An Independent and Interactive Museum Experience for Blind People

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ABSTRACT

Museums are gradually becoming more accessible to blind people, who have shown interest in visiting museums and in appreciating visual art. Yet, their ability to visit museums is still dependent on the assistance they get from their family and friends or from the museum personnel. Based on this observation and on prior research, we developed a solution to support an independent, interactive museum experience that uses the continuous tracking of the user's location and orientation to enable a seamless interaction between Navigation and Art Appreciation. Accurate localization and context-awareness allow for turn-by-turn guidance (Navigation Mode), as well as detailed audio content when facing an artwork within close proximity (Art Appreciation Mode). In order to evaluate our system, we installed it at The Andy Warhol Museum in Pittsburgh and conducted a user study where nine blind participants followed routes of interest while learning about the artworks. We found that all participants were able to follow the intended path, immediately grasped how to switch between Navigation and Art Appreciation modes, and valued listening to the audio content in front of each artwork. Also, they showed high satisfaction and an increased motivation to visit museums more often.

CCS Concepts

•Human-centered computing → Empirical studies in accessibility; Accessibility technologies; •Social and professional topics → *People with disabilities;*

Keywords

Museum accessibility; visual impairments; indoor navigation; art appreciation; non-visual interaction; interactive space.

1. INTRODUCTION

Museums are increasing the accessibility of their exhibitions and artworks to people who are blind through specialized tours [20, 33] and the access to tactile representations of artworks [31]. These efforts are motivated not only by laws (*e.g.*, the Americans with Disabilities Act (ADA) [34]) stating that museums should be accessible to people with disabilities, but also by the interest of blind people in

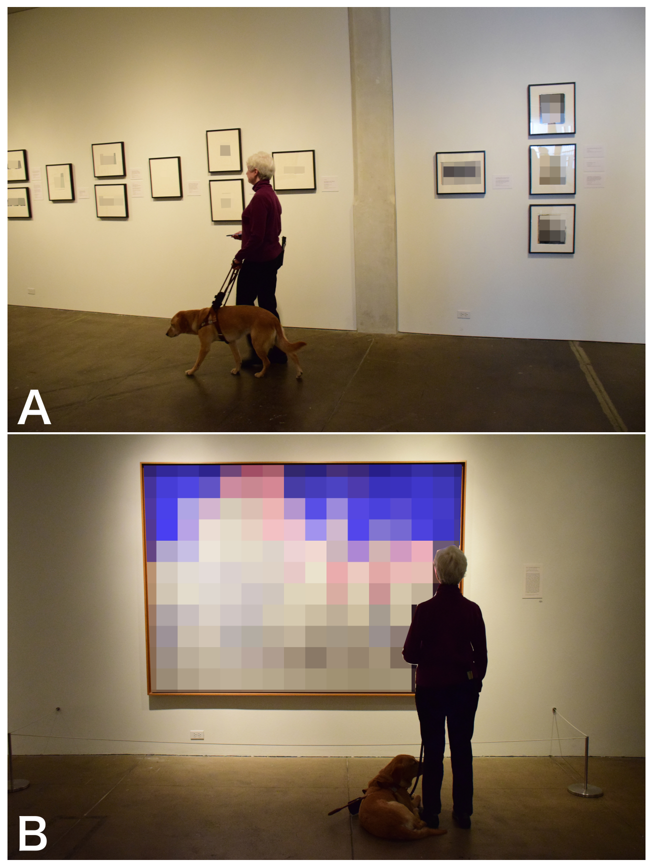

Figure 1: The continuous tracking of the user's location and orientation enables a seamless interaction between Navigation (A) and Art Appreciation (B). In (A), a guide-dog user receives turn-by-turn instructions and is informed about artworks within close proximity (*e.g.*, *Do it yourself (Sailboat) is on your right*). After turning her body to face an artwork within close proximity (B), the system automatically starts describing the artwork.

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visiting museums and enjoying visual art [3, 9, 18, 19]. Yet, their ability to visit art museums is still dependent on the assistance they get from their family and friends or from the museum personnel.

A potential solution to increase the independence of blind people in museums is the use of indoor navigation systems. Current smartphone-based solutions are now able to accurately localize the user [30] in the environment and are being installed in locations such as shopping malls [39], universities [36] or transportation hubs [11, 15]. These systems often focus on turn-by-turn guidance [39, 42] or rely on gesture-based interaction to navigate among lists of nearby Points-of-Interest (POIs) [7, 23]. However, the challenges of an independent museum experience go beyond navigation as the main goal is art consumption or appreciation. Nevertheless, accurate navigation assistance is still important since blind people value listening to audio content while they are near the respective artworks [19].

