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A methodology to make cultural heritage more accessible to people with visual disabilities through 3d Printing

This work aims to facilitate the experience of visually impaired people in cultural visits with the purpose that they can access in an inclusive and accessible way to their artistic and architectural heritage. For this objective, we have designed a set of reduced models that reproduce the different artistic elements that make up the heritage spaces so that they can perceive them by touch while visiting the site. In order to carry it out, different surveys have been done through laser scanner and automated photogrammetry and the models have been printed using a 3D printer, due to its accessible cost and because it is a very widespread tool in today's society. This experience has been put into practice, with the help of the service of specialized guides, in the city of Alcalá de Henares (Madrid), a World Heritage city, which houses numerous typological heritage samples, of different sizes and nature. In this sense, our proposal seeks to adapt the models to the narrative that is developed during the visit, finding the best time to introduce the typhlological material in every particular case. Besides, if the features of the work of art require it, several models at different scales must be fabricated to facilitate the comprehensive understanding of the heritage element: from the general to the particular. To assess the effectiveness of the proposed models, tests have been carried out with visually impaired people who belong to the ONCE (National Organization of Spanish visually impaired people) delegation of Alcalá de Henares, and who have valued the experience very positively, highlighting its usefulness and identifying its limitations and areas for improvement.

Keywords:
Accessibility; Inclusion; Heritage display; 3d print; photogrametry

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1. INTRODUCTION

The inclusion of persons with disabilities is a fundamental right enshrined in the United Nations Convention of 2006 (UN, 2006) and one of the pillars of the Sustainable Development Goals that seeks to reduce inequalities between people, especially those who suffer from some type of disability (UN, 2015). Specifically, Article 30 of the 2006 convention specifies the right of persons with disabilities to participate on equal terms and without discrimination in the cultural life of society: museums, tourism, heritage, entertainment, etc. Thus, since its approval this guideline has been acquiring a fundamental role in the development of our societies, implementing different actions through the cultural institutions of our environment (Mastrogiuseppe, Span & Bortolotti, 2021).
Specifically, significant advances have been made in the adaptation of buildings to remove architectural barriers in order to be used by people with reduced mobility —that is, the conditioning and accessibility of cultural containers—, however, there has not been such a clear expansion in the adaptation of the cultural experience for all people (Kruczek et al., 2024). While the physical adequacy of spaces has been regulated by norms and its translation is evident, the same does not happen with cultural immersion, because in this case, there are no clear guidelines for application, but its development has been guided by the experiences and contributions made mainly by some cultural and academic entities (Bortolotti & Mastrogiuseppe, 2019). An example of this is people with visual impairment, who encounter numerous barriers to perceive and understand cultural heritage, especially, in those spaces where architectural, pictorial, sculptural or decorative elements predominate (Leahy & Delia, 2022). Several investigations have been carried out on these experiences, which we will discuss below, and which are based on current technology as a support for interaction.
In this regard, it should be noted that advances in the recording of cultural heritage have progressed very significantly in recent years. New data capture techniques make it possible to document artistic samples digitally and three-dimensionally with high fidelity (Malik, Tissen & Vermeeren, 2021). Moreover, access to the technology that enables such work is becoming increasingly affordable. For certain cases with low technical requirements a survey can be carried out by a user via a cell phone (Vacca, 2023). The same happens with 3D printing technology, which has expanded enormously and is nowadays within the reach of anyone, allowing objects to be materialized at low cost due to the nature of the materials used by these tools (PLA, ABS, etc.) (Jandyal et al., 2022). All of this suggests that advances in these technologies will continue to develop in the coming years and new tools, devices and applications will appear that will facilitate actions. These are, therefore, ideal elements on which to work for the inclusivity of cultural heritage and, specifically, for bringing it closer to people with visual disabilities (Karaduman, Alan & Yiğit, 2022) (Neumüller et al. 2014).

