Design Guidelines for an Interactive 3D Model as a Supporting Tool for Exploring a Cultural Site by Visually Impaired and Sighted People

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Being able to explore and familiarize themselves with the structure and details of a cultural site before actually visiting it is fundamental for orienting visually impaired people during the visit; otherwise, it is particularly difficult to gain a global understanding of the structure and an overall impression of a square, a church or a large monument. Our project addressed this problem by using low cost 3D models combined with audio descriptions to enable visually impaired users to explore the cultural site autonomously. Audio descriptions are organized into three groups (for historical, practical and architectural information) and for each group several tracks are recorded giving increasing levels of details. Users can easily navigate through the audio tracks to follow their tactile exploration by listening to the information they are most interested in. Relevant details are reproduced separately and linked to the main model via the audio tracks. A goal of our model is to enhance the understanding of the cultural site also for partially sighted as well as sighted people, making them able to appreciate the details of the architectural design using both visual and auditory senses. We exploited low-cost and partially open-source technologies, thus rendering our system easily replicable. We evaluated the interactive system with blind, partially sighted and sighted users. Our user test confirmed the validity of our approach: (1) the 3D models and the tactile reproduction of details obtained via a low-cost 3D printing solution are well perceived by touch; (2) the semantic auditory information activated via perceptible buttons on demand and the different content levels for the audio tracks are suitable for an interactive, autonomous and satisfying exploration; and (3) relevant details are well perceived. Finally, we propose guidelines to use in the 3D reproduction of buildings or large sites based on our experience.

CCS Concepts:

• Human-centered computing~Accessibility design and evaluation methods • Human-centered computing~Interactive systems and tools • Applied computing~Fine arts

Additional Key Words and Phrases

Intelligent artefacts, Interactive Audio Model, 3D Modeling, 3D Printing, Blind People, Rapid Prototyping, Accessibility

1 INTRODUCTION

When sighted people visit a large architectural site, they immediately and effortlessly acquire a large amount of information directly related to the structure of the site. For instance, they are able to quickly estimate the relative distance of the parts that compose the site and the relative importance of each part. Furthermore, they can capture the overall architectural message directly from an overview of the site and appreciate small details that are not directly accessible to the touch. All this information is precluded to the visually impaired and need to be delivered to them in a different, accessible, way.

Tourism businesses and cultural heritage organizations in particular are recommended to use technologies such as augmented reality, virtual reality and 3D printing to enhance the visitor experience. In this perspective, the work [29] uses a case study as well as a proposed framework to illustrate that the effective use of multiple technologies in the context of cultural heritage locations contributes to the co-creation of value for both cultural heritage organizations and also for visitors' pre-visit, onsite and post-visit experience. The study [37] discusses the importance of including everyone, both disabled and non-disabled, in the usage as well as in the design of tactile 3D objects.

Although a significant number of studies have been investigating the use of different technologies in cultural heritage, people with disabilities and special needs still continue not to be included in the numerous solutions based on recent and new technologies. The work [31] includes an extensive overview of the literature addressing social computing in the context of cultural heritage, with a particular focus on issues of accessibility and social inclusion. Specifically, examples of technical approaches as well as various applications for the domain of cultural heritage (including cultural heritage resources and institutions) are described. Particular focus has been put on accessibility for the deaf/hard-of-hearing and disabled people, but very little consideration is given to the visually-impaired. McMillen [33] noted that museums should utilize new media strategies to enhance disability access like touch or interactive exhibits. She highlighted the need for additional studies to investigate whether social media could enhance museum access. Our study is intended to provide a further contribution in this context.

To the best of our knowledge, our approach differs from other projects in the literature, which report on the reproduction of the main monuments (externally), without details on how the buildings look inside and on the decorative elements. In particular, the reproduction of each monument is built considering a two-dimensional plane which cuts the monument at a height of approximately 1 m (3.28 feet) from the ground. This allows the users to perceive the internal layout of the spaces and the cultural value that a plan has in relation to the historical period (for example, the Greek cross plan, the Latin cross plan, etc.). This approach makes possible to communicate to users not only the aesthetic value of an artwork, but also the symbolic one. For instance, in a Latin Cross plan, it is possible to explain to the user the symbolism of the Christian religion used in architecture (e.g. the cathedral's plan shows the transept that intersects perpendicularly with the aisles forming a cross). This symbolism cannot be appreciated in all-round tactile reproductions since in this case it is it possible to perceive the external monument but it is impossible to get an idea of the interior space. This type of information can be very interesting both for visually impaired and sighted users.To the best of our knowledge, our approach differs from other projects in the literature, which report on the reproduction of the main monuments (externally), without details on how the buildings look inside and on the decorative elements. In particular, the reproduction of each monument is built considering a two-dimensional plane which cuts the monument at a height of approximately 1 m (3.28 feet) from the ground. This allows the users to perceive the internal layout of the spaces and the cultural value that a plan has in relation to the historical period (for example, the Greek cross plan, the Latin cross plan, etc.). This approach makes possible to communicate to users not only the aesthetic value of an artwork, but also the symbolic one. For instance, in a Latin Cross plan, it is possible to explain to the user the symbolism of the Christian religion used in architecture (e.g. the cathedral's plan shows the transept that intersects perpendicularly with the aisles forming a cross). This symbolism cannot be appreciated in all-round tactile reproductions since in this case it is it possible to perceive the external monument but it is impossible to get an idea of the interior space. This type of information can be very interesting both for visually impaired and sighted users.

Since our interactive 3D prototype should be used by both visually-impaired and sighted users, a complete evaluation we conducted was based on the following research questions:

- RQ1: Can a low cost three-dimensional interactive model be perceived by visually-impaired and sighted people?
- RQ2: Can audio tracks and tactile details on a larger scale be useful to provide additional information which can be easily accessed by the visually impaired and sighted users?
- RQ3: Are there any differences in the understanding between visually-impaired and sighted people?

Through RQ1 we intended to analyse if a low cost 3D model can be perceived correctly, in particular if the sizes of buttons and architectural details are adequate and if the positions and shapes of the elements can be designed to be understandable by touch. RQ2 is designed to find out if (a) additional audio descriptions can enrich the model; (b) the reproduction of tactile details is appreciated by the users (sighted or not); and (c) if different shapes are appropriate to deliver information semantically grouped into different topics selectable according to the user's preference. RQ3 is aimed at understanding if such a 3D model is perceived differently by a visually-impaired and a sighted user.

A general description of our approach and a preliminary user test are reported in our previous works [43] and [44]. This work gives a further contribution to the topic by providing:

(1) The description of the results obtained with a new user test conducted with a group of 16 sighted people, which extends the previous works with regards to the evaluation with the potential end-users. Thus, the new evaluation allowed us to extend the discussion of the results of a complete user test conducted with both sighted and visually impaired people in order to collect more general information on the 3D model usage.
(2) The proposal of a set of design guidelines for reproducing an accessible and interactive 3D model for a different site;
(3) More details on the approach used to design the 3D model and the interaction features, by providing additional information on how the model can be designed and printed, and how the additional components, such as the Raspberry device can be developed and adapted for such a model.

The paper is organized as follows: Section 2 introduces motivation and goal of our study; Section 3 discusses the previous related work, Section 4 describes our approach and methodology, and presents the proposed interactive 3D model. Section 5 describes the user tests conducted and reports the objective and subjective evaluation results. Section 6 discusses the results obtained. Section 7 proposes a set of guidelines to be followed to apply our methodology to new models. Section 8 concludes the paper.

2 MOTIVATION AND GOAL

Mental mapping of spaces and environments is crucial, especially for a blind person to orient him/her-self and move around independently better [22]. This occurs especially for unknown sites. Many digital maps are available, however, accessing them continues to be precluded to certain categories of users, and their usage presents numerous open problems and challenges in terms of accessibility [8]. Numerous studies show clearly that a robust and comprehensive map contributes to successful performance in real space tasks and mobility [19], [21] and [32].

On the other hand, partially sighted and sighted users may miss out on some important architectural messages due to the large number of details available simultaneously or the need to clearly perceive the thickness and relative position of architectural elements such as the columns in a nave.

While acquisition and preservation in the digital domain are well acknowledged and established processes for cultural heritage [23], 3D printing design still needs to be further investigated in terms of perceptions by touch and usage in real contexts. Some studies have been carried out to investigate how 3D printing could improve education and exploration for specific groups of users in some scenarios [2], [3], [21], [38] and [47]. For instance, in [47], the authors observed that participants explored a model while sensing the texture and shape of the components, measuring the size of the elements, counting the number of elements, comparing similar elements, and so on. Some design indications have been also provided. However, to the best of our knowledge, standards and guidelines for the design of systems making easier the understanding of cultural heritage are still missing for general audiences (e.g. sighted people). In [11] an excursus of proposed guidelines in the haptic and tactile design are reported. Although they can represent valuable support, they are not specifically proposed for cultural heritage. The work [37] concludes that further investigation is needed since no standards for the translation into multi-sensory 3D objects yet exist which guarantee an optimal information transfer. So, alternatives need to be researched, tested and codified, and finally conversion artists trained. Our work is aimed at adding a little step in this field, by proposing a 3D model for visually-impaired people, which could be useful also for those who are sighted.

On the other hand, new technologies, especially 3D printing, have opened up completely new opportunities to overcome the barriers to effective understanding and access to cultural sites by people with visual impairments [9] and [52]. In the literature, many projects have explored 3D printing to enable people with visual disabilities to access cultural sites, monuments, and any other objects that can be reproduced to facilitate a tactile experience [1], [6], [7], [12], [25], [51], [53]. However, using tactile 3D models may not be enough to access all the details of a large cultural site [23]. In fact, the correct understanding of a 3D reproduction is affected by personal skills, as well as the size (compared to the original), the reproduction details and the overall quality of the tactile model. In addition, some architectural details may be very small or not present in the model due to their size. Thus, to provide the correct perception of the structure of a large architectural site to a visually-impaired person, a 3D tactile model needs to be combined with audio tracks describing information that cannot be reproduced directly in the model [2], [20] and [48].

In our project, 3D printing and audio tracks have been used to deliver to the visually impaired people the overall understanding of the structure, which is directly accessible to sighted users. Moreover, the goal is to enable visually-impaired people to perceive all the important details, such as buildings or squares, including domes, plans and smaller details not directly accessible by touch. This entails being able to deliver a large amount of information and poses new challenges with respect to the reproduction of a single small artwork (such as a statue or painting). Our proposal is to build an interactive 3D model of the site, along with a set of separate models for the architectural details which cannot be included and perceived correctly in the main model. The model is equipped with buttons of different shapes (triangle, square and circle) which can be used to activate audio tracks describing different aspects (historical, architectural and practical) of each monument in the site. Buttons are placed along the perimeter of each building near to the main entrance so as to be easily located by the visually impaired. The tangible exploration of our model is enriched by short audio tracks which are divided into three groups according to the specific topic (i.e. architectural, practical and historical information) and associated to different parts of the cultural site. A set of audio tracks has been linked to each part of the model. The tracks have been divided into several subtracts according to each topic, which provide the user with information at a different level of detail. The reason for this is to avoid the frustration experienced when being forced to listen to very long audio tracks that describe every single thing. Additionally, the use of audio tracks allows the user a cultural visit in autonomy, without the need for a guide or a companion who highlight the person's disabled status.

This design is also useful for sighted people since it focuses on important details to be perceived in the architecture of the buildings, in the organization of the spaces and the details of the decoration that are important for the visitor by supporting their understanding through touching and audio tracks.

Therefore, the main goals of our approach are:

(1) to propose a reproducible strategy to build 3D tactile models for large cultural sites using a low cost solution through 3D printing technology;
(2) to test out a combination of tactile perception and semantically differentiated audio descriptions suitable for various types of users and interests;
(3) to make the user experience more comfortable through more identifiable and perceptible buttons and using different materials for the objects reproduced with different tactile effects;
(4) to propose a model which is interesting and attractive for sighted people, so as to make it inclusive for everyone;
(5) to avoid the need for specific skills and devices during exploration and allow an autonomous exploration by all the users. In particular, visually impaired people would be able to explore it without the help of a third person, thus improving the level of social inclusion and autonomy.

The model can be used before the actual visit to a cultural site (1) to provide an overview of its structure; and (2) to facilitate the explanation and discovery of the architectural and decorative elements.

3 RELATED WORK

In the last thirty years, different technologies have been used to make visually impaired people familiar with the surrounding environment and support them during their travels and museum visits. Raised line printing (tactile graphics) have been used for two decades to help the visually impaired to build a mental model of the geography of a site [50]. Technology is also very important to build innovative approaches, as well as to enhance integration and user social engagement while visiting cultural sites [31]. Thus, in recent times, the availability of 3D printers has allowed for the creation of new printed models to convey spatial and artistic concepts. This can be very useful for visually-impaired people to understand shapes, outlines, etc., provided that accessibility principles and specific guidelines are applied in the design of the models.

Although there are many projects aimed at using multimodal interaction to enable the visually impaired to increase access to artistic and architectural contents, most solutions do not consider large architectural sites or 3D interactive modelling. For instance, Bornschein et al. [6] present a drawing workstation for blind people using a two-dimensional tactile pin-matrix display. Users can draw using four different input modalities, namely menu-based, gesture-based, freehand-stylus and segmentation of real-world object silhouettes. The study described in [40] investigates a combination of vibration and speech feedback which can be used in order to make a digital map on a touch screen more accessible. Wang et al. [54] created a prototype of a tactile-audio map based on a combination of a tactile hardcopy and an SVG file used together to provide interactive access to a map image through a touchpad. The result is a tactile-audio representation of the original input image. Götzelmann [17] presents tactile maps augmented with barcodes which can be read using an app on a normal smartphone. These approaches, along with other ones like the studies presented by Brock [7] and Senette et al. [46] propose interactive tactile approaches which are not based on truly 3D models, since they adopt a 2D touchable format in which the representation is basically 2D with some parts in relief. In our study, instead, we combined a 3D modelling approach with audio descriptions in order to enrich the interaction for visually impaired people.

