Enhancing Blind Visitor's Autonomy in a Science Museum Using an Autonomous Navigation Robot

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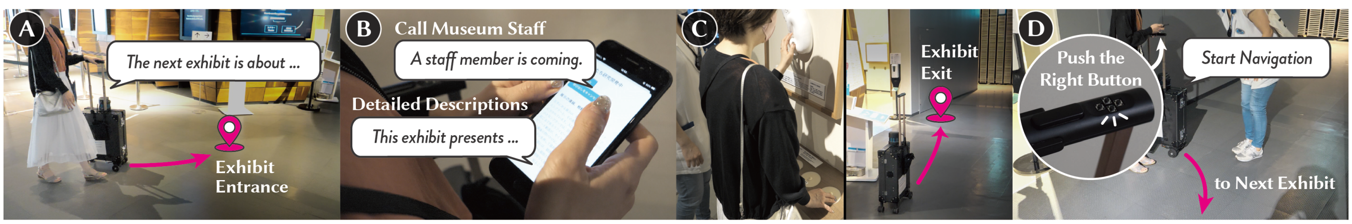

Figure 1: Science museum exploration with a suitcase-shaped autonomous robot designed to assist blind visitors. (A) The robot safely guides a blind user to an exhibit while narrating a short description of it. (B) At the exhibit, the user can listen to detailed descriptions using the built-in screen reader on a smartphone or call museum staff if additional assistance is required. (C) As the user and staff member interact at the exhibit, the robot moves and waits. (D) The user can continue the rest of the exploration by pushing a button on the robot's handle.

ABSTRACT

Enabling blind visitors to explore museum floors while feeling the facility's atmosphere and increasing their autonomy and enjoyment are imperative for giving them a high-quality museum experience. We designed a science museum exploration system for blind visitors using an autonomous navigation robot. Blind users can control the robot to navigate them toward desired exhibits while playing short audio descriptions along the route. They can also browse detailed explanations on their smartphones and call museum staff if interactive support is needed. Our real-world user study at a science museum during its opening hour revealed that blind participants could explore the museum safely and independently at their own pace. The study also showed that the sighted visitors who saw the participants walking with the robot accepted the assistive robot well. We finally conducted focus group sessions with the blind participants and discussed further requirements toward a more independent museum experience.

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CCS CONCEPTS

• **Human-centered computing → Accessibility technologies**; • **Social and professional topics → People with disabilities**.

KEYWORDS

Visual impairment, blind navigation, autonomous navigation robot, museum

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1 INTRODUCTION

Museums should be socially inclusive for all visitors, regardless of the disabilities they may have. Consequently, museums are improving the accessibility of their exhibits to blind people through specialized tours [28, 48] and access to tactile representations of artworks [45]. In addition to providing such non-visual museum experiences, increasing visitors' *autonomy* is also important to achieve high-quality museum experiences for blind visitors. Researchers have revealed two main challenges in making non-visual museum experiences accessible to the visually impaired: (1) enabling people to navigate a museum safely [9, 41, 65] and independently according to their interests [9, 10] and (2) representing visual artifacts non-visually through touch or audio [8, 9, 16, 26, 64–66].

This project focuses on the challenge of enabling blind people to navigate and explore a science museum safely and independently and to increase their autonomy in socially inclusive ways. Choosing a series of sub-exhibits at their own pace based on personal knowledge, interests, and comprehension time of a science topic is an inherent part of a science museum experience. By walking around a science museum's floor, blind visitors should be able to listen to the sound at various locations, sense the size of the sub-exhibits, and feel the atmosphere of the museum [9]. Thus blind visitors have to seek assistance from family, friends, museum personnel, or remote assistance [50]. Blind people prefer not to rely on such assistance all the time because they are concerned about imposing a burden on sighted assistants [9]. Furthermore, according to Small et al. [58], it is important for a better tourist experience to consider their various travel arrangements such as independent travel or travel with friends, family, professional attendants, professional caregivers, or commercial specialists. While previous research efforts have proposed various navigation systems [34, 36], they evaluated these systems' effectiveness in user studies in which blind participants walked on *pre-fixed* routes with the system. Therefore, how to enhance blind people's autonomy in public spaces, including a science museum, remains an unexplored challenge.

Autonomous robots have significant potential to allow blind people to walk independently in various spaces, such as shopping malls, airports, and museums [25]. Since blind people can follow the robot's navigation by holding its handle, they do not need to pay as much attention to orientation and can walk in a more relaxed way compared to mobile or wearable solutions [10, 29, 41]. Nevertheless, to the best of our knowledge, no study has been reported on robots designed specifically for assisting visually impaired people in museums and the social acceptance of such robots. Consequently, we pose a research question: *To what extent can an autonomous robot-based navigation system contribute to increasing blind visitors' autonomy and enjoyment in a museum?* and *How will sighted visitors perceive the robot guiding blind visitors in a science museum?*

We have developed the prototype of a system for providing independent museum exploration assistance to blind visitors by effectively combining the power of a navigation robot, audio guidance, and the intelligence of human assistants with the specific design target of a science museum (Miraikan - The National Museum of Merging Science and Innovation[1]. Blind users can control the robot's destination via an app by using the built-in screen reader on the smartphone[2]. The robot safely guides them to an exhibit while the app narrates a short description of the exhibit (Fig. 1-A). The users can also browse detailed explanations on their smartphones and call museum staff if interactive support is needed (Fig. 1-B–D).

The system evaluation entails two components: (1) a real-world user study with eight blind participants at a science museum and (2) a questionnaire on the robot's social acceptance by nearby sighted visitors The user study was conducted during the museum's regular hours of operation. During the study, the participants were allowed to go to any exhibit area in any order by selecting destinations according to their own pace and interests. We obtained the following findings:

- The blind participants could explore the museum independently and appreciated the ability to choose exhibits according to their own interests and enjoy the museum at their own pace, which had been impossible when they depended on sighted assistants all the time.
- The sighted visitors readily accepted the presence of a navigation robot assisting blind visitors at the museum without feeling any disruption or danger and without privacy concerns about the robot's camera.

We finally conducted two focus groups [24] composed of the blind participants. We discussed the participants' needs and challenges in depth to seek the balance between the automated system and human assistance for science communication toward a more independent museum experience.

2 RELATED WORK

2.1 Automated Mobility Assistance

When blind people visit museums, one of the biggest accessibility issues is mobility and orientation. Many blind people rely on help from their families or friends [8, 66]. Previous researchers proposed various types of mobile or wearable systems to guide visually impaired people in indoor public spaces, for applications such as providing navigation instructions to a destination [34, 36] and helping people avoid obstacles [40, 49, 67].