2. PREVIOUS EXPERIENCES

The contributions around facilitating the understanding of heritage to visually impaired people are very varied, although most of them seek to facilitate the cultural experience based on the reproduction of a heritage object -a model- so that it can be understood by touch (Scopigno, 2017). Likewise, there are several experiences that complement this tactile reading by incorporating texts in Braille reading and writing system or with audio descriptions that are reproduced when interacting with the physical object, either by pressing buttons or by sensors that detect proximity; promoting a more inclusive and immersive experience through touch, as we will point out below (Lo Turco Giovannini & Tomalini, 2021).
To facilitate the approach to these experiences, we have classified the different works according to the scope and scale of the reproduced objects, which, as we have mentioned, are intended to allow the understanding of the heritage through touch. In general terms, we can group the works into three scales: the territorial scale, which helps to understand a landscape context and the elements that compose it by assuming a large scalar reduction of the replica with respect to the original; the building scale, which focuses on the reproduction of a building or the parts that compose it, with a reduction typical of the graphic scales of architecture; and, finally, the object scale that reproduces on a real scale small-sized objects fundamentally linked to archaeology (Lombardi, 2018).

Fig. 1 - Church and Chapel of San Ildefonso. Alcalá de Henares (Madrid). By the authors

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In the territorial scale, the work of Lazna et al. (2022) stands out for the development of a landscape model in which a set of heritage buildings is located that has been printed with various types of materials; one of which is conductive and when touched activates an audio file linked to a tablet. In this case, although the experience tries to be more inclusive and complete, it requires several devices placed next to the model, as well as a web linked to the narratives; all of which implies a remarkable complexity in the assembly, presenting numerous problems of use. In this sense, also noteworthy is the work of Pistofidis et al. (2023), which has the same approach, replacing the conductive material with switches and sensors to activate the audio descriptions, complementing the sensory experience with the modeling of several buildings that can be held with the hands. By requiring complementary devices, these two proposals are fundamentally static interaction supports, which requires allocating a specific space within the heritage property itself to be visited. Finally, the proposal by Rossetti et al. (2018) to show the urban space around the Piazza dei Miracoli in Pisa (Italy) separates from the previous ones by proposing the horizontal section, at one meter height, of the architectures that make up this enclave, which allows understanding its distribution in plan to the detriment of the volumes of the building, as was the objective of the previous works.

In the building scale, and from larger to smaller, we can point out the work of Themistocleous, Agapiou & Hadjimitsis (2016) for the reproduction of the amphitheater of Curium (Cyprus), raised from photographs taken by drone flights, to obtain a photogrammetric mesh that is printed in 3D and that, due to its small size and low definition, serves by touch to get a very general idea of the architectural space and landscape in which it is inscribed. On a smaller scale, the research of D'Agnano et al. (2015) reproduces with great precision, at 1/50 scale, the cushioned facade of San Michele in Sola (Italy) by resin printing and that through the placement of a ring on the finger activates audio descriptions on a Smartphone or Tablet by touching certain architectural elements. In this sense, the contribution of Scianna & Di Filippo (2019) stands out. They use 3D printing to reproduce facade fragments, and not integral elements as the previous proposals, which allows to approach the morphology and facade elements, such as cornices, imposts, etc.; constituting in any case as mobile elements that do not require a static support as in the previous case. Regarding interior spaces, Pietrzykowska's (2015) proposal is interesting: it reproduces the interior of a large palace hall (Museum of the City of Lodz) by means of a large-scale model (1/25 scale) consisting of three of its interior elevations and whose vocation is the reproduction of ornamental details. In this case, we find that element is not very flexible and requires a space where it can be permanently located. Finally, we can point out the existence of the Typhlological Museum of Madrid (Fig. 2), inaugurated in 1992, which houses numerous reproductions of relevant buildings in the context of world architecture (García Lucerga, 1993). In this case, it is a space designed expressly so that, through touch, visually impaired people can experience and learn through large-format models that reproduce buildings in their entirety. Although it is a very interesting experience and highly valued by society, in this case the heritage object of representation is fully delocalized from its original context, and, therefore, it is far from all the proposals presented here, whose vocation is to facilitate the immersion of the visitor in the heritage space itself.