We now analyse more in detail some systems closer to ours. Urban et al. [52] describe an experiment carried out at the Technical Museum of Slovenia (Polhov Gradec, Slovenia). Their goal is the reproduction of the floor plan of the two floors of the museum in order to enhance the independent exploration of visually impaired users. They do not attempt to reproduce complex architectural details and do not use audio tracks, but use 3D printing to print braille descriptions directly on the map. They tested their prototype with visually impaired children. The results were with quite good with respect to the understanding of the global structure printing the walls in a little (2cm) relief with respect to the rest. Most of the problems appeared in the 3D printing of Latin and braille descriptive parts since the lack of precision of the 3D printing process made the descriptions difficult to understand for both sighted and visually impaired users. The paper also underlines the importance of including the final users in the design process, which is in line with our own results.

Another crucial feature to consider in the design of an interactive model is about the additional descriptions to give to the user while exploring the model. In this perspective, it is important to define what type of contents should be provided, and the modality to trigger them by the user. Tooteko [12] is based on a smart ring that allows users to navigate a 3D surface with their finger tips and thereby access an audio content that is relevant to the part of the surface that they are touching at that moment. So, the system has a high-tech ring to trigger the desired audio descriptions, a tactile surface tagged with NFC sensors, and an app for tablet or smartphone. When the ring reaches an NFC sensor it communicates with the app in order to activate the audio track. The 3D models are built using standard 3D printing. Sensor hotspots are inserted inside the model, which needs to be reasonably large to accommodate them. Hotspots also need to be at a reasonable distance to be clearly detected by the reader. Hi-Storia [26] proposes a similar approach.

In both [12] and [25], the sensors that trigger the audio tracks are integrated into the model itself. This choice has some effects on how the model is used by a visually impaired person. First, visually impaired people often use both hands for exploring a model, this means that while listening to an audio track, they can easily jump into another hotspot thus stopping the current track and triggering a new one [25], [28] and [35]. Moreover, this model require a post printing elaboration of the model to insert the hot spots. The model should be carved to find space for the hot spots, which is a risky activity and generally increases the final cost of the model, which may be too high for small museums or cultural entities. Finally, these approaches entail having an external person who explains to the user how to move and what to do before starting to browse the model, and there are no separate models for interesting details that cannot be included in the main model. Although these last features could be added easily they are currently not present in the models.

The Pedra Sabida expositor proposed in [53] tries to overcome those problems by proposing an interactive exposition support able to recognize the object currently explored by touch and give information interactively. In this project, it is also possible to activate tracks comparing two objects handling them at the same time and a welcome track explains the overall interaction mechanism.

3D Photoworks [1] proposes a different approach. Colour images are printed directly on the relief surfaces and infrared sensors are integrated into reliefs. Their interactive tactile prototypes accompanied by audio guides are based on motion capture [10] and [42]. Depth cameras, placed above the tactile template detect the movement of the user's hands. The main disadvantage of such hand tracking systems is their cost and complexity. Even though technologies are continuously improving and becoming cheaper, the current low-cost trackers are not very accurate. For example, while slow movements and limited rotations of the hand are usually traced effectively when the speed increases the position of the hand is easily lost and users can become very frustrated.

S. Giraud et al. [16] presents a 3D model representing a fictitious kingdom in two phases of its history. The model combined 3D printing, audio tracks and a micro-controller (Arduino) managing the audio tracks. The audio tracks are triggered by metallic pieces integrated into the model. The paper compares the use of tactile graphics with braille description of the same fictitious kingdom to the 3D printed model to understand their relative effectiveness in understanding spatial concepts. The test was carried out with 24 blind high school students aged 14-19 with no other disabilities. The study showed that 3D printed models with audio tracks improved both space and text memorization compared with tactile graphics with braille legend.

Halloway et al. [27] performed a controlled user study with 16 severely vision impaired adults finding a strong preference for 3D maps compared to raised line tactile maps. Specifically, in the study, the 3D map included a bridge which was perceived clearly by the users. The model was analysed in depth, and three versions were built based on the remarks of the visually impaired people involved in the project. This led to the outline of 8 guidelines for the model structure and the audio guides, and 3 remarks on how the touch should be performed to explore and read the maps. We will discuss these guidelines in detail when outlining our own guidelines later on. However, a very important point in which we agree with [27] is the fact that an audio track must be activated as the result of a definite action and to allow free two hands exploration without the risk of triggering unwanted audio descriptions. Nevertheless, our goal is slightly different in that we would like to make our touch reader able to understand specific notable architectural elements of the buildings more than the relative heights of them.

Quero et al. [41] proposed an approach very similar to ours, using 3D printing models integrated with multimodal features (audio tracks, wind, lights) for conveying spatial and semantic information related to different artworks in a museum.

A different approach is followed by Springsguth and Weber [49] and Koenig et al. [30] using a force feedback device (SensAble PHANToM) to render 3D objects defined in an electronic virtual map. Virtual maps are freely zoomable and may be easily adjusted to the level of detail needed. Using PHANToM, the touch reader can explore the map with a single hand experiencing forces very similar to the real touch on a tangible model. This allows to zoom and clipping in the 3D map. In this case, exploration can involve only one hand at a time and the need for the force-feedback device.

Our approach, explained in Section 3, is aimed at designing a low cost solution and moving the audio track activation outside the 3D model, while still using sensors to activate each track. It deals with large cultural sites using enriched floor maps built considering a two-dimensional plane which cuts the monument at a height of approximately 1 m (3.28 feet) from the ground and using a 3D printer. The advantage of this solution compared to a tactile map in relief, is that of guiding the visually impaired user into the space and at the same time telling them about the decorative elements, thus combining different types of information (spatial, historical, architectural).

4 THE INTERACTIVE 3D PROTOTYPE

In this section, we describe our model of Piazza dei Miracoli outlining the approach and methodology used in the design phase.

4.1 An overview of our approach

Our approach consists in reproducing an interactive 3D model user-centred design by combining tactile perception with audio tracks to explore the floor plans of monuments. This is due to the lack of floor plans and reproduction of indoor monuments that are perceivable by touch. Likewise, tactile reproductions usually lack specific details especially those too small in the reproduction scale chosen. These types of reproduction (floor plans and specific details) can, in fact, be very useful for learning and perceiving structural information that is evident to sighted users. It is worth noting that our approach can also be adopted when reproducing the facade of buildings, if needed, or part of it.

On the other hand, although in the very first stages of the design process we considered only visually impaired users, it soon becomes clear that the tactile model could also be very useful for sighted users to become aware of those architectural details, which would not be so evident in the original and real site. Thus, a group of sighted users were involved in our study in order to investigate if the 3D model prototype could be perceived and suitable also for those who have not vision impairments.

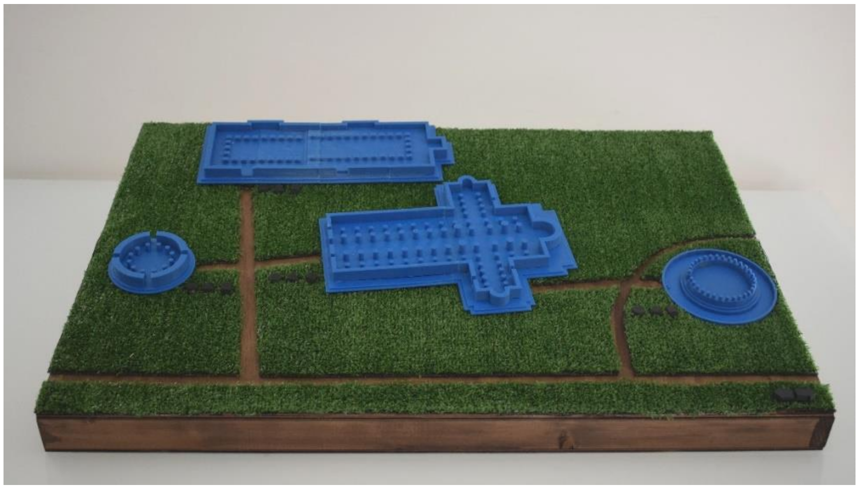

Fig. 1. The working 3D prototype of ‘Piazza dei Miracoli’

We developed a tangible 3D model of the four monuments located in “Piazza dei Miracoli” (home to the Leaning Tower of Pisa, Italy). The challenge was that each monument has a different floor plan: (1) the central plan of the Leaning Tower and the set of columns on the outside; (2) the Latin cross plan of the Cathedral; (3) the rectangular plan of the Monumental Cemetery; and (4) the central plan of the Baptistery. When visiting Piazza dei Miracoli, the arrangement of the various buildings in the square and the walkways that link them are clearly visible for a sighted person. Our goal was to deliver a similar perception of this overall arrangement for the visually impaired. The reproduction of each monument is built considering a two-dimensional plane which cuts the monument at a height of approximately 1 m (3.28 feet) from the ground. In this way it was possible to show the section of the perimeter walls and of the columns which are key to understanding the overall architectural setting (Fig. 1). This tactile reproduction enables visually impaired people to perceive the thickness and position of the columns, the difference between the columns in the central nave and the ones in the lateral naves, the position of different sets of arches, and so on (Fig. 2).

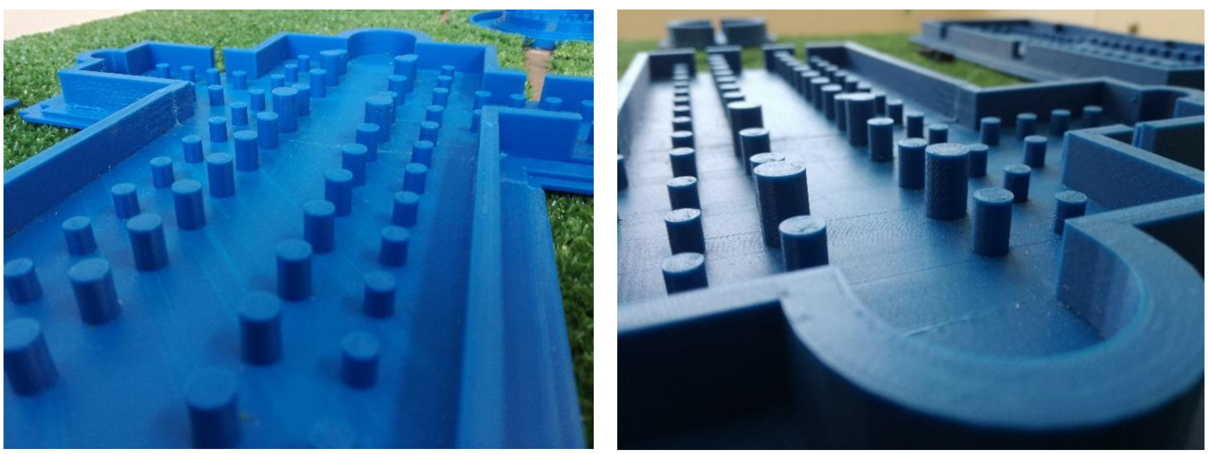

Fig. 2. Detail of the central nave and side naves of the cathedral

4.2 Methodology

In building our prototype we have been taken into consideration some advice for tactile graphics discussed in [5], [18] and [27]. However, these works address 2D maps which are quite different from 3D models. Furthermore, works like [40] and [54] consider the exploration of 2D maps using audio feedback to enhance the user experience and perception. Maps are widely used to support autonomous mobility for blind people. Maps can help a visually-impaired person to obtain information on a certain pathway as well as an overview of a specific zone. Acquiring information on certain details, for example differences between some elements (e.g. columns, doors or windows) may not be considered significant and so the map is not required to reproduce this type of information. However, it occurs for a reproduction of artworks and other details of cultural heritage. This is the reason why our approach is based on the reproduction of floor plans and details. Thanks to a range of 2.5–3.0 cm in height the user is able to perceive some elements which might be difficult to understand in a different modality (e.g. just via an audio description). So even an audio map would not be enough to reproduce certain details and particulars which are crucial to understand some concepts about the item of cultural heritage. This work is therefore focused on 3D models supplemented with audio contents to enrich the exploration with additional information. In this perspective, in our project, a new set of guidelines for interactive 3D tactile models, which will be described in section 6, has been proposed. The guidelines are mainly based on the results of our study. For instance, while working alongside some visually impaired users, it was noticed that there is a minimal distance between two 3D objects (e.g. columns) which needs to be maintained so that they are perceived correctly by a fingertip touch. Our system is built using source-based modelling [14].

A 3D model can be obtained using two different approaches to represent the structure of the artwork (monument, statue, etc.): (1) reality-based, such as via laser scanning or reflex camera; (2) source-based, via a digital representation of a work using computer graphics. Through this second approach, it is possible also to model a work that no longer exists, or that has only partially survived, and whose reconstruction is based on historical sources. The approach used depends on the characteristics of the work and on the goal of the project. When using 3D modelling for very large monuments, as in this case study, the cultural heritage object is simplified for a small-scale reproduction (unimportant details, such as the detailed acanthus leaves at the top of the columns, are not included). A source-based approach was used, which is faithful to the original architectural plan and to the historical facts. We decided not to reproduce details that might not be easily perceptible by touch.

Starting from the digital model, the tactile models were produced through digital fabrication techniques. To model a source to be printed the steps are: (1) obtain the floor plans in 2D; (2) model a 3D version based on the scale and the official sources (e.g. a circle on the plans is a cylinder in the 3D model); (3) select a simplified style for the plans, i.e. without architectural details; and (4) reproduce various details in the architectural style. The appropriate scale resolution and size of the details was decided in collaboration with visually impaired people throughout the design-development cycle (see Section 5).