Various systems have targeted navigating visually impaired people through specific locations, especially museums [10, 29, 41]. Asakawa et al. proposed a smartphone-based system for navigating blind people in museums [10]. The system offers seamless interaction for artwork appreciation by using the user's orientation. The system's app reads the description of artwork only when the user is oriented toward it, and the app seamlessly resumes navigation to the next artwork when the user changes their orientation. However, the system cannot help users avoid obstacles and other visitors. Meliones et al. proposed a similar system combined with an obstacle avoidance system, and they tested it in museums [41]. Although either of these navigation systems can guide visually impaired users to their destinations, a user may veer away from

[1]https://www.miraikan.jst.go.jp/en/)
[2]https://www.apple.com/accessibility/vision/

a navigation path, which leads to a longer navigation time and requires a higher cognitive load for mobility.

Several researchers have tested navigation robots for visually impaired people, with the robot either in front of the person [17, 37, 42, 46, 54, 59, 61, 62, 68, 69, 72] or to the side [12, 25, 32, 33]. These robots have sensors to detect and avoid surrounding obstacles, in the manner of a guide. In addition to obstacle avoidance, some robots also have functions for locating their position and navigating toward the user's destination [12, 17, 25, 46, 59, 61, 68]. CaBot is a state-of-the-art open-source blind navigation robot [25]. Visually impaired people can follow the robot by holding its handle; as a result, they do not need to pay as much attention to orientation and can walk in a more relaxed way. Nevertheless, to the best of our knowledge, no robot designed specifically for visually impaired people in museums has been studied.

Previous studies have evaluated the effectiveness of navigation systems, including navigation robots, through task-based user studies where blind participants were asked to walk along *pre-fixed* routes [34, 36]. Thus, how to improve blind people's *autonomy* in a museum remains an unexplored task [9, 10]. To overcome this challenge, we developed a navigation system that allows blind participants to explore a science museum with greater independence. We also conducted a real-world user study in which blind participants freely explored a science museum during its regular hours of operation. Furthermore, we asked sighted visitors about their impressions of such assistive robots.

2.2 Exhibit Accessibility

Increasing the accessibility of exhibits is an essential part of enhancing the museum experience of blind visitors [26]. Especially at science museums, many exhibits use diagrams, photos, videos, interactive displays, untouchable objects, and other visual media to communicate scientific content. Museums have made efforts to increase accessibility by introducing objects such as tactile replicas or reproductions and descriptive audio guides [43]. Some museums provide specialized tours or workshops [28, 48]. In addition, various assistive technologies have been proposed [53, 64, 66], such as tactile models created by 3D printing [70], tactile reproductions augmented with touch sensing and audio descriptions [7], and touch screens for exploration of visual artwork [2]. For the work described here, we created text descriptions of exhibits and made them available to blind visitors through our smartphone app. However, because the primary focus of this paper is mobility assistance, the various exhibits in the museum adopted for our user study, even inaccessible interactive touch displays, were used "as is." In these cases, we relied on the museum staff for help when the blind participants required such access.

2.3 Technologies for Communication in Museums

Communication with museum staff (e.g., curators and science communicators) is a valuable experience that increases visitors' comprehension of exhibits, especially in science museums with unfamiliar topics, academic details, and recent updates. However, visually impaired visitors often have difficulty finding available staff on site. The Brooklyn Museum provides a chat application that allows visitors to communicate with museum staff online [19]. Especially for visually impaired visitors, the capability to provide assistance and interpretation by museum staff and volunteers is a high-priority service [26]. However, even though blind visitors sometimes require sighted assistance, they prefer not to rely on such assistance all the time, since they are concerned about imposing a burden on the sighted assistants [9]. Accordingly, we implemented a calling function so that blind users can initiate communication with museum staff only when necessary.

Additionally, robots are a promising technology to guide visitors on behalf of museum staff. Researchers have deployed a variety of autonomous robots in museums for navigating and guiding visitors. Earlier works mainly focused on safe navigation, robust localization, and advanced automation (e.g., automatic recharging) in the deployment environment [15, 47, 60]. These robots have interactive displays for guidance with multimodal content and robotic faces to attract visitors' attention. Later works mainly focused on social interaction with visitors via human-like robots used as museum guides [6, 57, 71]. For example, to attract visitors' attention, a pair of humanoid robots talked to each other about exhibits [57], and another humanoid robot observed visitors' faces to adjust its head motion [71]. Recently, robots have used advanced speech recognition and text analysis technologies to answer visitors' questions [6]. By contrast, we mainly focused on the navigation function of robots while relying on museum staff for communication in museums.

2.4 Social Acceptance of Assistive Technologies for Visually Impaired People

To deploy robots for assistance in public spaces, including museums, it is essential to gain acceptance from not only the blind visitors but also the sighted visitors. Previous researchers investigated social acceptance [35] of various assistive technologies for visually impaired people, such as computer-vision-based assistance [1, 5], a wearable camera [4, 39, 52], and a drone [11]. Many of these studies focused on investigating the privacy issues related to camera-based assistance [1, 4, 39, 52]. In addition, visually impaired users' considerations of their own image and the public perception of assistive technologies have also been investigated [4, 5, 11, 31, 39, 51, 56]. These considerations can influence the adoption and usage of assistive technologies [18]. In this study, we conducted a real-world user study in a museum during its regular hours of operation, and we simultaneously investigated the social acceptance of the robot-based museum exploration system by 108 sighted visitors who viewed the blind participants walking with the robot in the museum.

3 SYSTEM DESIGN

3.1 Museum Experience for Blind Visitors

For blind visitors, a museum is one of the most challenging places to walk through and experience independently. Significant challenges face them in navigating a large space and appreciating exhibits. Previous works mostly attempted to solve these problems with mobile devices or audible icons in the environment [10, 21–23, 29, 38]. However, blind visitors find it difficult to focus on appreciating an exhibition while navigating its spaces and avoiding other visitors and obstacles [10]. Navigation with mobile robots is a promising way to reduce such stress in museum visits [25]. Therefore, in this study, we designed a museum navigation system using a mobile robot and a smartphone to improve a science museum experience for blind visitors, and we obtained feedback on the system through a user study and a focus group study.

We designed the proposed system for a science museum, Miraikan, which has scientific exhibits for all ages in a multistory building. The museum staff includes science communicators (SCs) with whom visitors can talk about the exhibits. We targeted one floor of the building, with an area of about 2,100 m^2, which includes 10 of the museum's 25 themed exhibit areas as shown in Fig. 2. The users can command the mobile robot through a smartphone app and the built-in screen reader (Section 3.2.1). The app will provide a brief description of the destination exhibit while navigating to it and also provide detailed descriptive content at the entrance of each exhibit. If the user wants to learn more details of the exhibit, an SC can be called from the app. In each area, visitors pass through an entrance and proceed toward an exit while observing the area's artworks and interactive displays. Making an exhibit fully accessible (e.g., artwork descriptions, interactive displays, narrow paths, and steps) is one of the fundamental factors in developing an accessible, independent museum experience [26, 43]. However, as mentioned earlier, this factor is outside the focus of this study. Accordingly, we relied on the SCs to support the participants in passing through the exhibit and filling this gap. The SCs usually communicate with museum visitors to increase their understanding of the exhibits. Before our user study, we held a training session for the SCs on interacting with visually impaired people.