Fig. 2 - Model of the Sagrada Familia of Barcelona (94x94x107cm) and the Colosseum of Rome (125x104x32 cm). Typhlological Museum of Madrid (ONCE). Photographs by the autors.

On the object scale, we can highlight the work of Ballarin, Balletti & Vernier (2018) for the 1/1 scale replica of an archaeological stone fragment containing a drawing, specifically seeking the reliability of the reproduction by performing a high-precision scan and, subsequently, different tests with various 3D printing materials. In the same vein, note the work of Maldonado, Rouco & Martinez (2021) for the reinterpretation from an accessible point of view of a ceramic fragment that also contains a drawing. In this case, they have chosen to alter the original piece by transforming the drawing into a low-thickness relief that allows blind people to interpret it by touch. This experience that seeks to transform two-dimensional elements into relief has also been put into practice by Cavazos, Iranzo and Cho (2021) through the three-dimensional reinterpretation of different pictorial works as a means for visually impaired people to approach plastic works, which are especially inaccessible to them. Finally, it is worth noting the work of Montusiewicz, Barszcz & Korga

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(2022) for the reproduction of a pot fragment that has been scanned and, also, a Braille description has been added to it so that it can be interpreted autonomously by blind people. However, projecting two-dimensional characters on a curved surface presents numerous problems because the deformations altered the meaning of some words. All these experiences with models have a flexible character, due to the lightness of the models and their small size, which makes it easy for anyone to hold it in their hands to enhance the tactile experience, either with the help of a guide or autonomously.

3. OBJETIVES

The aim of this article is to design a methodology to make the experience of people with visual disabilities more inclusive during visits to architectural heritage. It is especially intended to transmit concepts specific to architectural space such as proportions, the relative size of objects and their relative position in space. To this end, it is proposed to design and manufacture scale models of the main works of art of the site using 3D printing. This research proposes a new line of work where the models are not disconnected objects but rather material adapted to the real tourist narrative, connecting speech and touch. To do this, we begin by studying the historical-artistic explanations related to the heritage complex and agreeing with the tourist center on the formats of the models and the appropriate moments for using them. In addition to transmitting the spatial characteristics of objects, to better understand the tactile characteristics of works of art, reproductions must take care of two aspects: the scale of representation and the degree of realism of the replica. To do this, it is proposed to make several models for each artistic element in different sizes and textures.
To test the methodology, a complete experience of the process has been carried out. Starting with data collection, modeling of the works of art, digital fabrication, implementation in a real tourist visit and analysis with the collaboration of people with visual disabilities, to finally collect their suggestions and record the improvement proposals for the next phase of the Project. As a case study, we will take San Ildefonso Chapel (Fig. 1) at the monumental complex of Alcalá de Henares, a World Heritage City, which houses an important range of heritage elements that can be reproduced to facilitate an inclusive understanding. Specifically, for this work we have counted on the participation of the Guided Visits Center of the Fundación General Universidad de Alcalá, which is responsible for the visits that take place inside the historic buildings of the University. We have also collaborated with the ONCE (National Organization of Spanish visually impaired people) delegation of Alcalá de Henares, the most important organization of blind and visually impaired people in Spain, who have accompanied us during the process and have enabled us to contrast the results with volunteers from their association.

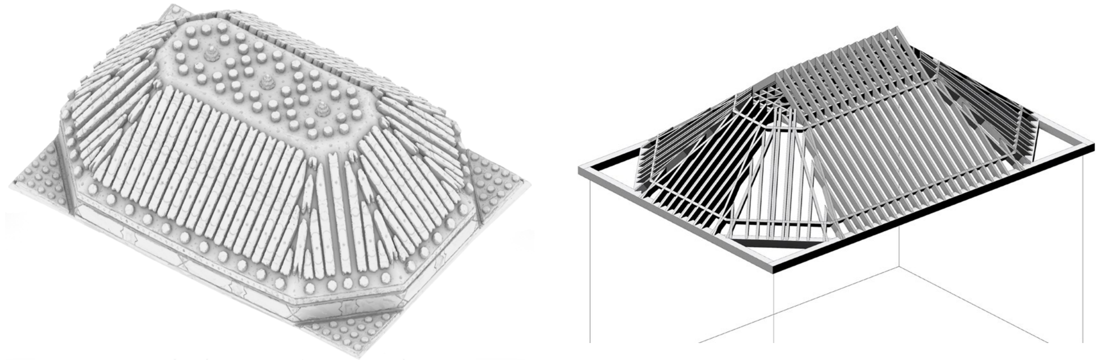

Fig. 3 - Models of the wooden coffered ceiling. Mesh from photogrammetric model (left) and 3D model of the structure of the ceiling (right). By the authors