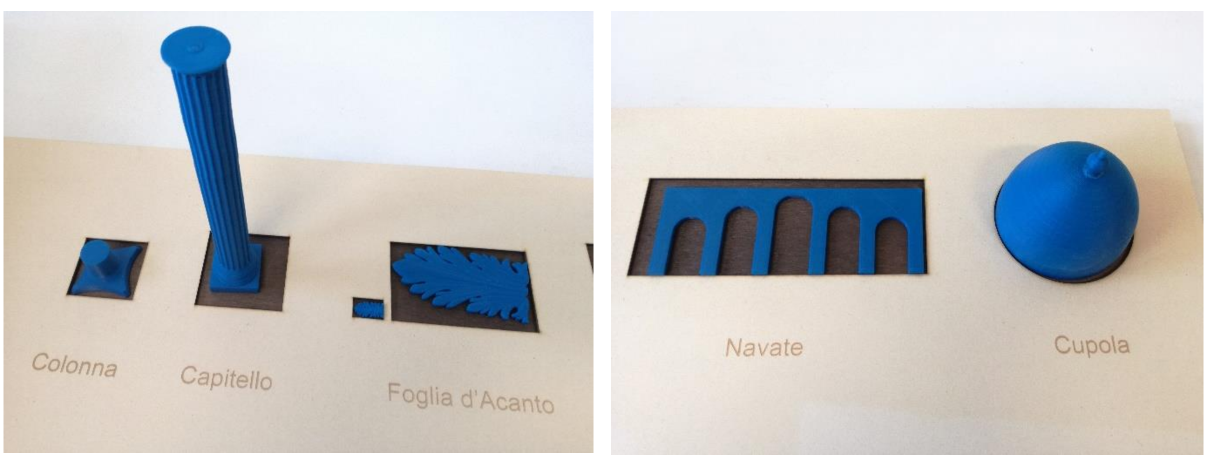

Fig. 3. The architectural elements: column, capital, acanthus leaf (left) nave, dome (right)

For the 3D printing, an additive technical process in which the object is produced by the gradual accumulation of material [45] was used. The 3D prints used a Fused Filament Fabrication printer (FFF) which melts and extrudes a thermoplastic filament, in this case acrylonitrile-butadiene-styrene (ABS), an oil-based plastic. The model sizes were chosen to ensure a good exploration of the relevant details, based on a participatory analysis made with blind users. To develop the digital models, the open-source software Blender was chosen. The slicing of the models to be printed in 3D was made with a proprietary software belonging to the suite of the printer used, a Zortrax M200 (available in our laboratory, cheaper printers can also be used). Because of the technological limitations of the printer used relative to the small size of the printing plate, for some of the models, such as the Monumental Cemetery or the Cathedral, it was necessary to divide the model and print it in separate pieces, glued together in postproduction. Moreover, 3D models were developed to reproduce specific details of the monuments that are relevant to understanding the overall structure, such as the dome and the nave profile of the Cathedral, and a Corinthian column representing the main architectural style of the Cathedral, the Baptistery and the Leaning Tower (see Fig. 3). In addition to the building plan, some decorative elements that are functional to understanding the monuments were reproduced as well. The blind users that participated in the tactile map design, pointed out the importance of understanding some elements mentioned in the tactile models and in the audio tracks linked to them. An example of this is knowing the style of the columns and the difference between the aisles, in addition to the dome, is useful to explain the difference in the size of the 4 central columns of the transept with respect to the others. For this reason, it was decided to create some architectural details on a larger scale. They were printed separately and are located on a panel placed near to the main model of the square (Fig. 4). These architectural details are connected to the main models via audio tracks. Each detail is introduced and described in the relevant architectural audio track, whose reproduction is triggered by the circular shaped button near the entrances of the building it refers to.

In short, the reproduction procedure is divided into the following phases:

1. creation of digital models considering the scale of reproduction;
2. selection of the details to be reproduced on a larger scale;
3. print, refinement and assembly of the models;
4. design of semantic touch buttons and preparation of audio tracks;
5. development of an interactive model (e.g., using a sensor processor such as Raspberry or Arduino).

Fig. 4. The panel with the architectural elements

4.3 The interactive 3D model

Our model is designed to render users entirely autonomous in their exploration of an artwork or structure. To meet this aim, each piece of information is provided through both tactile and audio information. The visually impaired can explore the model by touch and activate an audio description related to a specific monument/detail. Sighted people are able to visually observe the model and notice more details, which are more evident in the reproduction (for example by touching some particulars); they can also use the different buttons designed to listen to the audio tracks with additional information.

Spoken descriptions are organized into several audio tracks, which can be recorded by a person or via voice synthesizer through a specific audio content generation application, such as DSpeech [15] or Balabolka [4]. This means that the content can also be in different languages. In our prototype a person recorded the audio descriptions in order to make them more understandable for sighted users who might not be familiar with voice synthesizers. The device used to manage the interaction user-3D model is a Raspberry PI 3, a single-board computer that is a few centimeters wide, with general purpose input/output capabilities. There are many Internet of Things (IoT) platforms that can be used during the prototyping and production phase; a short review of the most popular ones is in [39]. A Raspberry device is relatively inexpensive and is equipped with WiFi, Bluetooth and several IO pins, the latest version costs about $35. The wiring can be simplified using bluetooth speakers and activating the pull-up and pull-down internal resistors to implement various interaction modalities with the physical buttons. That is, no extra circuit board with resistors has to be designed to interface Raspberry with sensors. The software is based primarily on Python, which is easy to use, and can be easily updated remotely via WiFi. It was thus possible to integrate Raspberry into the prototype, thereby reducing problems when moving and installing the prototype at the test site. The developed software was mainly in charge of interfacing the sensors and recording interaction timing for statistical studies during experiments. The same data report can be used to identify the audio tracks which have been used the least over a very long monitoring period in order to get indications on how to improve the user experience as far as content is concerned. The software is based on the classical schema “If This Then That” (IFTTT) [24] and new interactions can be easily created by adding rules that trigger even web actions like sending email alerts or instant messages in case of problems.

The Raspberry device is fixed below the prototype. Auditory descriptions are activated by buttons placed next to each model (e.g. near the main entrance of each monument in Fig. 5). Buttons are connected to the Raspberry with cables. In our prototype, each model has three buttons which are close enough to each other to be detected without moving the hand. The three buttons are differentiated by their shape which indicates a specific type of information: (1) circles for practical information, (2) triangles for historical overviews, and (3) squares for architectural descriptions.

For each type of information, there is a set of audio tracks. All tracks can be activated with the same button. The first time the button is pressed, an introductory track is activated, which gives general information on the monument. If the users are interested in more detailed information, they can press the button again to listen to the second track, which provides more details. In general, each button is associated with a set of audio tracks ordered according to the level of detail. Each time a button is pressed it stops the current track and starts the following one in the sequence. Users can thus choose how to explore each monument according to their interests and to the time available.

When the user approaches the model of the Piazza dei Miracoli, two proximity sensors activate a welcome audio track explaining how to interact with the model. The sensors are placed in front of the prototype and compute the distance between them and an obstacle in front of them. When a new obstacle (a visually impaired user) appears within a distance of between 0 and 50 cm, the sensors send the Raspberry device the information and the welcome audio track is activated. The user can then decide how long and how to interact with the other audio tracks. The current track can also be suspended by pressing a pause button placed at the bottom right of the prototype.

The total cost of the installation is divided between the purchase of hardware and the production of 3D artefacts.

With regard to the software, there are no costs because only open source software already available in the Raspberry platforms has been used.

The hardware includes the cost of the processing unit ($ 35), the buttons and the wiring ($ 15) and proximity sensors ($ 35).

The cost of the artefacts is actually attributable only to the cost of the plastic material used because we already had a 3D printer. Thus, we did not consider the cost to buy a 3D printer. However, for those who do not own a 3D printer or cannot afford it, there are professional services, offered in some cases by real industrial printer farms that offer online estimates, by uploading the model file, and subsequent creation and shipping in various materials and colours (www.sculpteo.com, https://i.materialise.com, www.3dhubs.com to name a few examples). Prices vary according to the materials, the techniques used and the level of finish required. Shipping costs can also affect the cost a lot especially for prints of a few and small objects. In our case we estimate a cost ranging from 50$ to 100$ if the artefacts had been produced externally.

Thus, the total cost of the installation is estimated to be no more than $ 200 by considering also the wooden support on which all the components are placed. Regarding the time for 3D modelling, assembling and manpower, a computer science student not skilled on IoT took a total of 1,5 person-month to plan, develop, model, configure, assembly and test the installation under the supervision of a tutor.

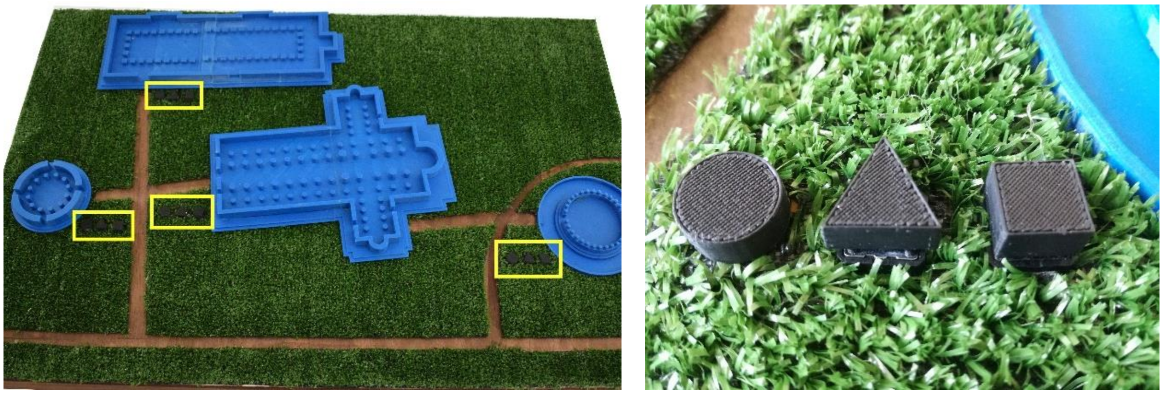

Fig. 5. The position of buttons near main building entrances (left) and detail of buttons (right)

Table 1 reports a portion of the audio descriptions assigned to the different buttons for each monument. “W_track” is the “Welcome description”, which is played when a person approaches the model. As we can see, at the end of the track, the instructions on the usage of the three buttons are described. When the user presses the Circle button near the entrance of the baptistery (C_baptistery_track1), track1 with the practical information of the baptistery is played. By pressing again the same Circle button (near the entrance of the baptistery), no additional track is available. When pressing the Triangle button for the baptistery, the first track (T_baptistery_track1) can be listened to for historical and artistic descriptions. By pressing again the same button (T_baptistery_track2), the second track is played (T_baptistery_track2). The same occurs if the same button is pressed again: the third track (T_baptistery_track3).

Table 1. Transcriptions of the audio tracks related to the monuments which are played when pressing the circle (C_), Triangle (T_) and square (S_) buttons

Track	Description
W_track	Welcome to Piazza dei Miracoli. We are in the monumental complex of the cathedral square of Pisa, where you can explore the monuments that represent the centre of the city's religious life. Immersed in a green meadow, the buildings symbolize the main stages of life: the baptistery celebrated the birth of man, the cathedral and the bell tower, also called the Leaning Tower, symbolize life and finally the monumental cemetery symbolizes death. In 1987 this cultural site was declared a World Heritage Site by UNESCO. The buildings are reproduced as a floor plan to help understand their internal structure. At the side of the main entrance of each monument there are 3 differently shaped buttons: a circle, a triangle and a square. By pressing them, you can listen to some information: the circle-shaped button will provide practical information, the triangle-shaped button will provide historical and artistic information, and the square-shaped button will provide architectural information. To pause the audio guide, simply press the current button and then press it again to proceed to the next track. To move the tracks forward or backward, instead use the arrows located at the bottom right of this model.
C_baptistery_track1	Monument 1. Welcome to the baptistery of Pisa which you can explore via a floor plan. The main entrance is accessible by climbing the two steps on which the building is located. Inside there are 12 columns and 4 openings. They replaced the existing doors in the building, from which it is possible to enter or exit. To get to the next monument, exit the main entrance and follow the path, but why not listen to the history of the baptistery by activating the triangle-shaped button before you to!
T_baptistery_track1	In 1152 the Baptistery of Pisa was founded, it was dedicated to San Giovanni Battista. The

	reason for constructing a building which as fascinating as it is enigmatic, was the desire to add an adequate complement to the Cathedral: a building which, in terms of position, size, material and style… Did you know that the baptistery of Pisa is linked to Galileo? Push the right arrow to listen to the next track!
T_baptistery_track2	The baptistery of Pisa is a highly symbolic building. Being the place where man's journey in faith begins, the structure is simple and sober and the few elements within it all have a spiritual reference. The 12 columns represent the apostles; the 8-sided baptismal font indicates the number of the days not yet created, the 3 steps on which the source is placed, refer instead to the Father, the Son and the Holy Spirit. The Baptistery is associated with Galileo Galilei, the famous astronomer, physicist and engineer: He was baptized here on February 19, 1564… Did you know that the baptistery is also famous for being a real musical instrument? Push the button again for the next track!
T_baptistery_track3	A feature that makes the structure unique in the world is its extraordinary acoustics. This peculiarity is due to the geometrical layout of the building, closed by a double dome. Initially, a single dome was created

5 EVALUATION

In this section, the user tests conducted to evaluate the interaction with the proposed 3D prototype are described and discussed.

