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Enabling Access to Cultural Heritage for the visually impaired: an Interactive 3D model of a Cultural Site

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Abstract

We have developed low cost interactive 3D models that improve access to architectural details of cultural sites for all, including people with vision impairments. Our approach uses rapid prototyping and 3D printing along with a very small single-board computer for automating user interaction. As a case study, we developed a prototype model of "Piazza dei Miracoli" (Pisa, Italy), the famous square where the Leaning Tower is located. The system is a combination of tactile information with audio descriptions to enable potential users to explore the artifact autonomously. We exploited low-cost and partially open-source technologies, thus rendering our system easily replicable. We evaluated the interactive system with a group of eight completely blind and partially sighted users. Our user test confirmed the validity of our approach: (1) the three-dimensional models and the tactile reproduction of details obtained via a low-cost 3D printing solution are well perceived by touch; (2) the semantic aural 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.

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Keywords: Intelligent Interfaces; Interactive Audio Guides; 3D Modeling; 3D Printing; Blind People; Rapid Prototyping; Accessibility;

1. Introduction

Access to the cultural heritage is being facilitated through new technologies that allow the reproduction of objects in different formats. Many applications are available in the field of virtual digital reproduction, however,

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most of them are visually oriented and are not suitable for the visually impaired. Fortunately, the evolution of 3D printing technology has opened up new opportunities for reproducing tactile models that also enable people with visual disabilities to access cultural sites, monuments, and any other object that can be reproduced to facilitate a tactile experience[1,3,14,15,16]. However, using tactile 3D models may not be enough to access all the details of a cultural site[6]. In fact, the correct understanding of a 3D reproduction is affected by personal skills, as well as the size (compared to the original), 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 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.

Our aim is to enable sighted and visually-impaired people to perceive the important details of large cultural sites, 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). We use an interactive three-dimensional model for the site, along with a set of separate models for the architectural details which cannot be included and perceived correctly in the main model. We also enrich the tangible exploration with individual short audio tracks on specific topics, thereby avoiding the frustration experienced when being forced to listen to very long audio tracks that describe everything. The main goals of our approach are to: (1) propose a reproducible strategy to build 3D tactile models for large cultural sites using a low cost solution through 3D printing technology; (2) test out a combination of tactile perception and semantically differentiated audio descriptions suitable for various types of users and interests; (3) make the user experience more comfortable through more identifiable and perceptible buttons and using different materials for the objects reproduced with different tactile effects. Essentially, our aim is to make an interactive 3D tactile model accessible to both sighted and visually-impaired users.

In addition, the model needs to be able to be explored autonomously by all users, so that it could also be used before the actual visit to a museum or cultural site. In fact, our model could be used as follows: (1) to prepare the user for a visit to a cultural site, providing an overview via a guided tactile exploration; and (2) to facilitate the explanation and learning by visually impaired people who often do not have the opportunity to directly perceive certain details, such as the architectural elements. Importantly, this can be done without the help of a third person, thus improving the level of social inclusion and autonomy of visually impaired people.

This paper reports the results of a user test that we conducted with eight visually impaired users to understand the level of user satisfaction. As a test case, we chose 'Piazza dei Miracoli', a very famous square including the Leaning Tower located in Pisa (Italy). In our model, we reproduce the layout of the buildings in the square rather than the entire buildings - the aim is to give users an overall idea of the relationship between one building and another, and then to understand the layout of each individual building. To achieve this, we reproduced the ground floors of the four monuments in the square: the Cathedral, the Leaning Tower, the Monumental Cemetery and the Baptistery. For some of the monuments, we also reproduced some details, such as the dome or the capitals, on a larger scale. 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.

The paper is organized as follows. Section 2 discusses various related works, i.e. similar projects to ours but which are less comprehensive compared to our approach. Section 3 describes our methodology. Section 4 presents the interactive prototype used in the test. Section 5 details the user test conducted. Section 6 reports the objective and subjective test results, and Section 7 concludes the paper.

2. Related Work

Although there are many projects aimed at providing the visually impaired with a multimodal interaction to increase access to artistic and architectural contents, most solutions do not consider 3D interactive modelling. For instance, Poppinga et al.[9] investigate a combination of vibration and speech feedback which can be used to make a digital map on a touch screen more accessible. Wang et al.[13] created a prototype of a tactile-audio map based on a combination of a tactile hardcopy and a SVG file used together to provide an interactive access to a map image through a touchpad. The result is a tactile-audio representation of the original input image.