4. SURVEYING AND PRINTING METHODOLOGY

The surveying process of the objects that have been reproduced in the form of a model has been carried out through an extensive campaign of photography and the subsequent production of point clouds, by means of automated photogrammetry (Structure from Motion). Depending on the complexity of the artistic element, about 150 photographs have been taken for the more complex ones, and about 80 for the simpler ones. The Leica BLK 360 laser scanner was also used for architectural representation. This has provided us with referenced data that have been used to control the scale and orientation of the models.
According to the experience of this team of researchers, there is a quantitative threshold of quality in data collection that allows architectural objects to be represented at different previously established scales, ranging from general plans of buildings at a 1/100 scale to detailed studies at a 1/5 scale that require much more information. For the entire set of the San Ildefonso Chapel, a point cloud with more than 580 million points has been created using a laser scanner, which corresponds to 23 positions of the BLK360. Regarding the photogrammetric models, three elements have been defined, the Coffered ceiling (Fig. 3), the Altarpiece (Fig. 4) and the Sepulcher (Fig. 5), clearly delimited by their interest. The definition of the model meshes varies between 6 million faces on the façade and 20 million on the tomb. This level of definition has proven to be more than sufficient for the purpose of this project. The resolution of the models could be reduced, but the test manufacturing times were reasonable, and it was not necessary to optimize them.
From the point clouds, textured meshes were

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generated using Metashape, Agisoft's automated photogrammetry software. These were then exported to programs that allow working with meshes, such as Rhinoceros. It is often necessary to complete or correct the mesh. Especially difficult is in the case of those artistic elements that have hidden faces and recesses that cannot be correctly recorded by the survey, generating holes in the mesh that have to be closed manually to be able to proceed with the printing. Once the development phase of the digital models was completed, they were printed using the Ender 3 Max printer, which uses the Ultimaker CURA software for processing. Due to its low cost and accessibility in the market, as well as its resistance, the material chosen for printing is PLA filament, which offers an adequate definition for the objectives of the project.

5. DEFINITION OF THE MODELS

Once the background information had been analyzed and the digital models had been made, the next step was to decide on the focus of the reproductions, which elements could be printed and what function they would fulfill within the process of the visit to the heritage environment. For this it was necessary to bring together the research team and the specialized tourist guides. Based on these meetings, it was decided to adopt the following guidelines as a means to produce the models. The guides of the General Foundation of the University of Alcalá have received specific certified training from Predif (Spanish Platform for people with physical disabilities) that enables them to implement typhological material in tourist visits and their indications were key to the development of this research.
First, it was decided to produce portable models, avoiding large and static models, similar to those of the Typhlological Museum of Madrid (García Lucerga, 1993), which physically condition the user experience, as well as the usefulness of the architectural spaces (Pietrzykowska, 2015), which is usually used for various cultural events that require flexible furniture. In addition, this prevents the models from being permanently exposed,

Fig. 4 - Model of the Altarpiece. Mesh from Photogrammetry (left) and modified mesh with corrections (Right). By the authors