In this paper, we present an interactive museum solution for blind people that combines indoor navigation assistance and accessible audio content of visual art (Figure 1). For that purpose, we adapted an open-source smartphone-based navigation app [39] that uses Bluetooth Low Energy (BLE) beacons and the smartphone sensors to accurately localize the user.

We use the continuous tracking of the user's location and orientation alongside the awareness of the surroundings to interpret the spatial relationships of the interactive space [5, 41]. Based on this knowledge, the user is able to seamlessly switch between two interaction modes: 1) **Navigation**, where the user receives turn-by-turn instructions (e.g., *turn right*) and information about the location of artworks (e.g., *'Do It Yourself (Sailboat)' is on your right*); and 2) **Art Appreciation**, where the user is able to listen to audio content of artworks, just by turning the body (the smartphone) to face a particular artwork.

In order to obtain feedback and test our solution, we installed it in The Andy Warhol Museum and conducted a user study where nine blind participants followed interest-based routes prepared by the museum personnel. We found that all participants were able to follow the intended path, showed high satisfaction rates, and an increased motivation to visit museums more often either by themselves or with sighted peers. In particular, they valued being able to listen to audio content in front of each artwork and to use their body orientation rather than gesture-based touchscreen commands to switch between navigation and art appreciation.

2. RELATED WORK

Current efforts carried out by museums to make their exhibitions more accessible to blind people usually fall into three main categories: guided tours, accessible tactile experiences, and comprehensive audio descriptions. Some museums provide specialized tours or workshops [20, 33], while others allow to *negotiate* a specific time for accessible visits [25]. Other museums either specialize in tactile art for blind people [10, 35] or provide tactile replicas or reproductions of a subset of their artworks [14, 31]. In addition, recent research efforts include using 3D-printing to ease the process of building tactile models [40, 44], augmenting tactile reproductions with touch sensors [2] or replacing tactile reproductions with haptic exploration of virtual models [22]. Finally, the use of audio guides, either with proprietary devices or the user's own smartphone [8, 12], is ubiquitous in museums nowadays. Still, they usually target sighted people and are not designed with accessibility in mind.

In addition to these efforts, prior research has focused on location-based accessibility, by trying to guide the user or providing audio content in the proximity of artworks. For instance, *Ping!* [26] uses audio beacons placed near relevant artworks; the user can select the artwork using a cell-phone based interface and then navigate by following the *ping* sound. More recent efforts such as the iOS app OutLoud [14] allow users to select and listen to audio content based on the user's current location. Eyes-Free Art [38] tries to improve the user experience with proxemic audio, by changing the type of feedback (ranging from background music to a detailed verbal description) depending on the proximity with a particular artwork. Other solutions try to provide continuous navigation assistance for blind people in order to increase their independence. Blind Museum Tourer [29] uses Bluetooth Low Energy (BLE) beacons and tactile floor tiles to help guiding the user, while some approaches [13, 21] use specialized, portable devices to help localizing the user and provide step-by-step navigation instructions. Yet, the interaction between navigation and art appreciation is often left unexplained or is not explored at all.

Another relevant line of research focuses on interactive spaces (mostly for sighted people) by taking advantage of both location- and context-awareness. For instance, based on the *Proxemics* theory [17], researchers have been leveraging the continuous tracking of users' location and orientation to ease the interaction between people and other elements in the environment (*e.g.,* transferring files between people, or interacting with public displays) [5, 28, 41]. This theory addresses interpersonal spatial relationships and how they affect the interaction with others and with the surroundings. In a museum, visitors' motivation is to see the artworks, and proximity plays an important role not only for sighted people but also for blind people [19]. However, the challenges of an independent museum experience for blind people go beyond providing content based on the users' location, due to their needs for turn-by-turn guidance. For that reason, it is important to seamlessly integrate the need for accurate navigation assistance and the context-awareness that enables blind people to appreciate art as sighted people do. Moreover, in order to understand the effectiveness and impact of solutions aiming at improving museum accessibility, it is important to conduct user studies, with the target population and in a real-world environment (e.g., in a museum).

3. BLIND MUSEUM EXPERIENCE

Our main goal is to develop an interactive museum experience able to support a fully independent visit by blind people. In order to complement prior research on the experiences of blind people in museums [3, 9, 18, 19, 37], we performed a short survey with 19 people with visual impairments that aimed to understand their motivations to visit museums independently and the requirements for a system that would serve such purpose [4].

In our survey, we found that an independent experience is valuable because blind people can enjoy visual art at their own pace; they do not want to rely on their sighted friends all the time; and the quality of the visual descriptions is highly dependent on the person providing them. Most participants referred to the importance of having a navigation system in order to visit museums more often; and that they want to receive audio content in front (not just near) of the respective artwork in order to have the same experience as sighted people have. In addition, participants reported being comfortable both with synthesized speech and recorded human voices, showing no clear preference between the two options. As for the content of the descriptions, an introduction or summary of the artwork and both its history and detailed visual description were reported as the most relevant elements.