3.2 System Overview

The museum exploration system consists of two major components: a navigational robot and a smartphone app. The robot navigates blind visitors to specified destinations while safely avoiding obstacles and other visitors. The smartphone is used as a system interface that allows blind users to control the robot's destination and listen to the descriptions of exhibits.

The system was designed based on the inputs from a blind author and staff members of the science museum (visitor service team and SCs). The blind author tested the navigation robot and the smartphone app to improve the system's design iteratively. In addition, we designed the function to Call SCs based on discussions held with two museum staff members of the visitor service team. In the museum, the museum staff usually assists blind visitors when they ask for assistance, rather than always guiding them. By referencing such a human system design in the museum, we designed the smartphone app to enable blind users to call museum staff if additional assistance is needed (e.g., they want to learn more details of the exhibit). We tested the function to call SCs with 25 SCs and revised the function based on their comments, such as the type of information displayed in the SC's smartphones. Two SCs also wrote the exhibit descriptions for use in the science museum.

3.2.1 Museum Exploration App. The smartphone app is the main interface of the museum experience for blind visitors. The smartphone is connected to the robot to control its navigational behavior and get feedback on its navigation status (e.g., avoiding obstacles). The app is designed to be fully accessible to blind visitors by working with the smartphone's screen reading software. In our user study (Section 4), we used the smartphone's speaker so that experimenters could also listen to the audio interface. We note that, in actual conditions where experimenters do not require use of the speaker, the users would naturally be able to use their preferred hearing devices (e.g., a bone conduction headset or open ear headset) during their museum exploration.

The user manages destinations by selecting specific exhibits from the list of exhibits. Since it would be too much work to enter all the exhibits one by one, the system also provides a predefined tour that navigates all the exhibits (Fig. 2). The app also shows a detailed explanation of each exhibit as a text-based web page so that users can browse the contents at their own pace using the screen reading software. The use of text-based content allows the user to change the speaking rate, which visually impaired people often wish to configure according to their preferences [30]. Users can also use gestures such as flicks or multi-finger taps on the screen to move the focus and read text information. In our user study, we informed the blind participants that they could visit all the exhibits by selecting the predefined tour but did not inform them about the spatial layout of the floor beforehand. Some participants visited all the entrances of each exhibit by following the predefined tour to briefly the whole structure of the floor, and then they visited exhibits their interested one by one (Section 5.4.2).

The app is synchronized with the connected robot's navigation status. For example, the app speaks as the robot tries to avoid other visitors. Detailed content is automatically opened when the user and the robot arrive at an exhibit's entrance. If the user becomes interested in the exhibit and wants to explore it further, they can call an SC through the app for further communication. The museum's SCs also have a smartphone app to promptly notify them of visitors' requests. While supporting a visitor, an SC can command the robot to move and wait at a designated waiting area near the exhibit's exit.

3.2.2 Autonomous Robot for Blind Navigation. As features to guide the user safely, the mobile navigation robot is equipped with a handle for the user to hold and visual sensors for awareness of the surrounding obstacles and other visitors. The handle controls the robot's speed and navigation state, and it has four directional buttons to provide user shortcuts (haptic handle in Fig. 3-A). The up and down buttons control the speed. The robot's maximum speed is 1.0 m/s, but we set the default speed to 0.5 m/s for the museum setting. The right and left buttons start and stop navigation. The handle also has a touch sensor for the robot to detect whether the user is holding the handle. The robot proceeds only while the user holds the handle, unless an SC commands it to move and wait.

3.3 Exploration Scenario

The following is a typical scenario of museum exploration for a blind visitor using the system.

(1) The blind visitor borrows a navigation robot (and a smartphone if needed) at the museum's reception area. For the user study, we specified a designated start area on the floor (Fig. 2, Start).

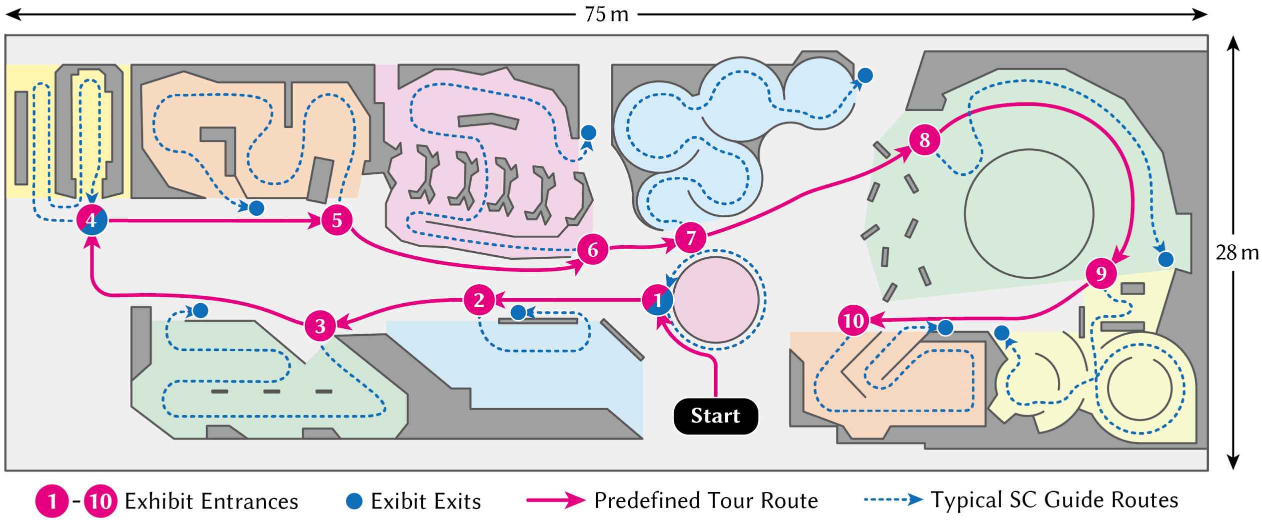

Figure 2: Floor map of science museum, predefined tour route, and typical science communicator (SC) guide routes

(2) The visitor opens the app on the smartphone and selects a tour from the list of tours or an exhibit from the list. Blind users control the smartphone using VoiceOver, the built-in screen reader on iOS devices.
(3) The visitor holds the handle and pushes the right button on the handle to command the robot to proceed (Fig. 1-D).
(4) The robot moves toward the next exhibit in the tour while the smartphone app narrates a brief description of that exhibit (Fig. 1-A).
(5) When the robot arrives at the exhibit entrance, the app automatically pops up a browser to show the detailed text-based web content of the exhibit.
(6) The visitor can browse the content on the app by using the screen reader, call an SC for further communication about the exhibit (Fig. 1-B and Fig. 3–B), or command the robot to proceed to the next exhibit.
(7) If an SC is called, the SCs' smartphones receive a notification with the user's location, and each SC can accept or decline the call (Fig. 3–D). When an SC accepts the call, The visitor's smartphone is notified that an SC is on their way. The SC arrives at the visitor's location, commands the robot to move and wait at the exhibit's exit using the visitor's smartphone, and accompanies the visitor into the exhibit (Fig. 1-C).
(8) In the exhibit, the SC explains the visual features of the exhibit, navigates the visitor to touchable features, helps the visitor interact with interactive displays, and answers the visitor's questions.
(9) After exploring the exhibit, the SC guides the visitor to the robot waiting at the exhibit's exit. The visitor can resume the rest of the tour by pushing the right button on the robot handle (Fig. 1-D).