Fig. 5 - Sepulcher of San Ildefonso. Mesh from Photogrammetry. By the authors

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which worries people with visual disabilities, since the misuse that the general public makes of the typhlological material causes its dirt and degradation, according to a trainer from the education department of ONCE.
Secondly, the tourist guides propose to produce models with a dimension of approximately one hand span (from 20 to 25 cm), so that they can be easily held with one hand while the other is used to explore their different shapes; positively valued in other previous experiences (Montusiewicz, Barszcz & Korga,2022). As well as so that they can be easily transported by the guides while they move through the different spaces (for example, inside a bag, backpack, or cart) and can pick each one at the right moment, that allows the user to connect with a dynamic, active, and inclusive experience during the cultural visit.
Thirdly, using references to understand the real size of the object, it is decided to dispense with standardized graphic reduction scales, 1/100, 1/50, 1/10, etc. Although for the architectural discipline it is something essential, most visually impaired people are not familiar with this type of reductions and it is usually difficult for them to imagine the size of objects in reality (D'Agnano et al., 2015). Consequently, a reference that can be understood by anyone, regardless of their previous training, is proposed. In this case, and due to the nature of the works that we will deal with, we propose their relationship with reality through anthropometric measurements (for example, the height of the altarpiece is two times and a half a regular human body and its width is one time). In the case of smaller pieces, it can be related to the parts of the hand, in case it cannot be printed to real scale, which would be ideal according to the experiences related to archeology (Ballarin, Balletti & Vernier, 2018).


Fig. 6 - Wooden coffered ceiling. San Ildefonso Chapel. Photography and 3D printed model. By the authors

Fourthly, it is recommended to avoid the use of audio descriptions linked to the models through some type of electronic device, due to the need for software and auxiliary elements (Smartphone or Tablet), as well as a fix space in which to place them, causing spatial and operational problems as remarked in almost all previous experiences (Lazna et al., 2022). Therefore, and as noted in the background, it is preferable to dispense with this type of immersive systems that require continuous maintenance. In this case, and according to our experience, we believe that the most inclusive narration is the one that can be performed by a tour guide accompanying the tactile reading of the model and supporting, if required, the user himself. Also, dispense with Braille printing on the model, since this language is not always known by all users (the rate of training is less than 20%) and has many regional varieties, also presenting various problems when projecting and printing the characters on the models (especially on curved surfaces) (Montusiewicz, Barszcz & Korga, 2022).
After agreeing on the types of models, it was decided to make models of three different artistic elements; from largest to smallest scale: the coffered ceiling, the altarpiece, and the sepulcher. Different models have been made of each of them,

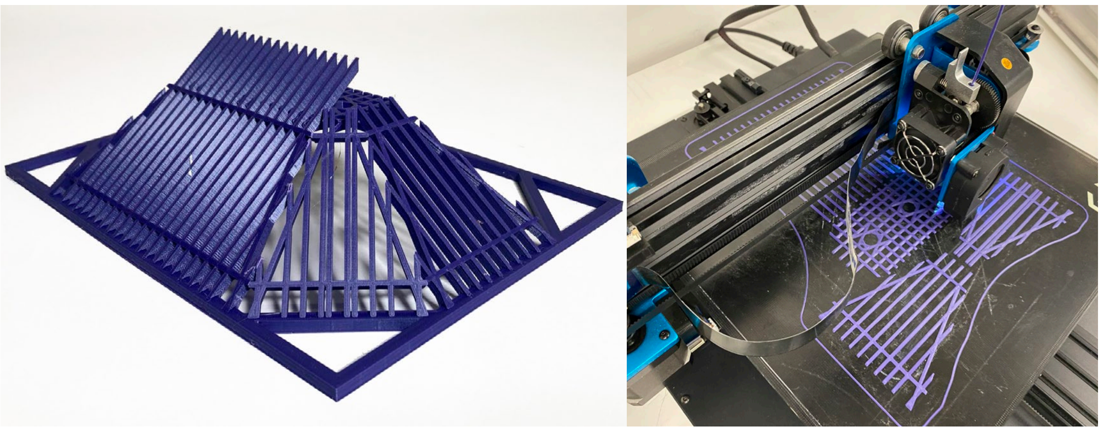
Fig. 7 - 3D printed model of the structure of the wooden coffered ceiling. San Ildefonso Chapel. By the authors