Informed by our survey findings and by prior research, we designed and developed a prototype system to support an independent, interactive museum experience for blind people.

3.1 Prototype System

The main requirements of our system are the ability to guide blind people along an intended path and to provide a way for them to enjoy visual art through audio content that thoroughly describes the artworks. In order to support both navigation and art appreciation, we developed a smartphone app that was extended from an open source project called HULOP[1].

HULOP's localization engine combines two techniques to accurately track the user's location and orientation [30, 39]: 1) multilateral localization using Bluetooth Low Energy (BLE) beacons; and 2) Pedestrian Dead Reckoning (PDR) using the smartphone accelerometer and gyroscope. Due to the unreliability of magnetometer measurements in indoor spaces, the orientation is estimated based on the BLE beacon-based localization history and the PDR trajectory. The main advantages of this solution are that users only need their own device (a smartphone), it is a cheap solution comparing to competitor alternatives (e.g., each beacon cost \$12-20 depending on order volume), and is known to provide practical accuracy (average location and orientation errors are about 1.5m and 12.4 degrees [6]) for turn-by-turn guidance to blind people [1, 39].

3.2 Seamless Two-Mode Interaction

The continuous tracking of the user's location and orientation allows us to interpret the spatial relationships between the user and relevant elements in the environment [5, 41], such as the route structure and the location of the artworks (that are manually annotated in our map). Based on this knowledge and on the fact that blind people want to listen to art content in front of the artwork, our smartphone app provides two interaction modes which activation depends exclusively on the user's location and orientation: Navigation, and Art Appreciation (Figure 2). During Navigation Mode, users receive turn-by-turn instructions to proceed in the intended path while being alerted about the artworks they are passing by. Art Appreciation Mode is activated when the users are next to an artwork and turn their body in order to face it, while Navigation Mode is resumed after turning their body to the previous orientation.

When the user is within close proximity of an artwork, changing between modes depends on the user's orientation. It is defined by equation (1), where θ_t represents the direction of the target point (an artwork, if changing to Art Appreciation Mode) and θ_u represents the orientation of the device held by the user. We defined T as 22.5° as it divides the frontal space into eight directions and is close to the angular error in estimating target directions reported in [27]. When changing back to Navigation Mode, θ_t represents the direction of the navigation path.

$$abs(\theta_t - \theta_u) < \angle T \qquad (1)$$

The system provides a short vibration and sound effect when the user reaches the correct orientation, which prevents users from performing slighter turns. In order to correct when the user overshoots the turn, we provide a "*make a slight right/left turn*" instruction when the user passes the correct orientation (also using T as the threshold).

3.3 Navigation Mode

The instructions provided during Navigation Mode are based on the smartphone app from the HULOP project, NavCog, as it is known to cause very few navigation errors [15, 39]. At the start of each segment, it reads the next instruction (*e.g.*, "*proceed 10 meters and turn left*"). When the user reaches the turning point, the system provides a verbal instruction (*e.g.*, "*turn left*") and a short vibration and sound effect. When the user completes the turn, achieving the correct orientation, the vibration and sound effect are provided again, followed by the next instruction. While the user is walking, the system provides information about the relative direction of relevant POIs within close proximity (e.g., "*Painting X is on your right*"). In our context, the most important POIs are the artworks, but can also be landmarks or obstacles that may affect the navigation (*e.g.*, "*a table is on your left*"). Examples of other POIs in navigation contexts are elevators, escalators, or restrooms.