5.1 Method

Since our prototype has been designed to be used by both blind/visually-impaired and sighted people, user testing was conducted by involving both categories of users. During the design phases, an early pilot test was indeed performed with a small group of end-users in order to better define some tactile elements so as to obtain an easily perceivable model by touch. Once an interactive prototype enriched with audio-tracks was ready, a more defined user test with sighted and non-sighted people was carried out.

The evaluation was conducted in order to collect user data on impressions, difficulties, and other general feedback relating to interaction with the prototype. The test procedure used was based on the thinking aloud protocol and is the same for both categories. The user testing was composed of (1) a set of exploration tasks to be carried out with the interactive system, and (2) a questionnaire aimed at collecting subjective opinions. Before starting the exploration, the background to the study and the main features of the 3D models were explained to the users. Each user was also introduced to the 3D model beforehand. Details on the features offered by the model (e.g. reproduction of the ground floor, audio tracks that can be activated via dedicated buttons, and specific details) were summarized. Next, the user was invited to approach the model so that the presence sensor could detect the person and start the first introductory and explanatory audio track. This initial training was 10 minutes long.

During the tests, both quantitative and qualitative data were collected. With regards to quantitative data, we collected the level of success and time involved in carrying out the tasks. The time spent acts as an index in assessing whether the interaction might be useful for helping a new visitor to explore the characteristics of the site before starting the visit. User satisfaction and experience were recorded by taking notes while the user was carrying out the tasks, and during the questionnaire.

In summary, twenty-four people were involved in the user testing: 8 blind/visually-impaired and 16 sighted. The group of eight blind/visually-impaired users was recruited through the local Association for the Blind. The sixteen sighted users were involved by the authors via an e-mail circulated through some mailing lists of the University, CNR, associations of visually impaired people and cultural associations.

In the work [43], the user testing conducted with the blind/visually-impaired people has been described. Herein, we extend the evaluation with the tests conducted with sighted people. The complete test with sighted and blind/visually impaired users and results obtained are thus described and discussed. A comparison between the two groups is also discussed.

5.2 The experiment

The test environment consisted of the 3D interactive prototype equipped with a pair of speakers so as to listen to the audio tracks. A board with a column, a capital, a leaf, a dome, arches, and so on was located near the 3D models. The interaction with the prototype was the main part of the experiment, and the exploration of the details (e.g. columns, capitals) was one of the tasks assigned to the users. All the users came from Pisa and knew "Piazza dei Miracoli", including its structure. In particular, the blind people learned the external structure of the cultural site thanks to all-round three-dimensional tactile model already available on the site. That model is purely tactile and no interactive elements or additional audio and tactile details are available. Consequently, through the study on the main interaction features, and the user experience while using the model we intended to collect useful information to evaluate the appropriateness of the model and answer the research questions. In particular, by focusing on the interaction with the internal structure of the monuments which differ from the other tactile model (i.e. the layout of the ground floor) and the details in large scale, we intended to evaluate if (1) the proposed low cost model is suitable to be perceived, and (2) the reproduction on a larger scale are appreciated by both the sighted and blind users. However, more specific information on these aspects was collected via questionnaire delivered after the test. Thus, the experiment was set up in this direction.

The model prototype was designed to be used in a real environment, but in this phase the main purpose was evaluating if the user was able to (1) perceive the elements as well as the details in order to understand if the scale used for the reproduction was appropriate; (2) use the interactive components designed to get additional information; and (3) if there were any differences in the perception and usage by the blind and sighted people. For these reasons, the prototype was evaluated in the laboratory through different tasks in order to analyse the various aspects rather than using it in a real cultural site. Users were asked to perform seven tasks while interacting with the prototype. A member of the research team introduced the tasks (one by one) and observed the user while he/she was carrying them out. The team member took notes on any difficulties or comments made by the users. The order of the assigned tasks was the same for all the users:

1. locate the button that provides the practical information associated with the Baptistery and find the next monument;
2. identify the number of doors in the Monumental Cemetery;
3. explore the Cathedral and identify the differences, if any, between the columns;
4. find the button that provides the architectural information associated with the Cathedral and go to level 3 in the audio tracks (i.e. the third track in the sequence);
5. explore the architectural details reproduced on a larger scale and place the dome on the four supporting columns present in the model;
6. discover the Cathedral doors, find the exit, and get to the next monument;
7. explore the models freely and identify the materials with which they were made.

The tasks are mainly focused to evaluate specific perception and interaction aspects. Task 1 involves the user being able to identify the buttons according to the positioning rule (near the main entrance of each monument) and to understand that the different geometric shapes related to specific audio information typologies. So the goal was to understand if the buttons' position in relation to the buildings was well perceived and the buttons' shapes were recognizable and understandable by touch for blind users and visually for sighted users. Tasks 2 and 3 verify whether the scale for reproducing the buildings is adequate for perceiving the key elements by touch while maintaining an appropriate scale for a good perception by sight as well. Task 4 assesses the usability of the levels of the audio tracks with special attention to the level 3 associated with the square button which links the main model with the board of the architectural details reproduced on a larger scale. Task 5 elicits user feedback on the architectural details, their reproduction, the selection made via buttons with a different shape, and the level of details of our design. Task 6 assesses how well users perceive the building elements and can orient themselves between the monuments and elements. This was aimed at analysing if the path (streets, entrances, etc.) are easily perceivable and understandable by touch and visually. The path to cover enables the user to touch the various materials used to reproduce the 3D models and elements, thus enabling users to carry out Task 7. More specifically, the last task was designed to allow the user to pay attention to the various materials applied to the model. The user was left free to explore, in order not to influence him/her in observing the different materials. This task is useful to understand the degree of influence of a material in the perception of a form, if it facilitates the recognition of a surface or affects it negatively. Tactile tasks were useful also to evaluate if sighted people were able to focus on those aspects which are not usually considered when visually observing an object.

Both quantitative and qualitative data were collected from the tests conducted. For each user, records were taken of the time taken to perform the requested tasks (task by task), the success in accomplishing the task, and the subjective information. A think-aloud protocol was applied to collect feedback, impressions and comments.

After the exploration, the users were asked to fill in a questionnaire which covered general information (age, education level, type of disability, etc.), and subjective data more related to the evaluation test (e.g. accessibility issues, audio descriptions). Specifically, the questionnaire was composed of four sections: personal information, prototype evaluation, user experience, and usability. Subjective rating questions on the prototype were given on a scale from 1 (the most negative value) to 5 (the most positive value). The list of questions is reported in the appendix.

5.3 Test with blind/visually-impaired users

5.3.1 Participants

Eight blind/visually-impaired people (7 males and 1 female) with an age range of between 40 and 70 participated in the test. Four were totally blind, and the other four were severely visually impaired. Their education level was generally very high (two bachelors, three Masters, one PhD), the other two had a school leaving diploma. The participants had studied: humanities (3 users), technical subjects (1), economics (3), and political sciences (1).

All the users were native Italian speakers. They all said they were interested in the arts (from 1 to 5 scale, a=4.37, sd=0.51) and ‘often’ visited cultural sites and/or museums (a=3.87, sd=0.99). All were familiar with ‘Piazza dei Miracoli’ and 87% of them had visited at least one monument in the square: 75% had visited all four monuments, and 12% had visited three monuments. All the users were familiar with audio-guides. Five had already interacted with a 3D model, while the others had never explored a 3D reproduction. The exploration with an interactive 3D model was a new experience for all the users when we conducted the test.

5.3.2 Objective results

All the users successfully accomplished the seven tasks, although users did have some difficulties in some tasks. The time required for carrying all the tasks is shown in Fig. 6, however the actual time each user spent to explore the model varied from 12 minutes to 1 hour (a=28.38, sd=15.28) since some users wanted to listen to many tracks and perform a complete tour of the monuments. In Fig. 6, two outliers are related to those tasks which presented various issues for many users:

Task 1: to perform this task, User 8 took 45 seconds. We observed that a totally blind user needed more time - compared to the average visually-impaired user - to become familiar with the models and their components.

Task 4: User 4 took 2minutes and 28 seconds to identify the architectural information button associated with the dome, and then to reach level 3. However, User 4 was the only user to listen entirely to the audio tracks for levels 1 and 2. All the other users skipped directly to the audio track associated with the level 3 (i.e. by pressing the square button three times). Tasks 1 and 7 required, on average, less time: an average of 20 and 16 seconds, respectively.

Task 6, which asked the user to identify all the doors in the dome and find the exit leading to the Leaning Tower, took longer (2 minutes and 43 seconds). This activity required a lot of tactile effort to explore the entire building perimeter, the path and the nearby space. It enables us to analyse whether the scale reproduction was adequate to perceive all the small details.

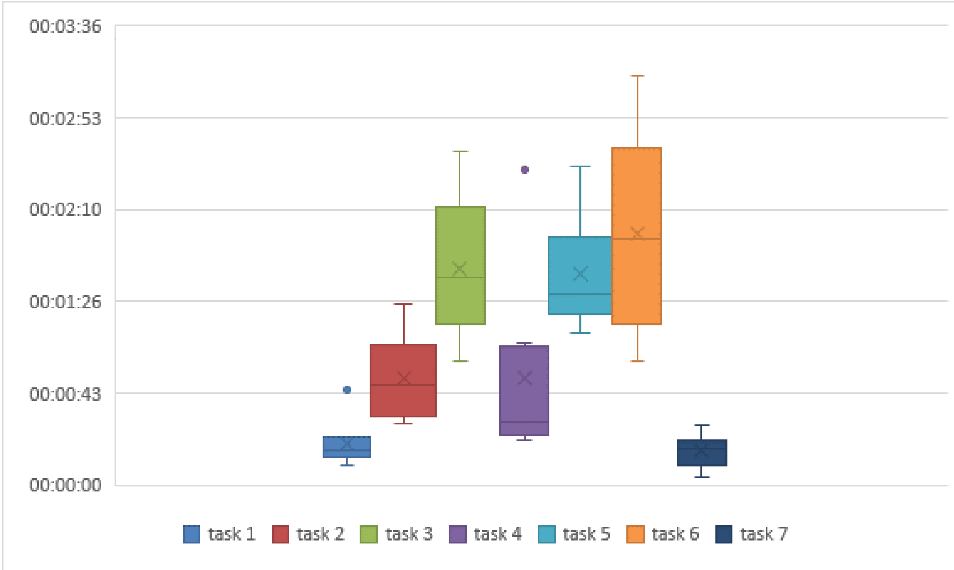

Fig. 6. Completion times of the seven tasks performed by blind/visually impaired users

5.3.3 Subjective results

The overall evaluation given by the participants was good: the participants assessed the type of interaction as good, with an average of 4.00, and expressed a positive feeling towards the 3D models (see Fig. 7).

Six out of eight users perceived an improvement in the interaction while exploring the models, one felt no progress had been made, and one felt that it had got worse. Six users judged the instructions to be absolutely clear (from 1 to 5, the preference was 5), one user judged it as clear (preference 4), and one as unclear (preference 2) with the reason being that they had difficulty in understanding the welcome track because they had been expecting it to be more didactic. Thus, six users rated the welcome track as clear. With regard to the buttons, all the users declared that they had identified them without difficulty and understood the association of the geometric shapes with the information typology. This was confirmed by the correct answers given by all users in the questionnaire and in carrying out tasks 1 and 4. All the users agreed in their evaluation of the usefulness of the audio support for the interaction, and felt that the audio tracks were clear and well categorized (a=4.62, sd=0.74). The reproduction scale was assessed as being adequate with an average of 3.8/5; with many users preferring the larger scale. All users recognized the materials used to reproduce the elements (plastic, synthetic grass, plywood), while considering realistic materials to be more appropriate for a more natural interaction and a better experience in the exploration.

Observing the users while exploring the models and carrying out the tasks, we noted several issues:

(1) some problems with the location of the board containing the 3D details;
(2) the movement-sensor activating the welcome track was too easily activated;
(3) some difficulties in understanding how to associate the specific details with the main monuments.

Finally, the users were asked to comment on aspects they liked and did not like about the experience, and make suggestions. Most of the positive aspects were related to the system: "The interaction experience is simple and engaging", "The audio tracks are interesting, not long and cover the various reasons for visiting a monument thanks to the different levels activated on demand according to the user preference and time", "I believe it is a valuable and very useful device".

The features that were liked the most were:

(1) the button design with different shapes for specific information categories;
(2) architectural details created on a larger scale;

(3) audio descriptions with increasingly higher levels of detailed information. One suggestion was to have a multilingual audio.

Negative comments tended to be related to:

(1) the representation scale; most users (6) found the scale of architectural details to be sufficient for the interaction, but a larger scale would have been preferable also for the main buildings;
(2) lack of colour contrast; a greater contrast should be applied in order to enhance the perception especially for the partially-sighted people;
(3) a modular tactile model composed of internal and external elements, which would have been preferred by some users.