Blind visitors walk with the robot while holding their white cane with their right hand, holding the robot's handle with their left hand, and listening to the description of the current exhibit from the smartphone in the user's shoulder pouch. When they want to manipulate the smartphone, they can stop the robot's navigation by releasing their left hand from the robot's handle.

3.4 Implementation

Hersh et al. reported that visually impaired people prefer a navigation robot that is inconspicuous and discreet but attractive and elegant, and one that does not draw attention to the user [27]. Accordingly, we selected a navigation robot that looks like a suitcase so that it can assimilate into the environment as shown in Fig. 3-A. The robot's hardware and software are based on an open-source project[3], which has been experimentally implemented in airports and shopping malls. The robot has a 360-degree 3D LiDAR and an RGB-Depth camera for safe navigation. The LiDAR sensor can detect surrounding objects such as walls and obstacles to build a 2D cost map (a space with grid cells having values, where a lower value represents free space). The navigation planner calculates the least-cost path to the destination exhibit. The navigation system has a predefined topological route map, which contains the museum's possible itineraries, to consider the tour route during path optimization such that the robot can navigate along the planned route instead of taking the shortest path. The robot applies an extended footprint, including the robot body itself and the user's body size, for path planning of safe navigation without collision, in the manner of CaBot [25]. The RGB-Depth camera can detect and track people in front of the robot using the YOLOv4 [14] image recognition engine, which enables the robot to behave in a social way such as keeping appropriate distance. Before the experiment, a researcher walked through the environment (2,100 m^2) to build a map for localization, which took about 30 minutes. However, the map needs to be re-built if the layout is significantly changed. We note that this period did not include preparing the exhibit descriptions linked to the map. We asked the museum's staff to write the descriptions.

[3]https://github.com/CMU-cabot/cabot

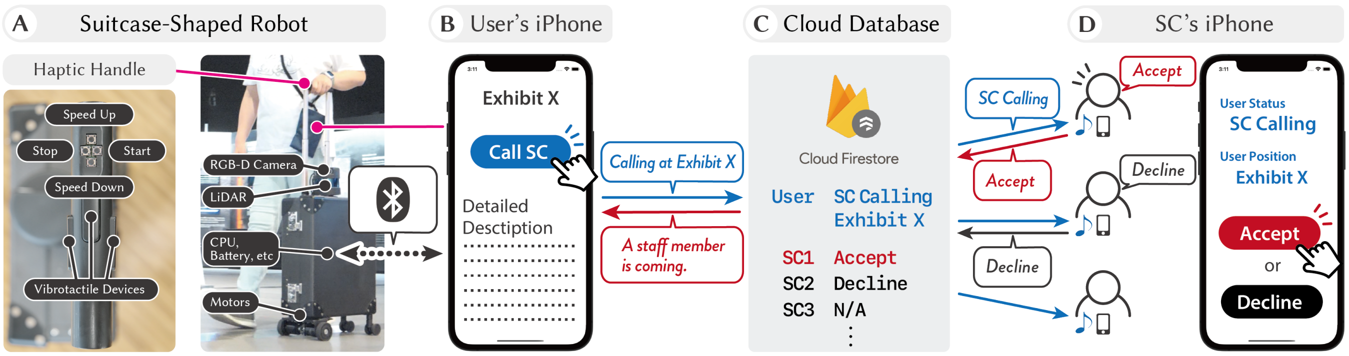

Figure 3: Overview of our prototype robot and the system for calling a science communicator (SC). (A) The handle of the suitcase-shaped robot has four directional buttons to provide user shortcuts. (B) The robot and the smartphone in the user's shoulder pouch are connected via Bluetooth, and the user can call an SC or listen to a detailed description of the exhibit. (C) The user's current status is maintained in a cloud database. (D) When the user calls an SC, the SCs' smartphones receive a notification, and each SC can accept or decline the call.

We developed an iOS app for connection to the robot via Bluetooth by using the SwiftUI[4] and Google Cloud Firestore[5] frameworks. The app was installed on an iPhone 12 Pro (Fig. 3). We customized the robot system to enable synchronization between the app and robot. The short descriptions for narration during navigation as well as the detailed contents were edited by the museum's SCs. The average length of the short descriptions is 73.9 words (Max: 113 words, Min: 45 words). By using a database on Google Cloud Firestore, the app can manage user status information, including whether the user is calling an SC and where they are navigating (Fig. 3-C). VoiceOver, the built-in screen reader on iOS, is activated to enable the users to control the robot and browse content on the app by themselves.

4 USER STUDY AND FOCUS GROUPS

To evaluate the effectiveness of the proposed museum exploration system and its acceptance by museum visitors, we conducted a real-world user study at the science museum during its normal hours of operation. We asked eight blind participants to freely explore and experience one floor of the museum for 90 minutes using our system. Our research questions are *To what extent can an autonomous robot-based navigation system contribute to increasing blind visitors' autonomy and enjoyment in a museum?* and *How will sighted visitors perceive the robot guiding blind visitors in a science museum?*. Thus, we designed an unstructured user study (i.e., we did not ask participants to walk along pre-defined routes). During the study, we also asked sighted visitors to complete a short questionnaire about the robot's social acceptance. Finally, after the user study, we conducted two focus group sessions with the blind participants [24]. In these sessions, we discussed their in-depth needs and issues for developing a more independent museum experience.

[4]https://developer.apple.com/xcode/swiftui/
[5]https://cloud.google.com/firestore/

4.1 Participants

We recruited blind participants via an e-newsletter to which 80 visually impaired people had subscribed. The subject conditions were as follows: totally or legally blind people, ages between 20 and 70 years, ability to manipulate an iPhone using VoiceOver, ability to go to the meeting place of the experiment (a station ticket gate) by themselves, and $70 compensation. We recruited the first eight blind participants to arrive (six men, two women) with ages ranging from 25 to 53 years (mean 39.25, SD 10.41), as listed in Table 1. All participants were totally blind and primarily used a cane. As seen in Table 1, three participants (P1, P2, and P6) visited museums once in a while, but the others had only visited a museum a few times in their life. Six participants (P2 and P4–P8) visited the science museum (Miraikan) for the first time in this study, and none of the participants were familiar with the museum.