[1] https://github.com/hulop

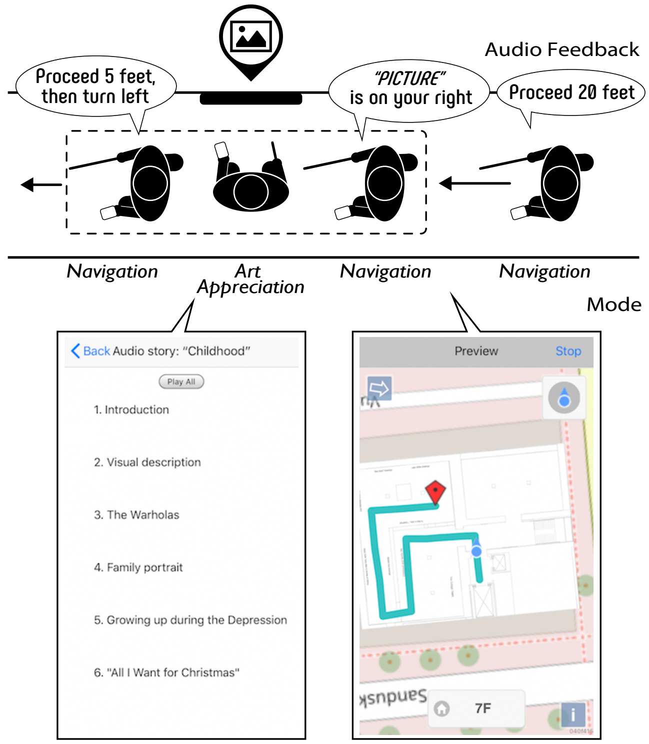

Figure 2: It shows the interaction between Navigation and Art Appreciation modes based on the user's location and orientation, with example audio feedback and screenshots of each mode.

Although NavCog provides periodic information about the remaining distance to a turn and an "*approaching*" message right before the turn, we found this to be prejudicial in our context when testing the app. Due to the small dimensions of our environment and to the high density of artworks, announcing an artwork would often be interrupted by a navigation command such as "*approaching*". Moreover, we found that the high localization accuracy and wide corridors did not require such announcements.

3.4 Art Appreciation Mode

When next to an artwork, the system alerts about its location (*e.g., "Photograph X is on your right"*). Users can then activate the Art Appreciation Mode just by turning to the respective side. After turning, the system starts reading the audio content automatically. This mimics the way sighted people appreciate art in a museum and goes towards the preferences of blind people to listen to audio content when in front of the artworks. The user can also perform gestures on the touchscreen in order to navigate through the audio content. For instance, a single tap would pause/resume, while right and left swipes would change to the next and previous chapter of an audio story, respectively.

Both previous research [3, 18] and our survey showed that the quality of the audio content is a crucial factor for blind people to enjoy their museum experiences. For that reason, all audio content was carefully prepared by the museum personnel and can be categorized into *Audio Stories* and *Text Content*. The content was created when designing an inclusive audio guide, *OutLoud* [14], which supported auditory descriptions, but not navigation. The museum personnel consulted with visitors - both with and without visual impairments - to design their audio guide content strategy. Their feedback influenced the design of the audio content, for instance, by breaking the audio content into chapters, instead of having a long description of an artwork as is often found in audio guides.

Audio Stories consist of recorded content that is part of the museum's inclusive audio guide. The speakers are scholars, curators, educators, or members of the artist's own family. Each story is centered around a theme, series of artwork, or time period, and includes an introduction, a visual description of a representative object, and several chapters of interpretive content. Previous research [14] and our survey [4] were used to determine the appropriate order to present the different chapters (*e.g.,* the introduction and visual description are more important than the details about the technique used and therefore are presented first). Users could navigate to the previous or next chapter by performing left and right swipe gestures on the screen, mimicking their usual interaction with VoiceOver (iPhone's screen reader).

Text Content refers to educational text, not available in the museum inclusive guide, that we included in the system to supplement participants' experience. It contains both visual descriptions and text that is visually portrayed in the walls of the museum, but is not accessible to blind people. Some of the *Text Content* provides a thematic overview of a gallery or collection of objects, while others might focus on a specific artwork. In our app, these are delivered with a synthesized voice.

In order to return to the Navigation Mode, users should turn their body to their previous orientation. When facing the correct orientation, the smartphone vibrates, makes a short *ping* sound and provides the next instruction (*e.g.*, *Proceed 5 meters and turn left*).

3.5 Installation at The Andy Warhol Museum

We deployed 28 BLE beacons at the seventh floor of The Andy Warhol Museum (see Figure 3) and built a localization model using HULOP's algorithm [30]. Moreover, we populated the map of the environment with the route structure and the location of the artworks and potential obstacles for navigation (our POIs). The Andy Warhol Museum [32] is the largest museum in the United State dedicated to only one artist, Andy Warhol. The museum contains an extensive collection of his art and archives which are varied from paintings, sculptures, photographs, films, and so on. The seventh floor includes mostly photographs and paintings/drawings places on the walls.

4. USER STUDY

We conducted a user study with nine participants (Table 1) who had at least 3 years of experience using iPhones. Participants used our prototype system on an iPhone 7 provided by the researchers with the built-in screen-reading software (VoiceOver) on Apple iOS 11. The iPhone's speakers, not earphones, were used so that the researchers could monitor their behavior more easily and check if the system worked properly. We wanted to run the study in a real-world environment, but at the same time to keep the study controlled. For that reason, the study was conducted when the museum was closed to the public so that the tasks would not be affected by the presence of other visitors (who could, for instance, block the user's path).