These approaches, along with other ones like the studies presented by Brock[1] and Senette et al.[12], propose interactive tactile approaches which are not based on true 3D models, since they adopt a 2D touchable format in which the representation is basically 2D with some parts in relief. In our study, we combined a 3D modelling approach with audio descriptions in order to enrich the interaction of visually impaired people. We will now analyze some more similar systems to ours in more detail.

Tooteko[3] 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. The system has a high-tech ring, a tactile surface tagged with NFC sensors, and an app for tablet or smartphone. When the ring reaches a 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[15] proposes a similar approach.

In both these projects, the sensors that trigger the audio tracks are integrated within the model itself. This has some important drawbacks. First, while listening to an audio track, the user can easily jam into another hotspot, thus stopping the current track and triggering a new one. This is annoying since blind people often use both hands when exploring a 3D object and listening to audio tracks[7,8]. Moreover, integrating sensors within the model is very costly, which may be prohibitive for small museums or cultural entities. Finally, these approaches entail the participation of 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 any interesting details that cannot be included in the main model.

3D Photoworks[14] proposes a different approach. Color 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[2,10]. Depth cameras, placed above the tactile template detect the movement of the user's hands. The main disadvantage of these 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 speed increases, the position of the hand is easily lost and users can become very frustrated.

Despite their limitations, all these systems represent an important first step towards real access to architectural sites, using tactile interactive models. Our approach, explained in Section 3, tries to overcome these problems by designing a low cost solution and moving the audio track activation outside the 3D model, while still using sensors to activate the tracks.

3. Methodology

Our approach consists in reproducing an interactive 3D model to explore the floor plans of monuments, rather than the main structure of the buildings. The reason for this is the lack of floor plans and reproductions of indoor monuments that are perceivable by touch. Likewise, the lack of detail provided by a tactile reproduction stimulated us to try to overcome such problems. These types of reproduction (floor plans and details) can in fact, be very useful for learning and perceiving details which are usually neglected for visually impaired people.

To develop the 3D interactive model, we focused on how to (1) design the digital models, (2) print and assemble the tangible models, and (3) make the system interactive and auto-explicative.

For instance, during the participative design with a totally blind person, we noticed that there was a minimal distance between two 3D objects (e.g. columns) which needed to be maintained in order to allow the visually impaired to perceive them correctly with the touch. Our system is built according to a modeling methodology based on source-based modeling. The 3D model can be developed using two different approaches in order to capture the artwork (monument, statue, etc.) structure: (1) reality-based, such as via laser scanning or reflex camera[11]; (2) source-based, via a digital representation of a work using computer graphics[4]. Through this second approach, we can also 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 our case study, the work is simplified for a small scale reproduction. We thus preferred to use a source-based approach, which is faithful to its original architectural plan and to the historical facts, and we decided not to reproduce details that might not be easily perceptible by touch. For more details on our approach and how the prototype was designed and developed, see our previous paper[17].

In brief, our methodology stems from the following phases:

- *Simplifying the digital models*. Preparation of a simplified digital model of the cultural site and monuments to be reproduced in the 3D format is the first phase for reproducing the tactile model. Simplifying and selecting dimensions are the two crucial aspects of this phase. In preparing our prototype, we followed guidelines and standards for tactile graphics[5]. However, these guidelines refer to the constructions of 2D models, thus we devised and added some rules especially related to 3D. For example, details and decorations should be removed from the digital model. Some of them should be reproduced separately with larger dimensions in order to provide details and additional concepts (see the next phase). Dimension selection entails deciding the minimum amount of space to be left between two elements in the model so that they are perceivable by touch by a finger tip. For example, in our model, we considered a one centimeter space between the columns and for the entrances.
- *Selection and choice of the details to be reproduced in a larger scale*. In this phase, we decided on the main elements that should be reproduced separately in a larger dimension. This may depend on the main purpose of the system, i.e. learning or visiting. It also strictly depends on the model features. In our case, elements such as arches, capitals and a leaf of the columns/capitals were reproduced in a larger scale so that they are easily perceivable by touch.
- *Printing, refining and assembling.* In this phase, the main task is to adapt the models to the characteristics of the 3D printer at hand (e.g. the maximum size of a printable block). For our prototype, the monuments were printed separately, smoothed, and assembled on a wooden table (see Fig. 1).
- *Semantic tangible buttons and audio contents.* According to the types of information to be reproduced for each monument, this phase addresses the following points (1) the design and printing of the various buttons to be located in well-defined positions; and (2) the preparation of the audio contents (tracks) to associate with the buttons. In our case, we opted for three buttons with different shapes located near the entrance of each monument. The buttons were printed and the audio tracks recorded.
- *Model interactivity*. The last phase consists in linking all the elements together to make the model interactive and usable by a visually impaired person autonomously for example by using sensors such as Raspberry or Arduino. In our model, we used a Raspberry PI 3 to orchestrate audio tracks, as detailed in Section 4.