Autonomous service robots are still uncommon in public spaces. Furthermore, compared with the conventional autonomous service robots, such as security robots and delivery robots, blind navigation robots are characterized by the user always moving beside the robot. Thus, for this part of the study, two experimenters randomly spoke to surrounding sighted visitors who saw the participants walking with the robot, and asked them to fill out a short questionnaire on the robot's social acceptance. As gratitude for answering our questionnaire, we gave them a ballpoint pen with the museum's logo. Through the four days in which the study was conducted, we obtained questionnaire responses from 108 visitors in total.

4.2 Procedure and Metrics

4.2.1 Preliminary Interview and Training Session. After obtaining an Institutional Review Board-approved (Application No.: 2020-039) informed consent from the participants, we conducted a preliminary interview of 10–15 minutes, in which we asked about their experiences in museums. Then, we provided them with approximately 20 minutes of training to familiarize them with the system. Specifically, they practiced walking with the robot, setting destinations with the smartphone app, and calling an SC.

Table 1: Demographic statistics of user study participants.

ID	Age	Gender	Eyesight	Museum visits	No. of visits to this science museum
P1	49	Male	Blind since age 14	1–2 times/year	Third time
P2	25	Male	Blind since age 4	2–3 times/year	First time
P3	35	Female	Blind since age 14	A few times	Second time
P4	29	Male	Blind since age 10	A few times	First time
P5	51	Male	Blind since age 8	A few times	First time
P6	29	Male	Blind since age 5	Once every 2–3 years	First time
P7	53	Male	Blind since birth	A few times	First time
P8	43	Female	Blind since age 3	A few times	First time

4.2.2 Main Session. After the training session, the participant moved to the starting position at the floor's entrance (Fig. 2). We told the participant, *"Please explore and experience the museum freely for 90 minutes with the robot."*[6] We did not specify which destinations to choose (the predefined tour or specific exhibits); instead, the participants chose the destinations according to their personal strategy and interests. The participants were informed that a researcher would walk behind them (5–10 m away) to assist them immediately if they required support. Since it was the first study that used a blind navigation robot during the museum's regular hours of operation, the duration of the study was limited to 90 minutes in consideration of the physical and psychological burden on the blind participants. We also informed the participants that they could take a break whenever they liked.

During the main session, two experimenters randomly spoke to surrounding sighted visitors who saw the participants walking with the robot, and asked them to rate five questions on a 7-point Likert scale (Fig. 5, Q_s1–Q_s5 (Questions for Sighted visitors)). The questions are related to the robot's social acceptance and were designed by us. After they answered the questions, we gave them a ballpoint pen with the museum's logo.

4.2.3 Post-Session Interview. After the main session, we conducted another interview, which took approximately 30 minutes. We first asked the participants to answer a set of questions (Table 3, Q_u1–Q_u6 (Questions for Users)) consisting of items answered on a 7-point Likert scale (1: strongly disagree; 4: neutral; 7: strongly agree). All questions are our own design; Q_u1 and Q_u2 are related to our research question on visitors' enjoyment and autonomy, respectively, Q_u3 and Q_u4 are about the system's overall experience, and Q_u5 and Q_u6 are about the effectiveness of our system's original features. Then, we asked open-ended questions about the advantages and issues of our system, their strategies for exploring the museum with it, and suggestions for improvement.

4.3 Focus Groups

After finishing the user study, we organized two online focus group sessions with four participants each. The sessions were semi-structured to focus on further requirements for our museum exploration system. Specifically, we first asked the participants for suggestions to improve their museum experience, namely, *"Can you recommend any new functions to improve our museum exploration system?"* We further inquired about possible solutions to better understand the exhibits' contents in contrast to our current system, which relies on SCs to guide blind participants in an exhibit. The two focus groups covered the same topics, and each took approximately 60 minutes. Each session was audio-recorded and transcribed for further analysis.

[6]All communication with the participants was in their native language. In this paper, we present any translated content in the form of *"translated content."*

5 RESULTS

5.1 Overview of Exploration Activity

Table 2 lists the order of exhibits visited by each participant. All participants started their museum exploration by following the predefined tour. Six participants (P1–P6) first completed the predefined tour without calling an SC, while two participants (P7 and P8) occasionally called an SC during the tour. After arriving at Exhibit 10 and finishing the predefined tour, six participants (P2–P4 and P6–P8) visited some of the exhibits again by repeatedly navigating to a specific exhibit from the exhibits list and calling an SC. The other two participants (P1 and P5) followed the predefined tour again and then called an SC when they arrived at an exhibit of interest.

Table 2 also summarizes the activity duration times, including A) the activities of walking with the robot, B) using the smartphone, and A+B) time spent alone without the SCs' support. During their 90-min sessions, the participants walked with the robot for about 9 min on average (Table 2-A). While we set 0.5 m/s as the default robot speed, all participants changed the speed (P1: 0.8 m/s, P2–P6: 1.0 m/s, P7: 0.9 m/s, and P8: 0.75 m/s). The walking style of the participants also differed (Table 2-Walking Style). The participants spent approximately 17 min on average operating the app, including selecting destinations, browsing descriptions, and waiting for SCs (Table 2-B). Participants released their left hand from the robot's handle and operated the app. They all called SCs 5 or 6 times and spent about 1 hour with the SCs. During the session, 2–4 SCs helped support this study. On average, the participants spent 26 min alone (about 30% of their time exploring the museum).

As an example, Fig. 4 shows the routes of P3 and the robot. P3 first followed the predefined tour and explored the entire floor. Then, she visited five exhibits (Exhibits 4, 6, 7, 3, and 1) again and called an SC at each exhibit, since she wanted to learn more and ask questions about these specific exhibits. We describe the

Table 2: Order of exhibits visited by the participants in the study (* indicates an exhibit where the participant called an SC), together with their walking style (with the robot and their cane or with the robot only), the durations of A: walking with the robot, B: using the smartphone, and A+B: the time spent alone

ID	Order of exhibits they visited (*: called an SC)	Walking Style	A) With Robot	B) Using Smartphone	A + B
P1	Tour (1–10), Tour (**1***, 2, **3***, **4***, 5, **6***, 7, **8***, **9***)	Cane & Robot	08:59	19:48	28:47
P2	Tour (1–10), **9***, **3***, **1***, **8***, **4***, **5***	Cane & Robot	11:53	17:31	29:24
P3	Tour (1–10), **4***, **6***, **7***, **3***, **1***	Robot only	08:25	16:25	24:50
P4	Tour (1–10), **3***, **5***, **8***, **9***, **10***, **6***	Robot only	08:31	11:11	19:42
P5	Tour (1–10), Tour (1, 2, **3***, 4, 5, **6***, **7***, 8, 9, **10***), **5***	Cane & Robot	10:27	13:43	24:10
P6	Tour (1–10), **1***, **3***, **4***, **8***, **9***, **10***, **6***	Cane & Robot	07:41	28:24	36:05
P7	Tour (**1***, 2–5, **6***, 7–10), **3***, **7***, **8***, **4***	Cane & Robot	08:38	14:23	23:01
P8	Tour (1, 2, **3***, **4***, 5, **6***, 7–10), **5***, **7***, **10***	Robot only	07:25	16:15	23:40
		Average	9:00	17:13	26:13