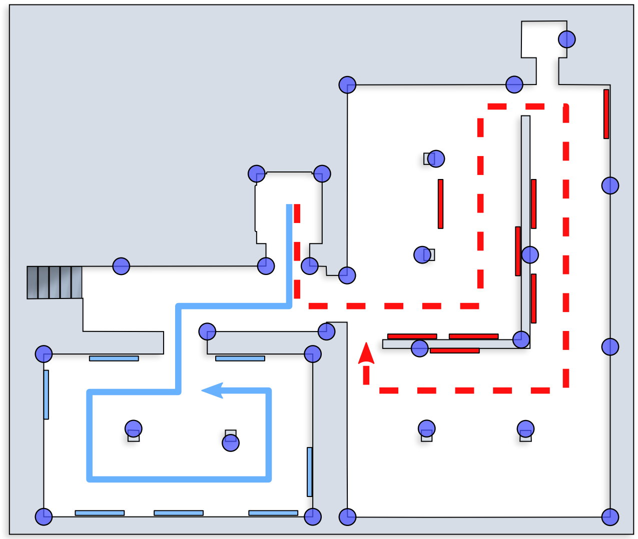

Figure 3: Map of the experimental environment and tasks; *Task 1*: Red dashed line, *Task 2*: Blue solid line. Artworks: flat rectangles; Blue Dots: BLE beacons

ID	Eyesight	Cane/Dog	Museum visits	Age	Sex
P1	Blind	Cane	A few / life	60s	F
P2	Blind	Dog	A few / life	60s	F
P3	Blind	Both	A few / life	40s	M
P4	Blind	Cane	Once / 2 years	70s	F
P5	Blind	Cane	A few / life	60s	M
P6	Blind	Both	Once / 2 years	30s	F
P7	Blind	Dog	A few / life	50s	M
P8	Legally blind	Cane	Once / a year	40s	M
P9	Blind	Cane	A few / life	50s	F

Table 1: Demographics of participants

This setting allowed us to understand the users' acceptance of the system, their opinions, as well as their performance in such optimal, controlled environment. The whole experiment was videotaped for further analysis.

4.1 Procedure

The researchers started by providing an overview of the user study and by describing the interface of the prototype system, including the Navigation and Art Appreciation modes and how to switch between them. Afterwards, participants performed a practice route comprising two turns and a single artwork. Participants were able to repeat the practice route in case they were not comfortable with the system. Before and during practice we explained how to hold the smartphone, because it affects localization accuracy and the interaction is based on its orientation. In addition, participants were told that the researchers would only be observers, but would always be nearby to ensure their safety and the safety of the artworks. Throughout the study, at least one researcher followed the participant at close distance, only intervening when necessary.

Then, participants were given detailed guidance for two tasks,

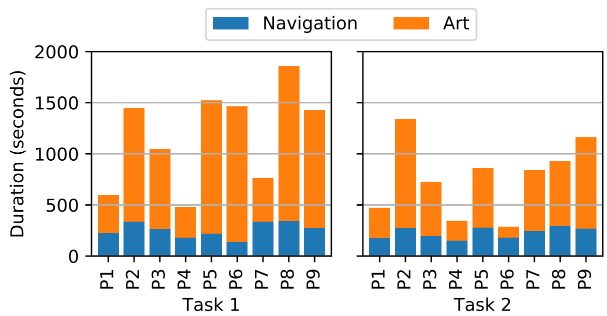

Figure 4: Task completion time and the ratio of spent time for the 2 modes for each user in *Tasks 1* and *2*

which followed interest-based routes for museum visitors: a chronological history route (*Task 1*), and a route for hand-painted pop art (*Task 2*). Each route and the location of the respective artworks are shown in Figure 3.

Task 1 (red dashed line in Figure 3) has eight artworks in total, including three readings of *Text Content*, and five *Audio Stories* with a total length of 1,670 seconds. Since we wanted to test the interaction between the two modes, we asked the participants to stop at each artwork to listen to at least part of the linked audio content.

Task 2 (blue solid line in Figure 3) has seven artworks, including four readings of *Text Content* and three *Audio Stories* with a total length of 1,040 seconds. In this task, participants did not have any constraints and were asked to enjoy the route as they prefer. They could stop and listen to the content for artworks they were interested, but could also skip other artworks.

After each task, participants reported their satisfaction (1- very low, to 5- very high) using 5-point Likert Items. After completing both tasks, we performed a post-interview to evaluate their overall satisfaction and of each feature, such as the quality of the audio content, the satisfaction with synthesized and recorded human voices, the navigation assistance, and the content based on proximity. Finally, we asked if such an application would motivate them to go to museums alone and if it would still be useful when visiting with sighted peers.

4.2 Results

In what follows, we present both a quantitative and a qualitative analysis of the user study.