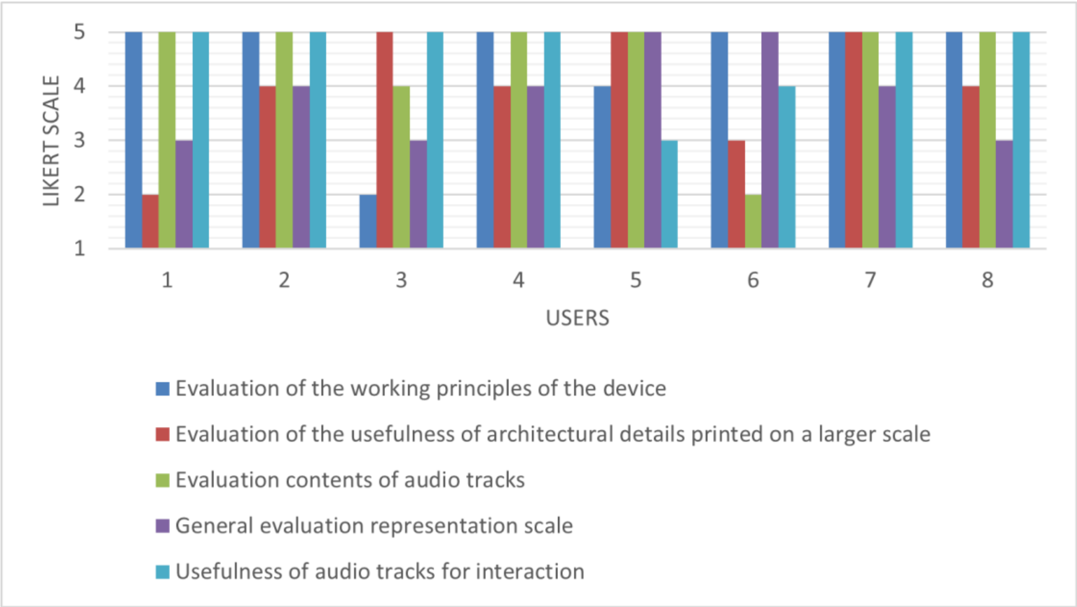

Fig. 7. Overall assessment of interaction experience of blind/visually impaired users

5.4 Tests with sighted users

5.4.1 Participants

The sixteen sighted users (8 females and 8 males) were aged from 20 to 59 years. They had no disability. With regard to the *educational* level, 6 had a bachelor degree, 5 a master's degree, and 5 a school leaving diploma. The studies ranged from humanities (4 users), architecture (1 user), communication science (1 user), digital humanities (3 users) and information technology (2 users) to technical-scientific subjects (5 users). All users were native Italian speakers except one, who speaks Italian as a second language. All users indicated their interests in arts (from 1 to 5 scale, a=4.18, sd=0.98) and 'often' attend cultural sites and / or museums (a=3.37, sd=0.80). All except one said they were familiar with 'Piazza dei Miracoli' and 81% of them had visited at least one monument in the square: 6% had visited four monuments, 25% had visited 3 monuments, 25% had visited two monuments, and 25% had visited only one monument, while 19% had not visited any monument. All users indicated they were familiar with audio guides.

Nine users had never explored a 3D reproduction, while seven had already interacted with a 3D model in a gaming, demo or exhibition context. The exploration with an interactive 3D model was a new experience for almost of all the users when we conducted the test: Two users had experienced an interactive model in an exhibition context as a reproduction of historical scenarios. During the test the users did not wear an eye mask, because the purpose was to evaluate the interaction with the tactile model considering real factors (usually a sighted person does not wear an eye mask when visiting a museum).

5.4.2 Objective results

The time spent in carrying out the tests - consisting of the task accomplishment by the participants - ranged from 10 to 20 minutes (a=13.3). The intervention by the supervisor researcher was needed to support four users in accomplishing task 4. All the other tasks were completed successfully by the participants, even though some difficulties were encountered by some users (see below).

Observing all the times spent carrying out each task, the diagram in Fig. 8 shows the lowest completion time (00:04) by user 9 for task 2, and the highest completion time (02:04) by user 13 for task 5.

The 5 outliers highlighted in Fig. 8 refer to those tasks with some difficulties often encountered by the sighted users, as shown below.

Task 1: to perform this task, user 2 took 47 seconds, user 11 took 35 seconds and user 16 took 51. This is because the three users had not immediately identified the correct button associated with the practical information for the baptistery (the circle). They activated the correct button only after having listened to the welcome track a second time.

Task 2: User 3 took 26 seconds to complete this task, which was about 16 seconds longer than the average of the other users. This difference may be justified by the fact that user 3 was not familiar with the monumental cemetery, so he/she needed more time to identify the doors of this monument.

Task 4: user 13 took 2 minutes and 4 seconds to complete this task, which was to identify the architectural button (square) and to listen to the information for the dome up to level 3. User 13 was the only one who listened to both tracks 1 and 2 without skipping directly to level 3.

Tasks 1 and 2 required, on average, less time to be completed: an average of 15 and 11 seconds respectively. Task 5 (1 minute and 5 seconds) required more time to complete, maybe because it required a combination of actions by the user. Two aspects were observed while carrying out this task: 1) the panel containing the architectural details was not placed at the same level as the 3D model, instead it was located at a lower level; this raised some issues in identifying it as part of the model; 2) three users encountered some difficulties in combining the 3D details with the floorplan model; this might be due to the different scales used for the objects and the main model.

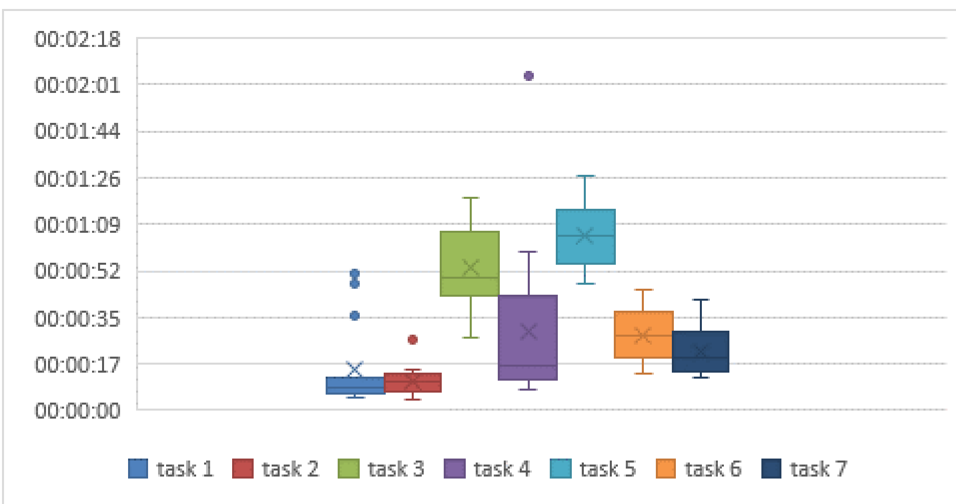

Fig. 8. Completion times of the seven tasks performed by sighted users

5.4.3 Subjective results

Our intention was to evaluate if the user was able to become more familiar with the system while using it. Fifty percent of the sighted users said that the interaction with the model improved as they used it, 44% that the interaction remained the same, while 6% was not able to give a judgment (see Fig. 9). Sixty-three percent of the users said the usage of the model was immediately 'very clear' (from 1 to 5 scale, the preference was 5), 25% the usage was 'clear' (from 1 to 5, preference 4), and 12% the usage was 'clear enough' (from 1 to 5, preference 3).

Regarding the button shape, 100% of the users said they were able to identify each button well, and to understand each type of geometric shape associated with the different information. However, only 87% of them correctly answered the question about the relationship between the button shape and information typology when filling the questionnaire, and only 68.75% identified the correct relationship while carrying out the tasks 1 and 4. All users agreed in considering the audio element useful for the interaction (a=4.37; sd=0.71) and almost all of them found the audio tracks 'clear' and 'well categorized' (a=4.62, sd=0.61).

The scale used to reproduce the monuments was considered adequate for sighted users (a=4.62, sd=0.5). All users recognized with no difficulty the material used for the model (plastic, synthetic grass, plywood) considering them suitable as regards the quality and price. However, 3 users out of 16 expressed a preference about the colours of the monument reproduction: they would have preferred printed white plastic. Regarding the details reproduced on a larger scale, 88% of users considered it 'very useful' to have the opportunity to touch architectural details on a greater scale.

Overall, the people gave positive feedback about the audio tracks: they found them nice and well structured, especially because each track is short and simple. In addition, they appreciated the button shapes because they are clear and useful for recognizing the semantic category. The simplicity of the audio tracks was appreciated also by the user who was a native English speaker.

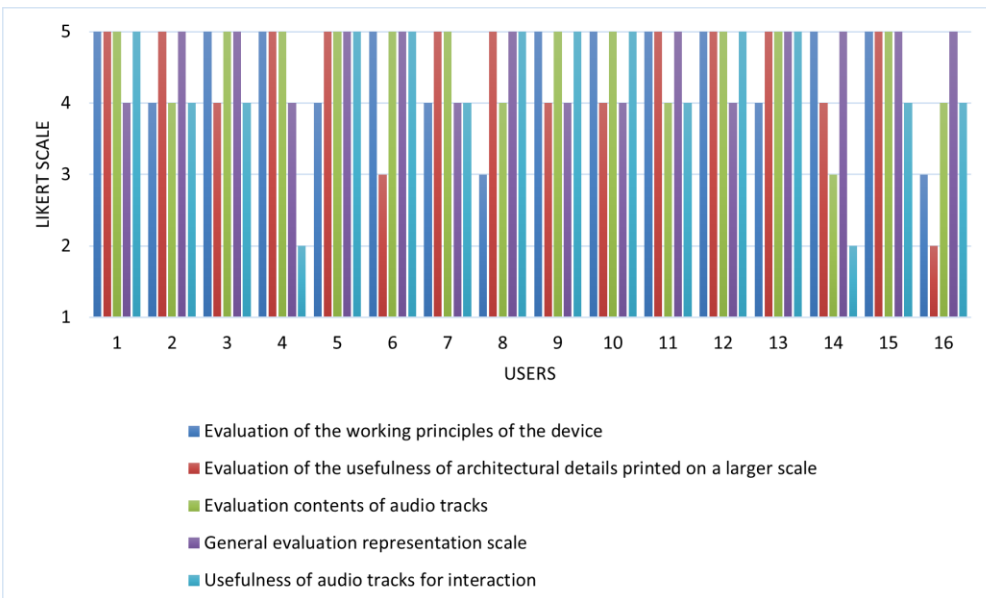

Fig. 9. Overall assessment of the interaction experience of sighted users

5.5 Comparison of results

The data collected about the evaluation of interactive 3D models (Fig. 7 and Fig. 9) were analysed via the IBM SPSS Statistic tool. The aim was to analyse if differences exist between the two groups of users (visually impaired and sighted) participating in the test in the perception of the same tactile models. All the users gave a judgment based on a likert scale (1-5) on: (1) working principles of the device; (2) usefulness of architectural details; (3) contents of audio tracks; (4) evaluation of representation scale; (5) usefulness of audio tracks for interaction.

To define the type of statistical analysis to be applied, the characteristics of the sample (different groups with different sample size) were checked. Primarily, there was the assumption of normality, which specifies that the means of the sample groups are normally distributed. Progressively, there was the assumption of equal variance, which specifies that the variances of the samples and of their corresponding population are equal.

Regarding the first assumption, the Shapiro-Wilk's test ($p > 0.05$) was applied for all data. This test and an inspection of the skewness, kurtosis measures, standard errors and a visual inspection of their histograms, normal Q-Q plots and box plots, showed that the all the sample data were not showing a normal distribution, even approximate. Therefore, it was necessary to continue the analysis by applying nonparametric techniques focused on the rank [36], [34]. A nonparametric Levene's test was used to verify the equality of variances ($p > 0.05$). Both groups, in relation to the 5 properties analysed, show homogeneity of variance.

The Kruskal Wallis's test [13] with the Dunn-Bonferroni's Post Hoc was applied and the results are shown in Table 2.

Table 2. Results of Kruskal-Wallis' test. The asterisk shows the category for which the null hypothesis (H_0) is rejected ($H_0 = p > 0.05$) and the mean ranks of groups are statistically different

Working principles of the device	$H(2) = 0.19, p = 0.66$
Usefulness of architectural details	$H(2) = 1.33, p = 0.25$
Contents of audio tracks	$H(2) = 0.02, p = 0.88$
Evaluation of representation scale	$H(2) = 4.97, p = 0.03$*
Usefulness of audio tracks for interaction	$H(2) = 1.08, p = 0.30$

There was a difference ($p < 0.03$) between the groups in the evaluation of representation scale (Fig. 10). The sighted users felt that representation scale of the monuments was appropriate, while blind users would prefer a slightly larger tactile representation. There was no evidence of a difference between the other categories of evaluation (from Fig. 11 to 14).

