forms that characterize it can be deduced.
On the technical operation and design it will be necessary to make an in-depth study later, but it is important to understand that this type of tool tries to establish a compromise between the scientific rigor of the conversion methodologies known up to now and the consumer tools with which it is possible to communicate interactive models in virtual reality. Although it may seem counterintuitive, since this project is aimed at a user base consisting purely of the blind or visually impaired, the best way to convey the information encoded according to this conversion method is with the use of a headset. In fact, the headset constitutes a portable tool that is capable of both emitting sound and considering and recording the user's movements in virtual space.
So, returning to the methodological structure of the application, it is useful to illustrate how it was planned to prepare users for the recognition and association of sounds with architectural form.

As shown above, modular 3D-printed models with simplified geometries were produced according to feedback from the users who tested them. Each of the parts represents an environment defined according to the thematic division made earlier (naos, ambulatory and crepidoma).
Testers were told the architectural meaning of the objects, the direction according to which it was correct to place them and were invited to ask any questions they could think of about the nature of the objects, whether architectural, functional, or geometrical.
After becoming familiar with the geometry of the shapes, a sound was played for each one, and the user had the option of listening to it at will. This operation was repeated until random listening to one of the designated sounds was intuitively associated with the corresponding object.

CONSTRUCTING THE SOUND MODEL

Once a relationship between sound and form was defined, the next step was to put the parametric model in Unity, a software dedicated to video game development and virtual reality. Sound sources, represented in the form of a sphere, were placed in the virtual space (fig. 8). The shape is determined by the fact that these are three-dimensional sound sources, the radius is sized at the discretion of the modeler as well as the position of the emission center. The sound intensity is maximum at the center and decreases as one approaches the outer limit according to a pattern that also varies with the project's needs.
While the 3D modeled environments have specific boundaries, these areas of influence are slightly overlapping to avoid an excessively abrupt transition from one environment to another, generating a cross-fade phenomenon as shown in the B section of figure 8.
The sounds are created according to the directions shown above, meaning that each geometric shape extrapolated from the models is associated with an audio source. The sound sources may resemble each other in rhythm and timbre, but their size and location in space causes the frequency to

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be different. Essentially, two similar shapes but in different sizes will have the same sound but performed by two different notes.
The change in elevation that one encounters when moving from the crepidoma to the ambulatory was marked through a change in pitch of the note corresponding to the geometric shape that characterizes the two environments, obviously not being able to reconstruct the object physically on a 1:1 scale.
Each sound source is spatialized and the direction from which it is perceived varies according to the listener's position in space. For example, if one stands with the Tempietto to his or her left, the auditory perception will be that of a sound source emitted from the left. Thus, the ultimate goal of this model is to allow the user to reconstruct the perceptual mosaic enacted during training into a coherent set of sounds, proportioned appropriately to match the structure of the environmental boundaries of the space and with the need to be responsive to the listener's actions.
The final product was exported as an APK file and installed on a MetaQuest 3 device.

CONCLUSIONS

Despite the difficulties in relating the construction of a sound model to the image of architecture, this study stands as a ground zero in a broader proposal to search for a methodology of conversion coherent with the forms of cultural heritage space. The procedures related to the acquisition and critical deduction of the relevant elements to be translated into sound show how the fundamental concepts of the discipline of representation remain at the basis of a procedure that also considers factors completely unrelated to it.
The idea of producing such a model arises from the awareness that we must compromise with the nature of perception and that we cannot propose the equivalent of a sound digital twin, but that we can construct an alternative method of communication capable of conveying architecture already filtered through a critical-representational process.
While on the technical side the results are encouraging and the use of virtual reality tools opens up endless possibilities from an immersive point of view, the theoretical-methodological process is still far from complete. It lays the foundation on scientific studies that support the hypotheses formulated but do not go into the specifics of all aspects covered in this study. Experiments related to the use of SSDs in virtual environments are various (Maidenbaum et al, 2016), but the idea of contextualizing an existing space by taking advantage of the coded language of historicized architecture and freely navigating within it could provide some new insights into the development of these devices.
The long-term goal is to produce a model that can be overlapped with real space, making the learning experience multisensorial and multimedial (Pasqualotto, Proulx, 2012), in an augmented reality context that does not impose a forced detachment from the reference site in order to be realized.
In conclusion: this kind of experience can be useful for the popularization of cultural heritage and the dissemination of buildings rooted in our historical-artistic context, such as the Tempietto of San Pietro in Montorio, as well as helping to break down perceptual barriers. It remains for now a communication tool whose assumptions are hopeful, but which needs scientific and especially interdisciplinary feedback in order to lay a solid foundation for the future.

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