4.2.1 Overall Performance and Completion Times

All participants were able to complete the two tasks and had no difficulties switching between the Navigation and Art Appreciation modes by changing their body and iPhone orientation. Figure 4 shows the total task completion times and the ratio between the time spent in the two modes. The navigation system successfully guided all participants to the artworks. They performed the two tasks in average times of 1,178 (SD=476), and 773 (SD=356) seconds, respectively. The average total duration spent by the participants in appreciating the audio content for the artwork for the two tasks were 921 (SD=462), and 543 (SD=312) seconds, respectively, and the rest of the time was consumed by navigation. This means, 74.5%, and 65.6% of the respective time was used for art appreciation in the two tasks. This slight difference is related to the larger number of *Audio Stories* (which are longer) in *Task 1*.

4.2.2 User Satisfaction

Participants' overall satisfaction was very high, scoring 4.94 on average (SD=0.16). The average satisfaction score for *Task 1* was 4.72 (SD=0.44), while for *Task 2* it was 4.89 (SD=0.33). Beyond these scores, all participants had positive comments about their experiences, both about the ability to navigate independently in the museums and about the accessibility of the artworks through carefully prepared audio descriptions. A few examples of the overall users' satisfaction are listed below:

Statement	Mean	SD
I enjoyed being able to listen to audio content	5.00	0.00
I enjoyed listening to the audio content in front of each exhibit or artwork	4.89	0.33
I would visit museums by myself if museums provide such an application	4.78	0.44
I feel that the navigation enables me to visit museums by myself	4.67	0.50
I would use this application when I go to museums with someone	4.56	0.53

Table 2: Subjective ratings of the prototype system

> "Actually it was very good because I really followed the directions correctly, it was very accurate, very well-done. The descriptions of the pictures were good. It was just all about a good experience" (P1).

> "It's good because I never experienced something like this. I never had this level of accessibility. So that's why I think it is amazing and great!" (P3).

> "I can't see paintings. I normally don't pay attention to what people paint. Because I can't see them anyway. You know, but actually, being able to listen, and here is the detail, I thought it was interesting that I could actually learn, you know, his personality, just by listening what he painted" (P3).

> "I was able to basically customize it for what I wanted to hear about. If I was interested in something or understood it [and] wanted to move on. I could . . . I can do it on my own speed. It was nice!" (P5)

4.2.3 Artwork Announcements

There were a total of 15 artworks $(8+7)$ in the two tasks, so the system should have made 135 announcements (9 participants $\times$ 15 POIs). From the log data, we found that the system missed 9 announcements out of 135 (6.7%), most of them located near a corner. Due to the wide corridors, in those situations users turned a few meters earlier than the intended location, which prevented them from getting close enough to the artwork and trigger the audio content.

In addition, participants did not check the content of an artwork 3 times (one time for three different participants) in *Task 1* out of 72 opportunities (4.2%) even though they had been instructed to stop and check the audio content for all artworks. One participant took a few steps while the system was describing one artwork and the system skipped the following artwork (because the distance between the two artworks was too short). In two other cases, participants could hear the announcement (as seen in the video replay) but they did not turn to listen to the content (perhaps due to distraction).

4.2.4 *Post Interview*

Table 2 shows the Likert items (from 1-Strongly Disagree to 5-Strongly Agree) we used in the post-interviews and users' average ratings. All participants rated the statements very favorably. The highest average rating (m=5.0) was related to the ability to listen to the audio content, showing a major impact of **audio-based descriptions** in the museum experience of blind people. In addition, the ability to enjoy such descriptions in exactly **in front of the artworks** was seen as very important:

> "I would want to be right in front of what is being described to me" (P2).
>
> "I want to know exactly what is around me . . . Our experience should be as normal as your experience would be" (P9).

Proximity-based art appreciation was found to be important both when visiting alone and when visiting with sighted peers, such as family members, children, and other social connections.

> "...hearing people near me comment on the same items. I think that would be interesting and really fun" (P4).
>
> "...if I'm with a group, it's more important to me to be in front of it" (P7).

Being able to **navigate independently** was very highly rated by participants, because they can not only enjoy art at their own pace, but also to process their experience::

> "I'd really enjoy just having quiet time afterwards to think about it... If I go with other people, it's not something that I can sit and be contemplative about afterwards.. because everybody's like now let's go get something to eat, let's do this..." (P4).

The lowest average rating (but still very high) was related to using this system while **visiting a museum with someone** (m=4.56). When asked to comment on that possibility, independence also played a very important role:

> "...if I was interested in something and my friend was not, my friend could move on. And I could stay, I wouldn't have to just follow them" (P6).
>
> "I don't wanna take away from their enjoyment [by] having to read me everything" (P7).