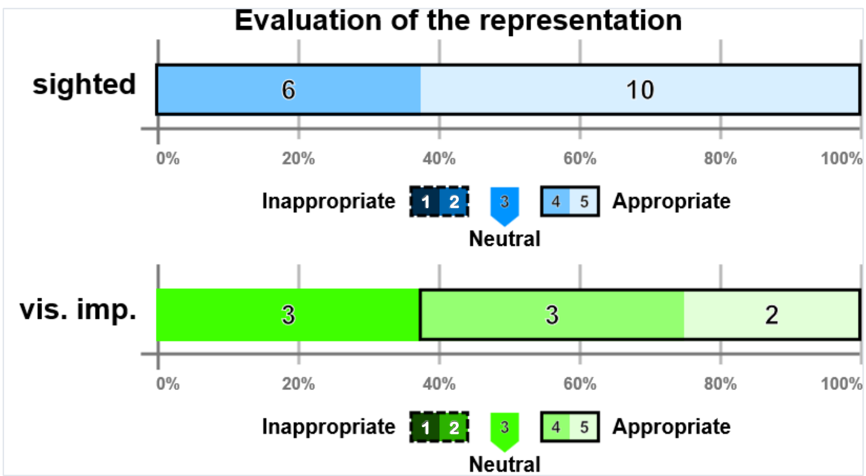

Fig. 10. Evaluation of the representation scale using Likert (1-5), the sighted users found the representation scale appropriate while the visually impaired would generally prefer a larger scale

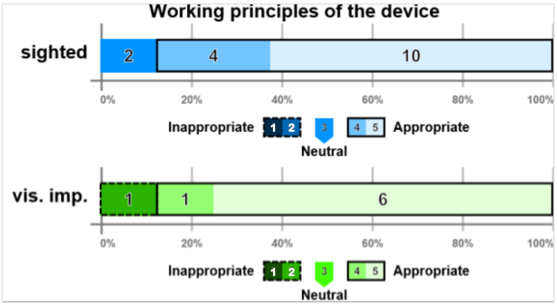

Fig. 11. Evaluation of the working principles of the device, sighted and visually impaired users gave a similar score

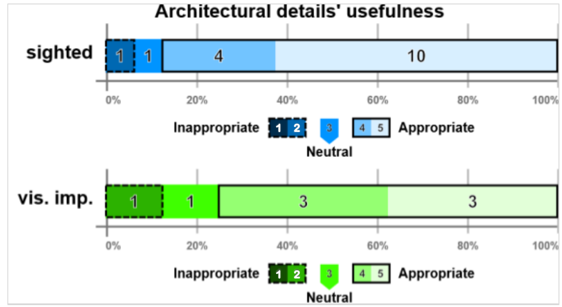

Fig. 12. Evaluation of the usefulness of architectural details, both sighted and visually impaired users found them very useful

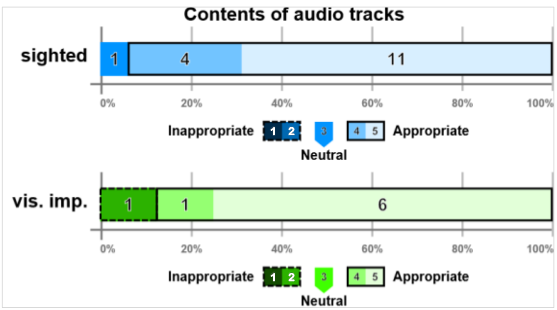

Fig. 13. Evaluation of the contents of the audio tracks, sighted and visually impaired users found the contents appropriate

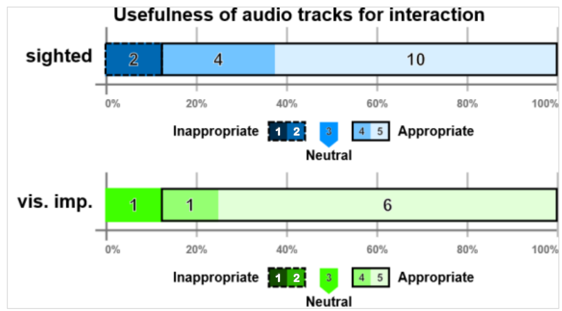

Fig. 14. Evaluation of the usefulness of audio tracks for interaction, sighted and visually impaired users both found them quite useful

5.6 Facilitator’s observations

We observed that task 4 presented some issues for both blind and sighted people, but for different reasons. One blind person spent a long time to perform the task, because he liked to listen to all the information provided by the audio tracks. Differently, four sighted users needed of support by the supervisor, and so they spent much more time because they did not remember the shape of the button providing the architectural information. For the same reason, a sighted user required a lot of time for task 1. For blind users, task 6 took more time due to the need to explore all perimeter in order to detect the doors by finger, one by one. On the other hand, sighted participants did not encounter any issue for this task. Finally, task 7 was immediately familiar for the blind participants, while it required certain support by the supervisor for the sighted people. To sum up, the sighted users completed the tasks faster than the group of users with visual impairment. In particular, the visually impaired had an average of 2 minutes and 43 seconds for the slower task (task 6), while the sighted had an average of 1 minute and 5seconds for the slower task (task 5).

We observed that the difficulties encountered by the sighted users were mainly due to a psychological, practical, and technological nature for the following states: Welcome track. 31.25% of participants did not pay enough attention to the welcome track and this did not allow them to get important indications to achieve correct interaction. These users had difficulty in identifying the semantic typology of information associated with the buttons and they had to listen again to the welcome track. Despite this, users considered the welcome track ‘very clear’ (a=4.31, sd=0.79). This did not happen for the blind people who carefully listened to the initial track, maybe because they are used to relying on audio contents.

Panel of details. The panel used for the representation of the details on a larger scale was placed alongside the main model, but at a lower height of about 15 cm less. This was for logistical reasons, and not for a specific reason. All the users stated they encountered some practical difficulties in locating the panel and details, although most of them successfully detected the elements: 81% of users appropriately identified the objects, while the remaining 19% recognized them only with a little suggestion by the supervisor.

Proximity detection. The technological issues we observed were related to the proximity sensors. Two proximity sensors were positioned on the front of the 3D model and covered an area of 83 cm in length by 60 cm in depth. Overall, the sensor coverage was found to be good. In some cases, however, when the user was in a position not covered by the sensors, the system did not detect correctly the user as being in the vicinity with the consequence of stopping and starting again the welcome track as soon as the user made just a little movement either towards or away from the sensor. This problem could be avoided by adding a greater number of sensors.

Touch sense. Using the sense of touch, blind users were more able to identify the size, distance and minimum details of the objects. For example, they were able to identify the distance between the columns well or also the slope at the base of the tower. The same sensitivity was not been observed for the sighted users who usually rely on sight to notice all the details. In addition, one blind user was able to observe that the plan was not sloping in the same way as the ground floor of the Leaning Tower. So, although the model did not include the layout of the buildings, it should have a light sloping to inform the user about the Leaning Tower.

Regarding the psychological aspects, for the sighted participants exploring a three-dimensional was not an unusual activity because 3D models are generally designed specifically for blind people. However, all the tasks clearly involving a sense of touch were also performed by the sighted participants. It was observed that they sometimes needed to be "guided" in a certain way. Usually, a 3D model is marked with braille label and is not coloured or developed with different materials, consequently a sighted visitor rarely considers using a 3D model made available for visually-impaired people. This is one of the main reasons for which the aim of our approach is designing a system which can be attractive and effective for all.

With regards to the user experience, the evaluation given by the participants was overall good, especially considering that this was a new experience for everyone: the participants positively assessed the type of interaction (average of sighted users: 4.53, average of visually-impaired users: 4.00, see the Diagram). None of the users stated that they had any uncomfortable sensation using the system.

6 DISCUSSION AND SUGGESTIONS

Based on our experience, an interactive three-dimensional model can be a useful tool for supporting both sighted and visually-impaired people in exploring a cultural site. The 3D model helps especially the visually impaired to get an overview of the site structure and of the main monuments. In particular, the 3D reproduction of some objects on a greater scale can offer a valuable way to perceive details which could be difficult to understand for a visually impaired person. The reproductions can be very useful also for sighted users who can pay more attention to certain features and particulars, which could be difficult to observe in the real monuments. Furthermore, some information can be added to the 3D model, in braille format for the visually-impaired, and in written or graphical format for other sighted users. However, the space available on the model is limited to very little text consequently, additional contents provided in alternative formats can be a valuable way to enrich the exploration of the model by everyone.

Audio tracks can offer various typologies of information, provided that they are arranged so that the user is not constrained to listen to (1) only one type of content (generally historical) or (2) tracks which are too long. Making various types of information available as well as using different ways to perceive the contents should enhance the user experience independently of their own abilities. This can help the visitor to explore the model of the cultural site before starting the visit, in a way that suits their personal preferences and interests. Thus, the augmented information and interaction modalities should both be considered during the design process of the 3D enriched model. In this perspective, the contents added to a three-dimensional reproduction should be (1) distinguishable according to the typology and semantic, and (2) structured so that the user can stop or go quickly through various contents.

Concerning the problems observed in identifying the different buttons and shapes associated to different types of information, the initial instructions (e.g. via the welcome track) play a crucial role. The test allowed us to observe that sighted people do not pay particular attention to it. Sighted users rely mainly on visualized information and so they are probably not familiar with listening so carefully to audio tracks, especially those containing instructions; on the other hand, visually-impaired people are more familiar with audio contents. How the instructions and descriptions are provided to the user becomes crucial for a successful welcome track, therefore, particular attention should be paid to how the welcome track is designed and structured. The user should be alerted to pay close attention to the instructions and indications provided as support for overall interaction. Furthermore, some additional tools giving information on the interaction modality could be made available to the user in a quick way in order to have at the hand the core instructions for the usage of the model (e.g., via dedicated button). In our prototype the audio contents were controlled directly by the model via specific buttons. However, the additional contents could be designed in different ways, such as through a specific app developed to work with the 3D model. This approach has not been considered in this study, but can be a further development to investigate other modalities. In our prototype we intended to develop a model which did not require any specific skill by the user and no additional tools to learn and use.

A variety of colours, materials, textures and shapes could be a key way to provide different perception modes. This could be useful to distinguish between different components and elements in the acquisition of knowledge of the reproduction by the sighted, those with low vision and vision impaired people. This could be very useful especially for educational purposes, but it is valuable also for preparing a visit by groups of people that may have restricted viewing due to their numbers. A good approach to distinguish various components and details can improve the model perception of all parts of the model. Although sighted users expressed a positive impression with regards to the perception by touch via different materials, they especially rely on sight to observe details. Thus, using colours or other graphical aspects in association with the different materials could be useful to improve the experience for sighted and people with visually impaired. On the other hand, blind people can get benefit from the various materials and textures, as well as the different shapes which can be clearly identified by touch.

With regards to the model reproduction, we especially focused on the ground floor plan in order to consider some elements which are not usually reproduced in a three-dimensional model. Nevertheless, the users (especially those who are blind) observed that a 3D model should have both (1) a ground floor tactile plan and (2) a reproduction of the entire building in order to get an overview as well as understand how the monuments have been built, often in stages. Although this study is based mainly on ground floor reproduction, we certainly agree with the users on the case for having a complete 3D model. Another factor we observed was that there were some difficulties in identifying the relative sizes of the objects, e.g. the height of columns. Thus, some comparative elements could be reproduced and provided together to the 3D model. In this way, the user can compare known elements with the particulars and details of the model. This could help them in this activity.

Finally, in relation to the research questions we can sum up the following:

RQ1, “Is a low cost three-dimensional interactive model suitable to be perceivable by visually-impaired and sighted people?”, the study points out that the three-dimensional interactive model prototype herein proposed can be reproduced with relatively low effort. However, basically the cost for reproducibility can be considered low, and the reproduced model is suitable to be perceived by the visually-impaired and sighted people as well, even if some adjustments with regard to the scale, colours, layout of buildings combined with the ground floor reproduction, etc. should be carefully considered in the design.

RQ2, “audio tracks and tactile details on a larger scale can be useful to provide additional information which can be easily accessed by the visually impaired and sighted users?”, the study reported that additional audio contents and tactile details are perceived as being useful in enhancing the user experience, especially thanks to semantic information and different shapes as well as the tactile details reproduced for certain particulars on a large-scale to be learned by a visually-impaired user and better observed by a sighted person. In fact, both visually-impaired and sighted users liked the audio descriptions, including the different levels used for the audio tracks to allow the users to access the desired contents.

RQ3, “Are there some differences in the perception by visually-impaired and sighted people?”, the study highlighted that some differences exist between people with vision impairments and sighted users, but just in terms of perception and time needed to explore. No statistical difference occurred in terms of usefulness and usage of the 3D model. The results revealed also that both categories of users appreciated the model prototype as a way to get an overview of the site while acquiring information or specific details s which can be observed on a larger scale. Thus, even though with different reasons, we can conclude that details on a large scale are useful for both types of people: blind users can become aware of characteristics and elements that they could not easily discover otherwise; sighted people, on the other hand, are able to focus attention on aspects that in the real model could be overlooked or not considered.

To sum up, the tests conducted pointed out that a 3D model can be perceived by both visually-impaired and sighted users. Thus, it could be exploited to increase autonomy in exploring a site or museum before visiting it. The study also revealed that both visually-impaired and sighted people can benefit from an enriched 3D reproduction and auditory contents. In this perspective, such an interactive 3D tactile model could be considered by the cultural sites and museums to enhance the user experience especially before starting the visit. 3D tactile models are widely used also by several cultural environments (e.g. museums, churches, etc.) or in many other situations especially to support blind people to learn more about the buildings and the main elements of real monuments and artefacts. However, those models are only equipped with braille labels and the limited space limits the amount of text or size of the key. On the other hand, additional information available in audio format linked to each element can help in having an enriched exploration of the model. Similarly, tactile details on a larger scale may offer the opportunity to explore some details which could not be perceivable in other ways by a blind person, or which are often not observed by a sighted person in the real object. Thus, cultural sites should consider reproducing on a larger scale some important and meaningful details needed to learn about aspects and concepts.

Briefly, the main aspects that a cultural site should consider when designing an interactive 3D tactile model to support the user on the visit or in the acquiring knowledge of a specific cultural heritage can be summarized in:

a) Consider reproducing the ground floor and the layout of the main buildings or artefacts to be combined in order to support exploration by touch.
b) Select the main features or details to be presented in detail in order to be reproduced on a larger scale; the items to be reproduced should be chosen according to the specific characteristics of the artwork or the detail to be explained and explored by the user. For instance, if a door or window has some specific features useful to illustrate a concept or to show some information (e.g., two-light or three-light window), that object should be reproduced on a large scale so that the user can perceive the features by touch.
c) Place the panel containing all the 3D tactile models reproducing the particulars near to the main model and on the same level.
d) Enrich the 3D models with additional auditory and tactile elements, such as audio descriptions, a variety of information grouped semantically and make it simple to use. Audio descriptions made available via tactile buttons should be easily identifiable, thanks to their size, shapes and position. Provide some braille labels for short keys or the main introductory instructions in brief.
e) Provide an introductory audio description which can be easily activated (e.g. via a motion sensor or any other intuitive method) to introduce the model and main commands and instructions to follow.

These are the main steps to suggest to the cultural sites in order to make available 3D and interactive models useful to support exploring and learning about artworks and objects. In the next section, design guidelines are described in more detail in order to provide more specific indications.