4. The interactive 3D system

We applied our methodology to a tangible 3D model of the four monuments located in “Piazza dei Miracoli” in Pisa, Italy. The challenge was to deal with the fact that each monument has a different floor plan: (1) the central floor plan of the Leaning Tower and the set of columns outside; (2) the Latin cross layout of the Cathedral of Santa Maria Assunta; (3) the rectangular layout of the Monumental Cemetery; and (4) the central layout of the Baptistery. When visiting Piazza dei Miracoli, the arrangement of the various buildings in the square and the walkways that link them together are clearly visible for a sighted person.

Our goal is to deliver a similar perception of this overall arrangement for visually impaired people. To achieve this, we reproduced a 3D model of Piazza dei Miracoli, including the four monuments. 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. We were thus able to show the section of the perimeter walls and of the columns, which are key to understanding the overall architectural setting (see Fig. 1). This tactile reproduction allows visually impaired people to perceive the thickness and position of the columns, the fact that the central nave is higher than the side naves, the position of different sets of arches, and so on.

Our model is designed to enable users to be entirely autonomous in their exploration of an artwork. To meet this aim, each piece of information is provided through both tactile information and audio. The visually impaired should be able to explore the model by touch and to activate an audio description related to a specific monument/detail. 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[18] or Balabolka[19]. This means that the content can also be in different languages.

The device used to manage the interaction user-3D model is Raspberry PI 3, a single-board computer that is a few centimeters wide, with general purpose input/output capabilities. Raspberry is relatively inexpensive and is equipped with WiFi, Bluetooth and several IO pins. The wiring can be simplified using wireless speakers and activating the pull-up and pull-down internal resistors to implement various interaction modalities with the physical buttons. The software is based primarily on Python, is easy to use, and can be easily maintained and 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.

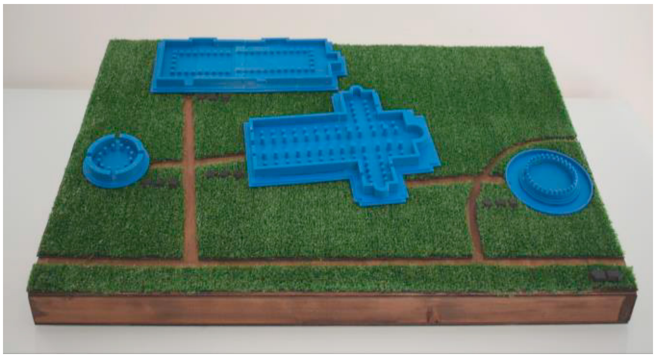

Fig. 1. Left: the model for Piazza dei Miracoli. Right: interaction with the cathedral dome

The Raspberry is fixed below the prototype. Aural descriptions are activated by buttons placed next to each model (e.g. near the main entrance of each monument in Fig. 1.left). Buttons are connected to the Raspberry with cables. In our prototype, each model has three buttons next to each other. These are easily detectable via 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 aural 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 user is interested in more detailed information, he/she can press the button again to listen to the second track, which gives more details. In general, each button is associated with a set of aural tracks ordered according to the level of detail. Each time a button is pressed, it starts to reproduce the following tracks in the sequence. Each user can thus choose how to explore each monument according to his/her interests and 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 itself. 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 person) appears within a distance of between 0 and 50 cm, the sensors send the Raspberry the information, and the welcome audio track is activated.

The user is autonomous in deciding the times and the ways to interact with the other audio tracks. A press on the button activates the corresponding track. The user can then navigate the tracks pressing the same button again. The current track can also be suspended by pressing a pause button placed at the bottom right of the prototype.

5. The user test

5.1. Overview

In order to evaluate the impact of our proposed approach on 3D exploration by visually-impaired people, we conducted a user test with our 3D interactive prototype. A group of eight visually-impaired end users was recruited through the local Association for the Blind. The evaluation was conducted in order to collect data on their impressions, difficulties, and other general feedback, relating to their interaction with the prototype. 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 users were given an explanation of the background to the study and the main features of the 3D models. They were then provided with a brief exploratory five minute session to become familiar with the system; no explanation was given about how the model worked since the prototype was designed for total autonomous use. The main description of the models, buttons and their functionalities are given in the first audio track (two minutes long). The scenario is similar for anyone who interacts autonomously with the 3D interactive reproduction before starting their real visit in order to get an overview of the cultural site.