In addition, participants found that the system could also be useful for their sighted peers:

> "Even as a sighted person, I think the benefit of this is the fact that you are getting a kind of like a personalized docent tour . . . you're getting pretty extensive art history . . . I would try to get them [his sighted friends] to get the system as well" (P8).

Participants were asked to evaluate the **two types of content**. All of them except P9 rated 5 for *Text Content* read by a synthesized voice. They found the synthesized voice acceptable because they listen to it every day on their screen readers. P9 rated it 2 because she "*loves human voices*". *Audio Stories* using a human voice were also highly rated (7 participants with 5 and 2 ratings of 4), as participants liked to hear the descriptions from people relevant for the artist's life or knowledgeable about this particular museums. On participant mentioned the following:

> "I really like to hear the human narration. That adds a little more personality into the whole experience" (P2).

Some participants provided a few suggestions to improve the human voices such as adjusting the volume, or adding more emotion.

5. DISCUSSION

In this section, we discuss our main findings and future research directions that can help supporting independent museum experiences for blind people.

5.1 Overall Museum Experience

All participants successfully navigated along the proposed routes without getting lost, suggesting that the accuracy provided by the system may be enough to successfully guide a blind user in the context of a museum visit. In addition, all participants found no difficulties to combine the two modes, navigation and art-appreciation. Users' performance was complemented by their overall very high satisfaction rates, which came from the ability to both having an independent experience, at their own pace, and listening to carefully prepared auditory content. Such setting ensures that visual impaired visitors can have their personalized museum experience without needing to over-rely on their sighted peers or needing to join specialized tours. We believe, and participants' comments support, that such a system would make blind people visit museums more often.

Despite the mostly positive feedback, we also observed some limitations that can result in further iterations of our system or in valuable lessons for other researchers or practitioners in this field. For instance, it can be easy to skip an artwork if the next one is within very close proximity. For this reason, it may be beneficial to explore feedback mechanisms that can warn the user in such occasions (e.g., using sonification to alert about artworks which were skipped) and/or functions that allow users to search for (or browse) and be guided to the closest artworks. Other examples are related to veering or small localization errors that can result in users skipping artworks near the corners or even slightly deviating from the path. Although NavCog has veering prevention mechanisms [15], these are more appropriate for larger, wider spaces, since slight deviations (which happened in the museum context) are difficult to detect. Future solutions should consider how to prevent or correct veering, for instance by combining vision-based techniques.

5.2 The Importance of Proximity

One of the reasons why blind people like to visit museums is related to experiencing its atmosphere [4]. Being able to learn onsite is different than reading about it at home. The same holds for sighted people, who can see an artwork in a book or online, but still prefer to visit museums as they value the onsite experience. Prior research had already referred to blind people's preference to appreciate art near the respective artwork [19] and our survey [4] supported such findings adding that they want to be right in front of the artwork, and not just near. The user study built on these findings, also showing that users want to have an experience as close as possible to the one of sighted people, and that by being in front of the artwork they could leverage some of the contextual information, such as listening to other people commenting the artwork. This preference is supported by users' high satisfaction about the ability to trigger the audio content based on proximity and orientation (Table 2).

5.3 Real-World Environment Challenges

Installing the system at The Andy Warhol Museum enabled us to test our prototype in a more realistic environment than what is usually found in the literature. It is important to note, however, that the study was conducted while the museum was closed. This was important, as a first step, to access the feasibility of our approach in an ideal, more controlled scenario. However, during opening hours the navigational and environmental challenges of museums increase. A main concern is how to cope with the presence of other museum visitors, who may be blocking the user's path or gathered near an artwork. During the study, users were only focused on the path and on the artworks, but it is very likely that they would come across several pedestrians if the museum was crowded. In such context, frequently hitting other people with the cane can be seen as socially disruptive, while needing to go around them can lead to users deviating from the intended path.

Additional challenges may arise if we consider other types of museums. While most of the artworks at The Andy Warhol Museum are placed on the walls, other museums may have fragile artworks in the middle of the room. In that case, it is crucial to guarantee sub-meter accuracy near such artworks to ensure their safety.

Potential approaches to increase localization accuracy and to help the user negotiating space with other visitors may combine this system with computer-vision and/or robot-based guidance, both to detect pedestrians and to guide the user through or around the crowds. While the first can help predicting future collisions [24], the latter may help reducing the user's load and attention on navigation (and space negotiation) to focus on the art experience itself.

5.4 The Social Aspect

Being able to have an independent experience was seen by participants as the main advantage of our system. Still, blind people often visit museums for the social aspect [4] and participants see themselves using the system even when visiting with sighted peers. A main reason is that users can enjoy their experience at their own pace, by skipping or taking longer at a particular artwork.