7 DESIGN GUIDELINES

Based on our experience as well as previous studies on tactile map design, we propose some design guidelines to be followed when preparing 3D models aimed at supporting visitors in exploring a cultural site. To the best of our knowledge, this is a first attempt to formalize potential criteria to suggest for designing a 3D interactive tactile model [37], especially for cultural heritage.

7.1 Driving principles

A number of works offer indications to keep in mind when reproducing maps, graphs and tactile diagrams. In drafting the guidelines herein proposed, these principles have been taken into account. In [11], the authors provide a meaningful summary of some research proposal for guidelines in the haptic interaction. However, they highlight the lack of a globally accepted set of guidelines for haptic interaction in general and for cultural heritage in particular. Other works propose guidelines for tactile graphics and maps, which allowed us to extend the contribution into the 3D printing for cultural heritage. The proposed guidelines for 2D reproduction of tactile maps points out some critical aspects, such as the importance of raised lines (i.e. their sizes) in order to well understand the path in addition to meaningful elements and concepts [50]. Nevertheless, a 2D tactile reproduction, although perceivable by touch, could be better suited to some types of information, like maps and graphics. Using touch to perceive more details and particulars (especially in artworks) may require three-dimensional tactile elements. In fact, certain elements, like symbols and buttons, may be more understandable and perceivable from a 3D reproduction. In addition, the features of columns and walls may be more understandable if they are reproduced in a format [27]. Different types of raised lines, even varying in thickness, are not enough to reproduce certain details and could risk becoming confusing when explored by finger. The study by Holloway [27] confirmed that 3D models are preferred by blind users to better understand and remember symbols and icons. This is the reason why our model for cultural heritage has been reproduced in a three-dimensional way. However, the available guidelines for 2D and tactile reproduction (e.g. maps and graphics) helped us to better define and illustrate some indications to keep in mind when designing a 3D reproduction perceivable by touch. More specifically, the guidelines proposed by BANA [5] and Tatham [50] were considered as the springboard especially for the simplification of the digital model and the symbols as well.

Holloway et al. [27] proposed 9 guidelines designed to give useful information to 3D model designers to facilitate exploration with the hands, especially by those who cannot see. In particular, they give indications about the possible need for perceptible exploration via finger, suggesting for example how certain elements (roads or items) should be designed (i.e. an indented path rather than raised lines). Those guidelines suggest a more general design approach to get an overall perception of the model with the use of the hands while avoiding elements that could bother exploration (guidelines 2 and 6). The guidelines proposed here are aimed at specifying in more detail some aspects referred to by those 9 guidelines, and to support exploration by both visually-impaired and sighted people. Furthermore, in addition to giving more precise indications on the steps to be followed in the design of the model (G1, G2, and so on), our guidelines also intend to focus on usability aspects, such as the consistency or the possibility of providing more precise and semantic information to the user. For example, guideline 1 Proposed in [27] suggests providing additional information to allow the user to better understand the 3D model. Our guidelines propose more specifically to use elements capable of distinguishing different types of information (G4, G6 and G7), with different shapes, colours or materials. They, therefore, better specify what Holloway et al. proposed. In addition, with regard to additional audio information, guidelines 8 and 9 [27] suggest developers use triggering points associated with clear actions that do not limit the understanding of the model. We better specify these aspects, by suggesting the usage of specific buttons, in terms of shape, colour and associated actions (G4). Finally, according to what is still suggested by the guideline 1 proposed in [27], our guidelines indicate more precisely how to add this information to the model: different levels of information to allow the user to get more details on demand (G6, G7 and G8), while at the same time having different types of information useful for the different categories of users (blind and sighted). This is in order to affect the interaction in terms of effectiveness and satisfaction by the user in the exploration. In short, the guidelines herein proposed are intended to better specify the more general principles expressed via the guidelines suggested in [27].

With regards to the guidelines for 2D tactile reproduction, the principles proposed by BANA [5] are mainly focused on indications on when and how tactile graphics should be combined with braille textual contents. However, some of them are interconnected with those we are proposing. Indications suggested by BANA include firstly “Simplify the drawing, by eliminating unnecessary parts and separating the graphic with too many components into sections” (e.g., guidelines 2.1, 2.5, 2.6 and 2.8), which are better specified for the 3D reproduction by our guidelines G1 and G2. Other guidelines in [5] are referred to the understanding of the reproduction, such as the principles 2.11 and 2.12. Lastly, other indications are about the possible transcriptions related to notes and any other type of information; principles 2.14 and 2.15 are two examples.

One of the important principles which should be addressed when designing 2D maps is the “clarity” of the exploration. In [50], the authors say that “...often, lettering is required and this provides tactile mapping with a significant source of clutter”. Braille code lettering requires a lot of space, and so orientating and understanding the map could be a challenge for a blind person. Accordingly, audio descriptions or information provided in a different way from braille coding make the exploration possible and clearer. This is the aim of the guidelines G6, G7 and G8 herein proposed, and more generally expressed by the principles in [27] through specifically guideline 1.

Our approach basically relies on 3D printing, with the aim to support (1) reproducible solutions and (2) low cost methodology. Three dimensional models can certainly support visually-impaired people in exploring environments and spaces in order to get useful information on shapes, materials and structure. This can nowadays be enriched by additional information like audio descriptions or additional contents provided via different modalities and tools, such as personal smartphones or directly by the model itself. This is in line with the first guideline proposed by Holloway, i.e. “As with tactile graphics, additional explanations should accompany 3D models to provide a context in which to understand the model”. In this perspective, our goal is providing potential principles and guidelines aimed at giving suggestions on how to prepare 3D tactile models to be used in different contexts, including educational and cultural purposes.

7.2 The guidelines

We propose 8 guidelines organized by 3 principles: reproducible, perceivable and understandable. Table 3 shows the proposed guidelines. For each guideline, the number, a short description, and some practical actions needed to apply it are reported.

Table 3. Design guidelines proposed for 3D interactive models

N.	Guideline	Implementation
G1	Manage and process the digital source reproduction via computer graphics before 3D printing it.	Simplification Scale
G2	Break down the 3D model into several small parts and make simplified digital sources available for each part.	Splitting the model
G3	Reproduce important components and conceptual elements in a larger scale.	Some particulars in a large scale
G4	Use distinguishable elements to make a distinction between different kinds of semantic information.	Different materials and textures Different shapes Chromatic contrast and colours Distinct audio tracks
G5	Keeping the content and layout consistency across elements.	Elements localization Elements shape Terms and terminology
G6	Add contents to enhance understanding of the model.	Audio contents Semantic information Caption and additional key Comparing elements
G7	Structure audio contents into different levels of detail.	Play and pause Go forward and skip
G8	Produce some simple initial instructions (welcome track).	Adequate length Simple terminology Easily accessible at any time

The first two guidelines (G1 and G2) are intended to confirm that, as for maps and tactile graphics, the digital source model used for 3D printing needs to be reworked. Firstly, decorative or other elements not necessary to understand the overall structure should be removed. This is also referred to by BANA [5] in guideline 2.1 ("A tactile graphic is a representation of a print graphic designed in a manner that is most meaningful to the reader. It is not an exact reproduction"), 2.5 ("Some eye-catching design techniques used in print, such as decorative borders, are irrelevant to the concept being taught and should be omitted"), and 2.6 ("Many frames or image outlines found around print diagrams should also be omitted if they would add extra lines without purpose"). An appropriate scale should be considered while designing the digital model. In [37] the need for various scales is suggested. Our guideline G1 recalls the importance of scale, but the need to use a larger scale is better specified in guideline G3; moreover, we also suggest using comparative elements to better understand the dimension of an object (see G6 for more details). Specifically, guideline G2 suggests that developers should also make individual parts of the model available in digital source format ready to be printed. In this way, only the desired parts can be reproduced (e.g. by a school), as well as having the possibility to make prints at different times (i.e. the 3D printing time may change according to the type of printer). Guideline G3 was proposed because the study found that both blind and sighted users appreciated the possibility to observe some details and features through a reproduction of a feature on a larger scale. For this reason, a specific guideline has been proposed, instead of including this requirement in guideline G1, in which indications for the scale were provided. Furthermore, guidelines G2 and G3 are in line with the principle proposed by Shi et al. [47] about "Improving Tactile Information", which suggests avoiding models with an overwhelming amount of details which may be difficult to perceive by touch. The user could explore a simplified version and get more details when better understanding of the model. Guideline G4 was proposed because, as observed in the tests, distinguishing information of different types through well-specified buttons and distinct material helped the users to better orient themselves in the exploration. Guideline G5 confirms the importance of the usability principle of consistency to support the user in learning and therefore in interacting with the model. Finally, the last guidelines provide precise suggestions on how additional content should be added to the model and therefore offered to the user in order to improve the understanding and the usage of the interactive model according to personal preferences. These guidelines are compliant with the principle "Controllable and Changeable Digital Content" expressed by Shi et al [47], which aims to overcome the potential issue of overwhelming audio feedback. They propose to use modes to change content and avoid overwhelming the user with information, by switching among different modes using a button.

7.3 Guidelines description

In this section, the 8 proposed guidelines are described in detail, while specifying the concept and how it could be implemented. They are presented according to the 3 principles (1) reproducible, (2) perceivable, and (3) understandable, in order to focus on the main effects that each principle can have on the interaction with the model.

Principle 1: Reproducible

Models should be successfully reproduced once they have been created using simplified digital sources that are made available to schools and specialised centres, i.e. to the staff which is responsible in replicating the process in a successful way. The procedure and method should be easy to apply and relatively effective in cost and needed time.

Preparing digital sources to be used for printing 3D models requires some steps in order to achieve objects perceivable by touch. These steps include the following guidelines:

G1. Manage and process the digital source reproduction via computer graphics before 3D printing.

When using 3D modelling for very large monuments, the artefact should be adapted to a suitable 3D reproduction (e.g., irrelevant details should be not included). We thus suggest using a source-based approach, which is faithful to its original architectural plan and to the historical facts. Before printing it in 3D, the digital source needs to be processed in order to modify the model to obtain a more adequate both tactile and visual perception. Scale and simplification play a crucial role in this process.

- *Simplification*, remove those details that might not be easily perceptible by touch. This depends on the scale used for the reproduction. In fact, the level of simplification needed is proportional to the scale used for reproducing the artwork. For example, in preparing the model for the reproduction of the inside layout, elements such as walls, columns, steps, tables, and other objects with large dimensions should be tailored. Items with limited size such as architectural details (e.g. capitals, leaves and other granular decorations) should not be included at this design level. Elements such as doors, windows and arches can be designed in the general model as an outline without very small details. On the contrary, when designing an artefact – or a component of it (see G4) - on large scale, details should be reproduced. This guideline extends those proposed by Holloway [27] (2, 3 and 6) and by BANA [5] (3.7 and 3.7).
- *Scale*, use an adequate scale for the reproduction and keep an appropriate distance between the elements. More specifically, use a scale of reproduction proportionate to the detail that you intend to provide from a tactile perceptual point of view. Too reduced a reproduction scale does not allow the smallest elements to be perceived by touch. A scale which is too large makes many details available, but the corresponding model requires too much space. Furthermore, exploring the model might not be easy due to the big size. To sum up, based on the level of detail to provide, choose an appropriate scale. The details, for example, should be reproduced on a larger scale, as it allows the blind to perceive decorative elements or small details (see G3). This guideline is in line with the guidelines (2 and 3) from Holloway [27].

G2: Break down the 3D model into several small parts and make simplified digital sources available for each part.

For each model, prepare and make available more than one digital source file, i.e. one for each single part. As a result, the operator or specialized centre can print each part independently. This procedure can be useful for large models which are composed of many parts: having one source file for each part or component allows the centre to print only the desired component. This process means assembling all the components to achieve the final 3D model, but can be useful adopted for other purposes. Furthermore, in this way simple and low-cost printers can be used, generally cover a very small print area (15-25 cm).

For example, if the model is composed of various monuments, or easily distinguishable components, each of them could be designed in a separate digital source so that it can be printed individually. This can be useful for (1) breaking down the model into several small parts in order to be printed also via less sophisticated 3D printers and, after that, to be assembled; (2) reproducing single objects which can be used as an individual reproduction. For instance, if the model is composed of four monuments, consider splitting it into four parts.

Principle 2: Perceivable

Information and model components must be presented to the users in ways they can perceive. To reproduce a model that can also be perceived by touch, different shapes, sizes and materials can help. Other elements, such as colours, can be useful to enhance and perceive the differences and main concepts even by those who have a residual vision or are sighted. In particular, the study found some differences between sighted (preference for white) and visually impaired (preference for various colors). Despite this, we can observe the use of different colours can help visually impaired people to better distinguish the various components of the model. The guidelines proposed are aimed at suggesting this type of approach.

G3: Reproduce important components and conceptual elements on a greater scale.

Choose and reproduce on a large scale those relevant elements or conceptual components from the model which are considered to be worth being perceived by touch or visually observed in order to understand or learn certain meaningful features.

This guideline extends guideline G1: guideline G1 refers to the model as a whole, in which it is necessary to present the essential elements needed to understand the overall structure/shape as a whole). Instead, guideline G3 refers to individual elements (particulars of the monument/artwork), which may have a certain importance in terms of education and understanding. More specifically, the models of the whole buildings should be firstly provided. Then, it should be equipped with what cannot be perceived in the main model because of the limited scale. These additional details should be reproduced individually on a larger scale to allow perception - and therefore understanding - through touch also in terms of details. Thus, although these two guidelines (G1 and G3) seem to be in contrast or seem to say the same thing, in fact they complement each other and refer to two different aspects of the model and therefore of perception. On the one hand, G1 gives indications on the simplification of a more articulated and complex general model in order to be able to perceive it as a whole especially by touch. On the other hand, guideline G3 focuses on the need to reproduce some parts or components of the model in such a scale as to be able to explore those details that may be important for learning certain concepts. Therefore, this guideline (G3) specifies the importance of reproducing in a large scale some particulars which risk not being perceived if reproduced in the same scale used for the overall model (as indicated by G1).