5.2. Participants

The test involved eight visually-impaired people (7 males and 1 female) with an age range of between 40 and 70. 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. Experiment

The test environment consisted of the 3D interactive prototype equipped with a pair of speakers 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.

Users were asked to perform seven tasks while interacting with the prototype. The tasks were aimed at collecting feedback on the main interaction experience especially in terms of a new user visiting the museum/site for the first time. A member of the research team proposed 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.

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 are related to specific audio information typologies. Tasks 2 and 3 verify whether the scale for reproducing the buildings is adequate for perceiving the key elements by touch. Task 4 assesses the usability of the levels of the audio tracks: level 3 associated with the quadrangular button links the main model with the board of the architectural details reproduced in a larger scale. Task 5 elicits user feedback on the architectural details, their reproduction, the selection made, and the level of details designed. Task 6 assesses how well users perceive the building elements and can orient themselves among the monuments and elements. 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.

For each user, we recorded 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 rated on a scale from 1 (the most negative value) to 5 (the most positive value).

6. Results

6.1. Objective data

We gathered quantitative data on the level of success and time involved in carrying out the tasks. The time spent acts as an index to assess whether the interaction might be useful for helping a new visitor to explore the artworks in a museum before starting the visit. User satisfaction and experience were collected by taking notes while the user was carrying out the tasks, and through the questionnaire.

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 by each user varied from 12 minutes to 1 hour (a=28.38 minutes, sd=15.28).

Two outliers are related to those tasks which presented various issues for many users (see Fig. 2.left):

Task 1: to perform this task, User 8 took 00:00:45 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 its components.

Task 4: User 4 took 00:02:28 minutes 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 00:00:20 and 00:00:16 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 (00:01:59 minutes). 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.

6.2. Subjective data

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. 2.right).

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 he 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 motivation to encounter difficulty in the welcome track understanding which they had been expecting 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 the 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; many users preferred 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) location of the board containing the 3D details; (2) some movement-sensors were 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 why one might be 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 scale of the buildings; most users (6) found the scale to be sufficient for the interaction, although a larger scale would have been preferable. (2) Colour contrast; a greater contrast would be better. (3) The reproduction of the floor plans of the buildings, but also for the layout of the main sculptures at the site.

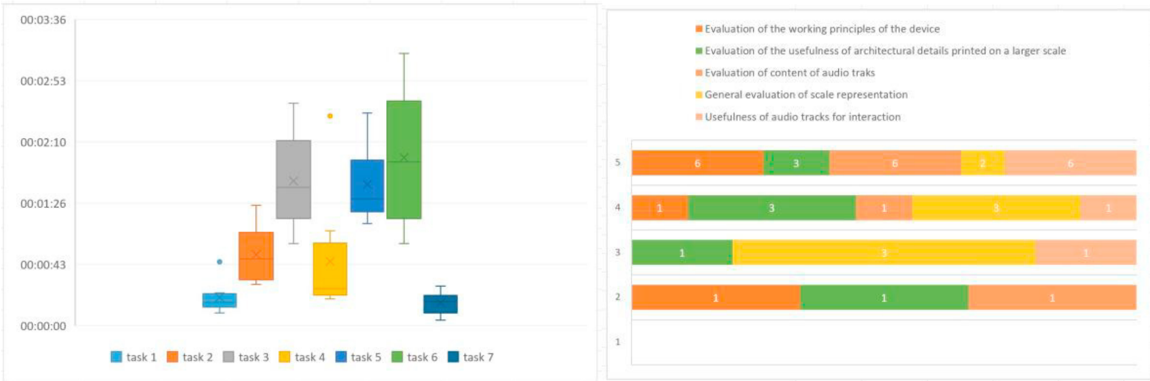

Fig. 2. Left: Completion times of the seven tasks: Right: Overall assessment of interaction experience

7. Conclusions

We conducted tests with eight visually impaired users in order to evaluate the effectiveness of our interactive prototype for enhancing the experience of visiting a cultural heritage site. The test confirmed the validity of our approach: all the users completed the assigned tasks in a reasonable time (averaging around 28 minutes). The 3D models were perceptible by touch, though some users would have preferred a larger scale. Users appreciated the specific details of the monuments and elements that were reproduced in a larger scale. The structured audio tracks and the easily identifiable buttons were clearly perceptible by touch and were positively valued as they enable the visitor to focus on what they really want to listen to.

The user questionnaire highlighted possible further developments and improvements, such as using real materials to make the touch perception more realistic and making the system multilingual.

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