Some participants thought that their sighted peers could also benefit from the audio content provided by this system, which is not unexpected as most museums provide audio guides to their visitors. In addition, it is relevant to note that some audio guides for the general public already use BLE beacons to provide audio content depending on the user's location. However, they are often based on proximity, which prevents such systems to provide accurate, continuous navigation assistance (which is required for blind visitors). The accurate localization provided by our system means that the general public could also use our system as a location-based audio guide and benefit from its audio descriptions. Still, sighted people would also benefit from a few adaptations that would increase its usability. For instance, the visual feedback on screen could be enriched, and the default order of the audio chapters could vary depending on the smartphone having an active screen reader or not (as in [14]).

An application that can be used by all visitors could potentially support shared experiences between blind and sighted users in the future. For instance, blind users can exchange opinions with other blind or sighted users (friends, acquaintances, or strangers) either to discuss interpretations of the artworks or to ask for particular details that may not be available in the auditory descriptions. Also, users visiting with friends could potentially use the system to keep track of each other, enabling independent experiences by easing the ability to reconvene later on with their friends and family.

Despite the increased independence given by such a system, it is also important to consider potentially negative situations, in particular when system errors or user misinterpretation of an instruction may lead users to act in a unexpected manner. For instance, a localization error may lead the user to turn to an artwork too late or too early. It is relevant to further study the impact of such errors and behaviours in a social context like visiting a museum, both from the blind user's and other visitors' perspectives.

5.5 The Impact of Individual Differences

Individual differences can play an important role in the user's interaction with the system and in their museum experience. Our system is mainly designed for blind people, as it relies on audio and tactile feedback, and most study participants were fully blind (one was legally blind). Still, it would be interesting to understand if people with low vision could benefit from such system and what kind of changes or adaptations would be required. For instance, people with low vision could benefit from the use of magnifier tools from the phone's accessibility services for visual feedback about the route or the textual auditory descriptions. On the other hand, depending on their visual abilities, users may need less information about the route and focus mostly on the descriptions of artworks.

The choice of navigation aid is also known to impact how blind people navigate [15, 16, 43]. However, in the context of a museum visit the differences go beyond (and differ from) navigation. While in navigation tasks the guide-dog helps the user walking faster to the destination and avoiding obstacles, when appreciating art users wants to walk slowly along the wall to obtain audio feedback within close proximity of the artworks. In the user study, two participants (P2 and P7) performed their tasks with guide dogs and needed to learn how to interact with their dog. At first, the guide dog was ready to turn before the system instructs the user to turn, because the exhibition room is wide and safe. Seeing the open space, the guide dog would turn much earlier than intended, which could cause the user to miss some of the artworks near the corners. Realizing of such behaviour, users started guiding their dogs based on the navigational guidance instructions provided by the system, instead of just following their dog. This suggests that instructions should be provided to guide-dog users prior to their interaction with the system. This is specially relevant because guide-dogs may help coping with the challenges of the environment (e.g., other visitors), but can also lead to skipping relevant artworks or deviating from the path.

5.6 Navigation and Exploration

The ability of blind users to navigate independently in the museum was given by timely turn-by-turn navigation instructions to follow routes prepared by the museum staff. Although such routes were carefully prepared, following a thematic or chronological order, it does constrain users to fixed, non-personalized routes. A potential solution to personalize user's experiences include calculating routes depending on their preferences. For instance, users could select particular exhibitions, artworks or artists of interest, letting the system calculate a route according to such preferences. Other alternatives may provide users with more control to decide their own course while visiting the museum. Still, navigation instructions are still important to allow users to explore the environment independently. For instance, future solutions may still provide turn-by-turn guidance, while providing options to the users at relevant intersection points (e.g., "*Turn right for the Pop Art exhibition, or turn left for Andy Warhol's life story*").

6. CONCLUSION

This paper described a prototype system to support an independent, interactive museum experience for blind people. It is characterized by a seamless interaction between Navigation and Art Appreciation modes, accomplished by accurately tracking the user's location and orientation. We installed our system in a public museum and performed a user study with 9 visually impaired participants to evaluate it in a real-world scenario. All participants were able to complete the two interest-based routes and their satisfaction rates were high. Results showed that the app was effective to improve their museum experience and that they are motivated to use it when visiting museums either by themselves or with sighted companions. In particular, users found it very important to listen to the audio content in front of the artwork (not only near), supporting the use of body orientation as a trigger for switching to the Art Appreciation Mode. In the future, we plan to understand how to cope with the challenges (*e.g.*, pedestrians blocking the way) and opportunities (*e.g.*, leveraging shared experiences or the museum atmosphere) that arise from visiting the museum during its opening hours. Moreover, we plan to study how blind people access and perceive audio and tactile content, and customize their experience according to their preferences and their needs.

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