Fig. 8 - Photography and 3d printed model of the Altarpiece at the Chapel of San Ildefonso at Alcalá de Henares. By the authors

some general and others in detail in order to have a better description of the important details.
An interesting aspect to consider is the degree of intervention of researchers in digital models. The meshes that emerge from the data collection process and subsequent processing are very faithful to reality. However, the printing of these pieces can cause difficulties, as sometimes defects or slight deformations of the surfaces are slightly changed or exaggerated by the printing process and can distort the character of the work of art. This is the case of works of a more architectural nature, such as facades or roof structures. For this reason, it is sometimes preferable to lower the level of realism of a model, introducing a certain abstraction in the shapes through pure volumes that regularize the mesh.
To explain the coffered ceiling, several tests have been carried out with different approaches (Fig. 6, 7). A model of the textured surface, from the 25 x 20 x 8 cm mesh (15 hours of printing, €8 cost). A model of the roof structure, 28 x 20 x 9 cm (8 hours of printing, €5 cost). And finally, a detailed model measuring 25 x 20 x 10 cm (6 hours of printing, €2 cost).
The ceiling is the most architectural element of the three represented. Its geometric configuration follows a rigorous law, with parallel, perpendicular, and diagonal lines in nine planes that form a well-ordered polyhedron. The mesh shows us the shape of the surface with its small errors and imperfections resulting from the deformations of the material and the passage of time. In this case, in addition to printing the mesh, it was decided to build an idealized model that shows the wooden structure according to its original shape.
For the Altarpiece, several prototypes have been made in different sizes and materials (Fig. 8). An overall model of 25 x 12 x 10 cm (12 hours of printing, €10) and a detail model of the central figure of 15 x 10 x 4 cm (5 hours of printing, €5). This object has sculptural and architectural aspects at an intermediate scale. A mixed mesh has been used for manufacturing. The digital model obtained by photogrammetry has been maintained in the sculp-

Fig. 9 - Sepulcher of San Ildefonso. Universidad de Alcalá. Photography and 3D printed model. By the authors

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tural panels while the columns, shelves, slats, and pediments have been modeled in 3D, giving the set roughness values according to its dual character. Numerous tests have been carried out for the printing of the Sepulcher (Fig. 9). The final model uses only the mesh from automated photogrammetry, which provides excellent definition of the details, because its material is light in color and rough in texture. The sculptural nature of the work and its scale make it advisable to stick to the result of the original digital model, without introducing architectural geometries that would have been very rigid. It must be emphasized that this is the only element that is within reach of the visitor and that some parts of the sculpture can be touched directly. The model is 25 x 20 x 16 cm (30 hours of printing, €15).

Fig. 10 - Guided visit to San Ildefonso Chapel. Typhological material test group touching the plasterwork. Photography by the authors

Fig. 11 - Typhological material test group touching the 3D printed model of the Altarpiece. Photography by the authors

HERITAGE STUDIED	REAL SIZE (M)	MODEL SIZE (CM)	PRINTING HOURS	COST (€)
COFFERED CEILING (textured surface)	13,23 x 9,02 x 3,61	25 x 20 x 8	15	8
COFFERED CEILING (ceiling structure)	14 x 9,81 x 4,16	28 x 20 x 9	8	5
COFFERED CEILING (roof structure)	11 x 9,81 x 4,16	25 x 20 x 10	6	2
ALTARPIECE (overall model)	2,69 x 2,02 x 5,55	25 x 12 x 10	12	10
ALTARPIECE (detail of central figure)	0,80 x 0,36 x 1,48	15 x 10 x 4	5	5
SEPULCHER	3,15 x 2,47 x 1,95	25 x 20 x 16	30	15

Table 1 - Summary table of the final models produced.

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6. EVALUATION AND EXPERIENCE WITH THE MODELS

To better understand the possible applications of typhlological models, the researchers joined a group visiting the San Ildefonso Chapel of the University of Alcalá. The session lasted an hour, covering all the places of interest in the place. Next, a script was created with the proposal of the times and places in which it was appropriate to use the models.
After preparing the material and coordinating it with the visit program, a testing session was organized with the collaboration of the ONCE delegation. The Typhological material test group was made up of three people with visual disabilities, Pedro, Carmen and Luis Miguel, a rehabilitation technician, Víctor, as well as the specialized guide, Ana and the authors of this research. Of the three ONCE members, only one had visited the Chapel before. The other two had no prior references to the contents of the visit. These three people have lost their vision in their adulthood. This aspect is important since many formal references can be associated with memories prior to the loss of the sense of sight. Of the three, only one can read Braille.