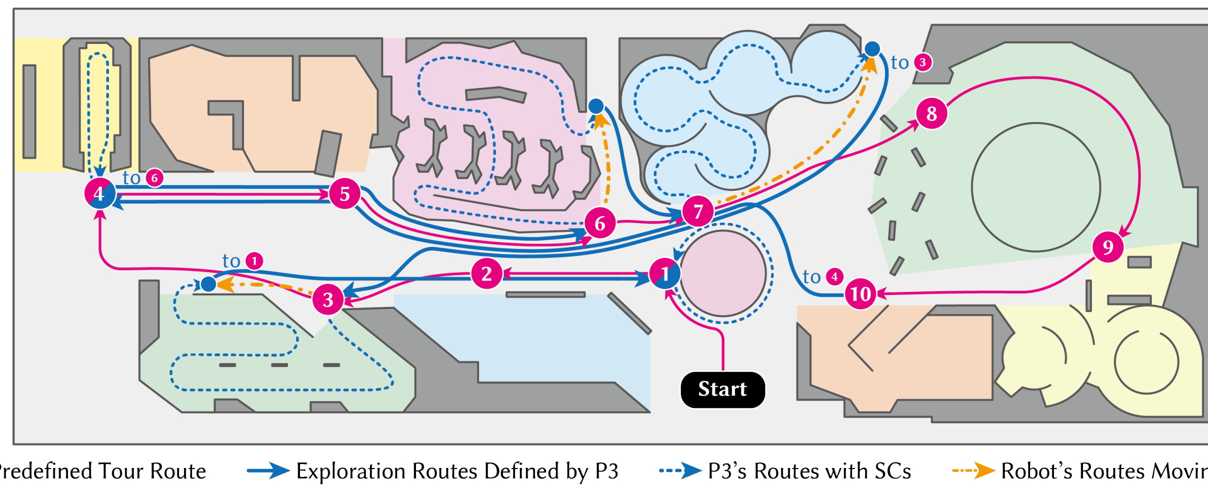

Figure 4: Example showing the routes of P3 and the robot in the user study. P3 first followed the predefined tour and explored the entire floor (exhibits 1 to 10). Then, P3 visited five exhibits again and called a science communicator (SC) at each one (Exhibits 4, 6, 7, 3, and 1).

participants' comments on their museum exploration strategies later, in Section 5.4.

5.2 Subjective Ratings

Table 3 summarizes the results for the six Likert-scale questions (Q_u1–Q_u6). All of the participants agreed (by a score greater than 5) that they enjoyed experiencing the museum with the robot (Q_u1); that they could explore the museum independently at their own pace (Q_u2); that they did not feel any danger while walking with the robot (Q_u3); and that calling the museum staff was effective (Q_u6). For usability (Q_u4) and the effectiveness of the exhibits' short descriptions (Q_u5), all of the participants except P6 gave positive scores. While we gave participants a training session of only 20 minutes, in the main session, all participants were able to operate the system with little or no assistance from us.

5.3 Social Acceptance of the Robot

Through the four days in which the study was conducted (two participants per day), an average of 272 people per day visited the museum (SD 52.7)[7]. We obtained questionnaire responses from 108 visitors in total, for an average of 13.5 visitors per blind participant. The age distribution of the sighted visitors was as follows: teens and younger: 22 (20.4%); 20–29: 21 (19.4%); 30–39: 30 (27.8%); 40–49: 27 (25%); 50–59: 4 (3.7%); 60–69: 2 (1.9%); 70 and older: 2 (1.9%). Figure 5 shows the questionnaire results (Q_s1–Q_s5). For all questions, the

[7]Before the COVID-19 outbreak, around 4,000–5,000 people per day typically visited this museum.

Table 3: Summary of Likert-scale responses (1: strongly disagree; 4: neutral; 7: strongly agree)

Question	P1	P2	P3	P4	P5	P6	P7	P8	Median
Q_u1: I enjoyed exploring the museum with the robot.	7	7	7	7	6	7	7	7	7
Q_u2: I could explore the museum independently at my own pace.	7	7	7	7	6	7	7	7	7
Q_u3: I did not feel any danger while walking with the robot.	6	6	7	7	7	5	7	7	7
Q_u4: The system was easy to use.	5	7	7	7	7	3	7	6	7
Q_u5: The narration of the exhibits' short descriptions was effective.	7	5	7	7	7	2	7	7	7
Q_u6: Calling the museum staff was effective.	7	7	7	7	7	7	7	7	7

value of the first quartile was more than 5 points, and we observed that more than 75% of the visitors accepted the user and the robot. The details of the results are as follows: 99.1% agreed that a robot for blind visitors should be introduced in museums (Q_s1); 78.7% felt that the movements of the blind visitors and the robot were natural (Q_s2); 86.1% did not feel that the blind visitors and the robot were disruptive (Q_s3); 88.9% did not feel any danger from the blind visitors and the robot (Q_s4); and 78.7% accepted the robot's camera capturing them (Q_s5).

5.4 Qualitative Feedback

5.4.1 Overall Experience. All participants appreciated that our system enabled them to explore the exhibits independently at their own pace: A1:*"Just like sighted people who enjoy museums, I could walk around the exhibits by myself at my own pace and request an SC when I wanted a guide. It was a fun experience that I've never had."* (P6); and A2:*"I could go around the exhibits at my own pace in my preferred order. When I go with a friend, I do not want to spend a long time on exhibits that my friend is not interested in, even if I want to go. With this robot, I could go around my favorite exhibits as much as I wanted."* (P8)

We conducted the user study during the museum's regular hours of operation. Although other visitors constantly came and went on the floor (272 people per day on average during the study), five participants (P3–P5, P7, and P8) did not feel any danger while walking with the robot: A3:*"(When I used the robot,) I did not have any stress while moving. I could focus on the audio summary of the next exhibit and listen to sounds from the exhibits. I could get into the atmosphere of the exhibits."* (P3); and A4:*"Even in an environment with people, the system properly stopped or avoided people, so I could walk with confidence."* (P7)

5.4.2 Museum Exploration Strategies. The orders of the exhibits that the participants visited varied among them. All of the participants started their museum experience by following the predefined tour to explore the whole floor. After completing the predefined tour, six participants (P2–P4 and P6–P8) went to specific exhibits according to their interests, while two participants (P1 and P5) followed the predefined tour again: A5:*"After grasping the whole structure of the floor by following the tour, I went to the places that interested me and that had high priority for me one by one. It was good to grasp the whole structure of the floor not only by listening to the voice guidance for the exhibit list but also by listening to the sounds from exhibits and feeling the atmosphere while walking."* (P2); and A6:*"At first, I went around the floor and grasped the rough structure and size of the floor and what I was interested in. Because I could not remember the exhibits only by listening to their titles, I followed the tour again [by not selecting a destination from the list] and remembered the exhibit contents by listening to the summary while walking. Then, I requested an SC at the exhibits I was interested in."* (P5)