For example, to make details recognizable by touch, the particular features such as a two-light or three-light windows, or particular shapes for doors or arches should not be included in the global model, but in the separate reproduction in a larger scale. So for a clear perception of the details of an object, it should be designed in a larger scale separately from the global model. Examples are the reproduction of capitals, doors and windows, individual small objects such as leaves or little decorations. Appropriate geometrical scale and some comparative elements could be considered in the design in order to better perceive the elements. This approach is linked to the guidelines (2 and 4) proposed by Holloway.

G4: Use distinguishable elements to make a distinction between different kinds of semantic information.

Use diverse symbols, materials, shapes and colours for varying semantic typologies of information. By semantic information we mean contents which can be grouped according to a certain context, meaning or semantic field. For instance, different semantic typologies can be provided when delivering information to the visitor: practical, architectural and historical. Buttons with different shapes and colours can be used for each typology (e.g. a circle for practical information, a triangle for historical, and so on). This can aid the user in easily and quickly identifying each category. The shapes herein suggested for the buttons are just an example. The designer may use different shapes, provided they are clearly distinguishable from each other. To ensure a good understanding of their usage, it is important to provide a clear explanation of their use in the welcome instructions. Moreover, these instructions should be by hand at any time. A specific well detectable button could be used to provide those instructions. Similarly, different materials can be used to give information on various contents, such as a very smooth material might be used for reproducing marble or glass, or a rough texture can help in perceiving asphalt or grass. Many other examples can be provided to introduce various typologies of contents to be provided. This allows the user to perceive specific parts and components more easily. This guideline is a specification for 3D reproduction of the guidelines (1, 2 and 4) proposed by Holloway [27].

This guideline can be applied via different approaches:

- *Different materials and textures*: If the tactile model to be reproduced consists of several parts with various components, different materials and/or textures help to make the different components more distinguishable by touch. Different textures and materials help the user in recognising specific parts or details.
- *Different shapes for distinguishing semantic contents*: Use different and distinct shapes to convey semantic information in order to enrich the three-dimensional model. For instance, use buttons with different shapes to associate them to different information and contents.
- *Chromatic contrast and varied colours*: Colour the various parts and components of the model in different ways. Ensure a good colour contrast to increase perception. Partially sighted users are helped both by the contrast and by the different colours in identifying the various parts that make up the model.
- Distinct audio tracks to categorise various typologies of information or different levels of detail.

G5: Keeping content and layout consistency across diverse elements.

Consistency is in general important for the user. This is particularly significant for visually-impaired users because they rely on consistency features. Consistency is a usability feature that allows users to better understand the context and available functions. It is important that all the components of the whole model adopt the same actions for buttons performing the same tasks (e.g., circle for practical information, triangle for historical contents, and square for architectural descriptions), and that buttons performing the same typology of action (e.g. all circle buttons related to the different monuments) have the same layout (e.g., dimension, shape and colour).

The same can also be applied to the terminology for the audio descriptions or materials used for reproducing various textures. Using shapes, materials, textures or terms inconsistently can create confusion in understanding and perceiving objects and contents. The consistency has already been considered for tactile 2D graphics by BANA [5] in guideline 2.18 about the terminology and texture. Our guideline extends the concept.

To sum up, Guideline G4 suggests using different features to distinguish different elements (e.g., a circle for practical information, a triangle, for historical, etc.), whereas guideline G5 requires that the elements with the same functions (e.g., all the buttons associated to the practical information) be consistent by keeping the same layout, i.e. shape, size and colour (e.g., the circle shape).

This guideline specifies in some way the guideline 5 in [27].

Thus, when designing the model consider:

- *Location of elements*: Specific elements, such as buttons or keys, must be placed in well-defined positions. The chosen places must remain consistent throughout the model. For example, the buttons used for the audio information of a monument can be placed on the right of the basis of the monument itself. The same location must be chosen for each monument. Follow this criterion as much as possible. This helps the user to better localize the buttons.
- *Shape of the elements*: preserve the same shape selected for a given semantic information type throughout the model. For instance, if a 'circle' button is assigned to practical information, use this shape for the same task for each object. Keep the consistency for all shapes used for the various purposes and functions.
- *Terms and terminology*: Be consistent with the terminology used in the initial instructions, and also in all the contents used to enrich the model.

Principle 3: Understandable

Contents, information and the operations on the model must be understandable for a wide variety of people. The guidelines proposed to apply such a principle are mainly related to how to design the info content as well as how to structure and use it in the model.

G6: Add contents to enhance model understanding.

To enrich the model, in-depth contents and practical explanatory information can be added. The additional contents should provide explanations of different nature, such as practical instructions, historical and architectural insights, and specific details. Alternative and more detailed descriptions on visual features and aspects could be specifically useful for visually-impaired people. This guideline extends the guideline (1) proposed in [27].

In preparing additional contents consider:

- *Audio contents*: record multi-tracks contents to associate with the model components and details. The tracks should be structured according to semantic information (see next point), and on the basis of a multilevel description of artworks and details. Additional audio descriptions should be well prepared and structured in order to provide different levels of details and information to the user so as to better understand the layout and outline or any other visual elements, which could difficult to distinguish. For example, consider providing a first general level to describe a building, a second one to provide some details (e.g. information on windows and decorations); the third level for further details, such as the description of each typology of window, a further visual description of some additional information on architectural elements, etc. (e.g. how the two-light or three-light windows, the arches, and so on).
- *Semantic information*: group contents based on semantics, such as historical, practical, architectural, descriptive information, etc. This helps the user to choose the contents to listen to according to their own interests and needs (e.g. a user could choose to listen to practical information rather than historical contents).
- *Caption and additional key*: code and report elements aimed at supporting the user in understanding each haptic or audio object, or any other content available on the model. For instance, write in braille code the building names (or an abbreviation) and code other elements, such as indications on how the cultural site (i.e. the model) should be explored.
- *Comparing elements*: to understand the size of an element, it should be related to a type of well-known object. For example, to understand the height of a column, it can be compared to a reproduction in scale of a person to help the user to understand the size.

The additional contents can be added to the model through (1) ad hoc hardware buttons located near the object which the information refers to, or (2) commands and gestures designed for the user interface of a mobile app – if the model is handled by an app. These modalities are a specification for the guidelines (7, 8 e 9) proposed in [27].

G7: Structure audio contents into different detail levels.

Any type of information and contents should be made available at a variety of levels. This helps the user to read contents according to their personal preferences. The contents should be recorded in multiple audio tracks structured in multiple levels of detail. The first track will give basic information. The following tracks will contain insights and further details. The user can decide to read up to the desired level, otherwise if the user is interested in a specific topic, they can move ahead by listening to the following tracks. Alternatively, the listening can be stopped at the current level. On the contrary, a single description/track would require the user to listen to it entirely or to stop at a random position. More structured information offers the opportunity to enrich the contents up to the level of interest. This approach specifies in more detail guideline 9 proposed by [27]. Furthermore, the following points also address guidelines 7 and 8.

In reading the contents, the user must be able to:

- *Play and pause*: the content should be activated and stopped at any time based on user preferences.
- *Go forward and skip*: the content must be navigable. It must be possible to go ahead and skip descriptions.

An example to apply a solution which incorporates these properties consists in designing (1) ad hoc hardware buttons to navigate and play and pause – if the contents are handled directly by the 3D model – or (2) commands and specific gestures to interact with the interface – if the contents are controlled by an app working with the 3D model.

G8: Make available some simple initial instructions (welcome track).

Initial hints should be given to the user about the use of the model as a whole. They should be recorded in audio form on a “Welcome track”, which the user can listen to at the beginning and each time needed. In preparing the welcome track consider:

- *Short length*: The initial track should be short. If listening to it is time-consuming, the risk is that the user will not pay attention to the crucial concepts and indications.
- *Simple terminology*: The language should be very simple. Use short sentences to describe the model and the main actions available as well.
- *Accessible at any time*: Crucial hints and instructions should be easily accessible at any time and close at hand. The user should be able to listen to them at any time. For instance, an easy-to-locate button could be assigned to the initial track.

This feature could be developed through a (1) dedicated easily detectable button; (2) the presence or movement sensor; or (3) a command or specific gesture available on the user interface of the mobile app.

8 CONCLUSIONS

In our study we considered an interactive 3D model as a support tool for the exploration of an environment - in this case a cultural site – by visually impaired and sighted people. Visually impaired people do not have the same opportunities as sighted people in having an overview of a cultural site especially if these include buildings and large monuments. For this reason, three-dimensional models have been increasingly proposed to help those who cannot rely on sight for this perception. In addition to 3D tactile exploration, we intended to investigate the opportunity to augment the information in order to extend the experience of the exploration to both those who can see and cannot.

In summary, we have presented the results of a study on the effectiveness of an interactive 3D model equipped with audio tracks in helping visually impaired and sighted people to understand the global structure and appreciate important details of a cultural site. The model is designed to be easily replicable and low cost. Our testbed is a 3D interactive reproduction of ‘Piazza dei Miracoli’, the famous square in Pisa where the Leaning Tower is located. The prototype was evaluated by 24 users through a user test: the model was explored by 8 visually impaired people and 16 sighted people. The evaluation given by the participants was overall good, especially considering that this was a new experience for sighted people. Nonetheless, the tests revealed that audio contents were considered very useful by all the users. The structured multi-level tracks and semantic information were particularly appreciated by the users (a=4.6 for sighted users, a=4.7 for visually impaired users).

Based on our experience and on the results of this study, in this work we propose a set of guidelines aimed at designing 3D interactive tactile models as a tool to explore spaces and environments (e.g. for other cultural sites) by both sighted and non-sighted people. The 8 guidelines proposed take into account the main aspects related to the exploration of a model: (I) reproducibility, (II) perception, and (III) understanding. The proposed set of guidelines intend to be a first step in the formalization of suggestions and indications to consider when designing an interactive and augmented 3D model aimed at supporting the exploration by everyone, especially by those who cannot rely on sight to perceive a site.

The interactive 3D prototype proposed in this work is mainly oriented as a supporting tool for visitors of a cultural site or museum. However, the idea herein proposed can be applied for other cases, such as topics in educational and learning fields. The prototype has been designed so that it can be used without any specific skills or additional tool. The visitor can approach the model and interact with it using the tools made available on the model itself (e.g., sensors and buttons). However, the model could be further extended through specific applications that are able to work with the model itself and at the same time can be installed on the user's personal device (e.g., smartphone or tablet). This would overcome the current limitation of the model in relation to the number of users who can interact simultaneously with the model itself.

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APPENDIX - QUESTIONS COMPOSING THE QUESTIONNAIRE ON LINE

Personal information

1. Gender
2. Age
3. Educational qualification
4. Field of study
5. Type of disability
6. Do you like art? (1..5)
7. Do you often visit museums or cultural sites? (1..5)
8. Which monuments of the square did you visit inside? (Baptistery, monumental cemetery, cathedral, Leaning Tower)
9. Do you know the cultural site of Piazza dei Miracoli? (Yes No)
10. Have you ever had the chance to touch a 3D printed element before? (Yes No)
11. Have you ever interacted with an interactive 3D touch device before? (Never, Sometimes, Often)
12. If you answered yes, can you give an example?
13. Are you familiar with audio guides? (1..3)
14. In what context did you use an audio guide? (Museum, Exhibition routes, Other)

Prototype evaluation

15. Did you find the operation of the model intuitive? (1..5)
16. Did you find the initial welcome trace that introduced the layout of the model clear? (1..5)
17. If you answered 1 or 2 to the previous question, indicate why.
18. Did you easily identify each monument? (1..5)
19. If you answered 1 or 2 to the previous question, what were the main difficulties you encountered?
20. Did you find the buttons easily? (1..5)
21. If you answered 1 or 2 to the previous question, what were the main difficulties you encountered?
22. Did you understand that the buttons have different shapes? (Yes No)
23. If you answered yes to the previous question, select the type of button shapes (Rhombus, triangle, ellipse | Parallelepiped, rectangle, circle | Trapezium, circle, square | Circle, triangle, square | Pentagon, triangle, rectangle | I don't remember | other)
24. Each button has a different type of information associated with it. What kind of information does the circle give? (Practice | Historical | Architectural)
25. Each button has a different type of information associated with it. What kind of information does the triangle give? (Practice | Historical | Architectural)
26. Each button has a different type of information associated with it. What kind of information does the square give? (Practice | Historical | Architectural)
27. Did you find the audio tracks clear? (1..5)
28. If you answered 1 or 2 to the previous question, indicate why
29. Did the size of the monuments allow you an easy tactile exploration? (1..5)
30. Did you find architectural details printed on a larger scale useful? (1..5)
31. Did you understand when to touch the architectural details placed near the model? (yes / no / only for some details)
32. If you answered "no" to the previous question, indicate why.
33. Do you think the audio support was useful for the purposes of the interaction? (1..5)
34. Could you recognize the type of material of the objects you touched? (Yes No)
35. If you answered yes to the previous question, could you indicate which ones?
36. As you explored the model, did you perceive that the exploration was improving?

Overall evaluation and suggestions

37. The functioning of the model was clear without difficulty (1..5)
38. If you answered 1 or 2 to the previous question, indicate the difficulties you encountered.
39. Evaluate the interactive touch device as a whole. (1..5)
40. If you answered 1 or 2 to the previous question, indicate why.

41. Would you find it useful to insert a model of this type in cultural sites and / or museums as an aid to facilitate learning? (1..5)
42. Indicates at least one thing you liked least
43. Indicates at least one thing you liked most
44. What changes and / or improvements would you make to the interactive touch device?
45. Do you have comments, comments or suggestions?