Fig. 12 - Typhological material test group touching the 3D printed model of the Sepulcher. Photography by the authors

After a general introduction the tourist guide refers to the plaster decorations on the walls. This space has rich Gothic and Renaissance plasterwork (Fig. 10). Then we move to an area where the visitors touch the walls, as an exception for this experience. Next, the group is directed towards the altar area of the Chapel and the description of the altarpiece begins (Fig. 11). After a contextual explanation, the printed model is presented. Ana guides the visitor's hand as she describes the different parts of the object. She repeats the process with every visitor.
Visitors highlight the complexity of the scalar relationship between the real object and the printed model. The measurement of the altar table is used as a reference. The sculptures represent human figures in various positions, none of these figures are life-size. The rehabilitation technician, Víctor, proposes an improvement that consists of including in the rear area of the model some marks of known size or a human figure in low relief, which allow us to understand the size of the set.

Fig. 13 - Typhological material test group touching the 3D printed model of the Coffered wooden ceiling. Photography by the authors

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Later the group focuses on the Sepulcher of Cardinal Cisneros (Fig. 12) and the same guidelines are repeated, a general description and a time of individual tactile presentation. In this case, the reference of the size of the Cardinal sculpture is used to understand the scale of the replica. Observers confirm that it is enough to understand the size of the sculpture group. However, some parts of this work are accessible, and touching is permitted for this experience. This circumstance is especially interesting for this project, as it allows us to contrast the effect of the reduced model and the direct experience of the real object. This section offers both perceptions, one of the entire element and another of the sculptural details. Again, the explanations were coordinated with the touching times.
Finally, the session focuses on the wooden coffered ceiling (Fig. 13). This is the largest element, and the models have two functions, one is to explain the texture of the surface, whose geometric decoration of eight-pointed stars has a characteristic design, and another is the spatial and structural function of the piece. This type of roof is double, on the lower side there is the decorated coffered ceiling and above it there is a wooden roof that protects the artistic piece. Between both structures there is a maintenance space. The models for this explanation are key to understanding the complexity of the element and are highly valued by visitors.
A series of proposals to improve the experience emerge from the session. For example, it is proposed to print a plan of the entire space that indicates the relative position of each point of interest. The researchers confirm their intention to produce this material for the next phase of the project. The incorporation of higher precision printing techniques, such as resin, is also suggested. The models of the Madrid Typhlological Museum use this material. Another idea is to complement the experience with adaptations to different degrees of disability. For example, for people who have visual impairment, it would be interesting to provide an electronic magnifying glass. Podotactile pavements coordinated with the plant model could also be added. In addition, the use of totems with letters in high relief and good contrast is proposed. These last initiatives are faced with some difficulties, the most important of which is that the Chapel room is used for various formal events and tourist furniture cannot be included.

7. CONCLUSIONS

This research has been able to verify that typhlological models are excellent support for the dissemination of architectural heritage. The communication of the volumetry, scale and relative position of the elements improves significantly when these models are included at the appropriate moment in the tourist experience.
The models printed and the scales chosen have proven to be effective. The working group has valued the characteristics of the typhological material very positively. As proposals for improvement, tests are requested with technology and materials that offer greater quality and definition, without increasing weight or size. It is also requested for a future experience to print a plan of the complex that includes references of the points on which the explanations of the route will be concentrated.
It has been demonstrated that the human resource, the explanation of the tour guide, is the one that provides the highest quality. The models alone, displayed for independent use, are reduced to mere disconnected objects. The main contribution of this research is that typhlological objects and tourist narration can be integrated into a single dynamic and personalized activity. The models are made available to the guides, who enrich their use through appropriate indications. The value most appreciated by users has been the simultaneous action of speech and palpation.

8. ACKNOWLEDGEMENTS

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