5.4.3 Narration of Exhibits' Short Descriptions. Three participants (P1, P4, and P7) gave positive comments on the function of narrating the exhibits' short descriptions: A7:*"(When I walked with the robot,) the feeling was close to being guided by a person. When I moved, I trusted the robot and could walk while listening to the short descriptions and surrounding sound and thinking about the next exhibit."* (P1) On the other hand, P6 commented that the narration function was not effective: A8:*"I was not used to the robot yet, and it was difficult to concentrate on listening to the short descriptions."* (P6)

5.4.4 Calling an SC. As seen for Q6 in Table 3, all of the participants greatly appreciated that the system could call museum staff when needed: A9:*"I did not want to bother the SCs by asking them to guide me all the way. The function to call an SC only when needed was good."* (P8); and A10:*"Compared to walking with a single staff member all the way, I'm glad I could talk to various SCs."* (P3)

5.4.5 System Usability. Although seven participants rated the system as easy to use (Table 3, Q4), some participants provided suggestions for improving the user interface: A11:*"When the robot stopped, I could not understand whether it had stopped because there was a person in front of us or I had held the handle incorrectly. I would like to know why the robot has stopped at the same time it stops."* (P6)

5.5 Focus Groups

This section summarizes the participants' comments in the two online focus group sessions (Group A: P2, and P5–P7; Group B: P1, P3, P4, and P8).

5.5.1 Toward a More Independent Museum Experience. When we asked the participants for suggestions to improve their museum experience, all of the participants commented that they wanted to listen to audio guidance while walking through an exhibit area: A12:*"Among the exhibit areas that the SC introduced, there were some exhibits where I could experience the sizes of museum objects by walking around them. Rather than just listening to guidance in front of the entrance, it would be nice if I could listen to the descriptions*

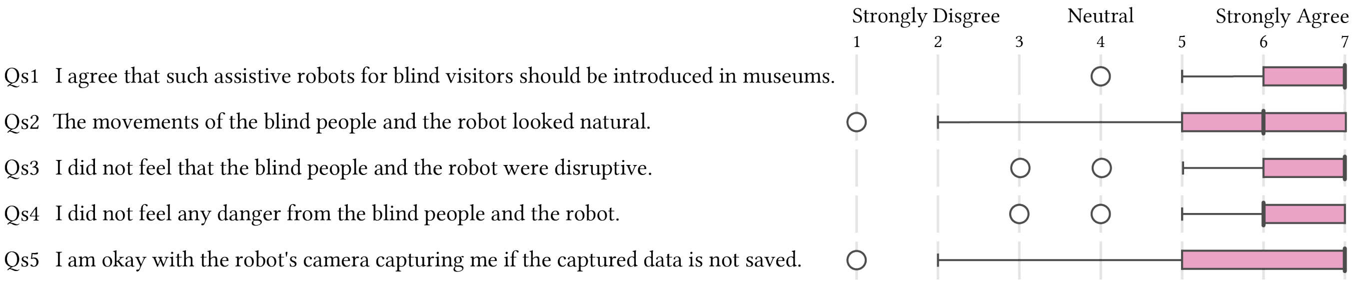

Figure 5: Questionnaire results of the social acceptance of the robot

while walking inside with the robot and experiencing the objects' sizes." (P2)

In the proposed system, we rely on SCs to guide blind participants through an exhibit. Five participants (P1 and P5–P8) wanted to call SCs to have them discuss the contents of an exhibit rather than explain the exhibit. In addition, six participants (P1, P3–P6, and P8) commented that they wanted to learn about the exhibits' contents more independently: A13: *"I called an SC every time I wanted to enjoy an exhibit in this experiment, but I would prefer to call an SC only when I have questions after I understand the exhibit as much as I can with the robot."* (P1); and A14: *"Because I come up with questions as I walk around exhibits, it would be nice if the AI [Artificial Intelligence] could respond. If the system explanation is only one-sided (like the current system), I would prefer to call an SC and enjoy exhibits while asking questions."* (P6)

6 DISCUSSION

6.1 Independent Museum Experience

The proposed system successfully enabled blind participants to explore a science museum by effectively combining the power of a navigation robot and the intelligence of human assistants. All of the participants agreed that they enjoyed exploring with the robot (Table 3, Q1) and could explore the museum independently at their own pace (Table 3, Q2). While previous studies have evaluated the effectiveness of navigation systems, including navigation robots, through task-based user studies where blind participants were asked to walk along *pre-fixed* routes [34, 36], in this study, the participants chose to visit a variety of exhibits according to their own interests and strategies (Table 2, A5 and A6). In the user study, participants interacted with the system for about 26 minutes on average, meaning the system-human ratio in elapsed time was roughly 30:70. (Table 2). Nevertheless, the participants appreciated the independent museum experience in the user study because such experiences have not been possible for them when they visited a museum alone or with their families and friends (A1 and A2).

The participants rated the predefined tour highly because they could experience and grasp the rough structure and size of the floor by walking through it rather than just listening to a long verbal description of it before navigating the museum (A5 and A6). The narration of the short description of each exhibit during navigation toward it was effective for independent museum exploration (Table 3, Q5). Participants appreciated that the short descriptions were useful for accessing the information about exhibits and selecting the exhibits of interest. The participants could gain an overview of the upcoming exhibit while walking (A7).

The participants unanimously agreed on the effectiveness of calling a museum staff member (SC) via the smartphone app (Table 3, Q6). They commented on their need to ask the museum staff for support, but at the same time, they typically hesitate to take the time of museum staff for an entire visit, or they feel uncomfortable being accompanied by a human assistant. In contrast, our system enabled blind visitors to call staff members for support only when they needed it. They felt comfortable asking for support from multiple assistants, and they enjoyed communicating with multiple assistants (A9 and A10).

6.2 Safety Concerns

Maintaining a sense of safety for both blind and sighted visitors is one of the critical challenges in deploying navigational robots in a real-world museum setting. While many previous navigation systems, including navigation robots [12, 17, 25, 46, 59, 61, 68], were evalated in controlled environments where there are no surrounding pedestrians [34, 36], this user study was conducted during the museum's regular hours of operation, when other visitors to the floor constantly came and left. Even in such a real-world situation, the participants could walk with the robot through the museum floor without any incident or safety concern (Table 3, Q3). They could rely on the robot's navigation and focus on the museum experience (A3 and A4). Three participants in particular explored the museum without taking their cane (Table 2-Walking Style). In addition, 86.1% of the sighted questionnaire respondents who saw the participants and the robot also did not feel any danger from their movements (5–7 points in Fig. 5, Q10). We cannot generalize these results to other situations without more data, especially for cases when the museum is crowded. Nevertheless, neither the blind nor sighted visitors had any particular safety issues or concerns in the study environment. This is an encouraging result that can be regarded as a beachhead for designing our next exploration system for real-world deployment.

6.3 Social Acceptance

In the user study, the surrounding sighted visitors accepted the navigation robot well (Fig. 5): 99.1% of them agreed that assistive robots for blind visitors should be introduced in museums (5–7 points in Fig. 5, Q7), and the percentage of visitors who felt that the blind people and the robot were disruptive was only 2.8% (1–3 in Fig. 5, Q9). Researchers have previously reported on blind users' considerations of their own image and the public perception of assistive technologies [4, 5, 11, 31, 39, 51, 56], but in this study, 78.7% of the sighted visitors regarded the presence of a blind user and robot as natural (5–7 in Fig. 5, Q8).

Privacy concerns about camera-based technologies have been discussed in previous studies [1, 4, 39, 52]. We mounted a camera on top of the robot, and thus we expected this feature to raise privacy concerns. However, we found that the sighted visitors generally (78.7%) accepted the robot's camera capturing them (5–7 in Fig. 5, Q11). Privacy concerns are usually considered the most serious challenge for the practical deployment of camera-based assistive technologies. However, we found that the use of a camera may not be a deal-breaker for social acceptance and practical deployment in science museums if the robot operates to assist blind people.

On the other hand, we could not investigate how the experience of sighted visitors could be affected by the use of the navigation robot because the robot navigated blind users among sub-exhibitions rather than inside each sub-exhibition. For example, if the robot navigates blind users in the crowded sub-exhibitions, there are some interactions with surrounding people, such as waiting in line to experience exhibit objects. Designing systems that conform to such social norms is important to realize assistive systems with high social acceptability. The impact on the museum experience of not only the bind visitors but also the surrounding sighted visitors should be investigated.

6.4 System Usability

We built the museum navigation system by combining a blind navigation robot [25] and a newly developed smartphone application. The application allows blind users to select the robot's destination and listen to the exhibits' short descriptions. Although seven of the eight participants rated the system as easy to use (Table 3, Q4), we also found opportunities to improve the user interface. P6 negatively rated the system's usability (Table 3, Q4) and the effectiveness of the exhibits' short descriptions (Table 3, Q5). His point concerned the transparency of the robot's actions. For example, he commented that he wanted to know the reason for stopping each time the robot stopped (A11). The robot can be designed to explain the reason for each stop while navigating, like assistive systems that informs the user about nearby points-of-interest (POIs) [55]. However, such additional information may conflict with the exhibits' short descriptions and overwhelm users with too much information. Consequently, we need to carefully balance the information presented. One possible solution is to provide the blind users with a means to ask the robot about the reasons for the robot's behaviors.

In addition, P6 commented that he could not pay attention to the short descriptions because he had to pay attention to the robot (A8). This situation might improve with more usage of the system. In this study, only P6 gave negative ratings, but we should expect more diverse feedback, given the variety of skills and experiences among the blind population. Accordingly, we should carefully design and evaluate interface options and personalization features to meet each user's characteristics (e.g., walking and smartphone skills).

6.5 Toward a More Independent Museum Experience

The proposed system successfully improved the independence of participants by focusing on navigation and exploration among sub-exhibitions (A1 and A2). We found a strong preference of users to be independent. Most participants commented that they would like to spend more time without being dependent on SCs (A13 and A14). Six participants commented that they would like to understand each exhibit's content as much as they can with the robot and then call an SC only when they have questions (A13). All of the participants wanted robot navigation "inside" each sub-exhibition, rather than just listening to guidance at the entrance, as was the case in this study. Each sub-exhibition consists of several panels/exhibits every 1 to 2 m, so the robot should be able to navigate a user among panels/exhibits along a typical route on a finer scale.

Beyond this finer navigation and explanation, blind visitors strongly prefer independence in their science museum experience, but enabling non-visual science communication is the challenge. One possible future direction is the use of automated or remote question-answering (Q&A) technologies. Five participants agreed that science communication was a valuable experience in the museum because it enabled them to ask questions (A13–A14). They also commented that they preferred even this question-answer part to be automated; for example, this could be done with a remote assistance system [3, 13], a chat system with museum staff [19], or an AI-based Q&A system [6, 44, 63] on the robot or the app.

At this moment, the appropriate balance between independent exploration with an assistive robot and human assistance for science communication is not clear. Blind visitors require human assistance, but they would also prefer an independent experience, as we observed in the focus group sessions. We hope to improve our system to navigate inside sub-exhibitions and integrate automated or remote Q&A technologies.

6.6 User Study Limitations

During the user study, an average of 272 people visited the museum every day. However, before the COVID-19 outbreak, approximately 4,000–5,000 people visited the museum on a typical day. Since the adopted system was derived from a navigation robot project[1] that had been tested in crowded environments such as shopping malls and airports, we assumed that the robot could navigate blind users safely in a crowded museum while avoiding collisions with pedestrians. In contrast, a robot in crowded environments may stop more frequently than in the environment used in our experiments, and this may affect the blind visitors' exploration experience. Thus, in the future, we plan to verify whether the robot can work in such a crowded environment and how the system's usability will be affected.

Although the duration of this user study was limited to 90 minutes in consideration of the physical and psychological burden on the blind participants, most visitors would spend more time enjoying the museum. The longer visitors spend in the museum, the more they need facilities other than the exhibits in the museum. Engel et al. reported some blind people's requirements for indoor navigation, such as toilets and automatic machines [20]. To realize a more practical and helpful system, we would like to survey blind visitors' needs for the museum navigation, design an interface for blind users to receive a variety of information and send instructions to the robot, and conduct user studies without time limits.

7 CONCLUSION

In this study, by effectively combining the power of a navigation robot and the intelligence of human assistants, we developed and evaluated a museum navigation system that enables blind visitors to explore a science museum with greater independence. The system consists of a navigation robot and a smartphone app. The smartphone app allows a blind visitor to select destinations of interest and hear descriptions of the exhibits. The navigation robot detects obstacles and nearby visitors to avoid collisions and leads the user to their destination safely and independently.

Our evaluation was divided into three components. The first was a user study conducted at a real science museum with eight blind participants. All participants could navigate the museum safely, without any collisions, and explore the exhibits at their own pace and according to their own interests for 90 minutes. They unanimously agreed on the effectiveness of calling a museum staff member (SC) for assistance or interaction regarding exhibit contents. The second component was a questionnaire on social acceptance by nearby sighted visitors. The questionnaire results revealed that the sighted visitors accepted the navigation robot without feeling any disruption or danger and without significant privacy concerns about the robot's camera. The third component consisted of focus group sessions with the blind participants. These sessions revealed that although the participants were very happy with the system, they would prefer to increase their independence and talk to a human science communicator only when an interactive conversation is needed. They also commented that they would like to use the robot in other use cases, such as at airports, shopping malls, and hospitals.

The notion of "independence in public spaces" may be one of the grand challenges in navigation technologies for blind people. We will improve the system to allow further independence by focusing on the science museum, with not only improved navigation features but also a Q&A system and user behavior analysis to provide more flexible assistance with exhibit objects. This research aims to enable the blind to experience a deeper scientific museum experience by integrating human assistance and automation.

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