BentoMuseum: 3D and Layered Interactive Museum Map for Blind Visitors

Xiyue Wang
Miraikan – The National Museum of Emerging Science and Innovation
Tokyo, Japan
wang.xiyue@lab.miraikan.jst.go.jp

Seita Kayukawa
Miraikan – The National Museum of Emerging Science and Innovation
Tokyo, Japan
seita.kayukawa@lab.miraikan.jst.go.jp

Hironobu Takagi
Miraikan – The National Museum of Emerging Science and Innovation
Tokyo, Japan
hironobu.takagi@miraikan.jst.go.jp

Chieko Asakawa
Miraikan – The National Museum of Emerging Science and Innovation
Tokyo, Japan
chieko.asakawa@miraikan.jst.go.jp

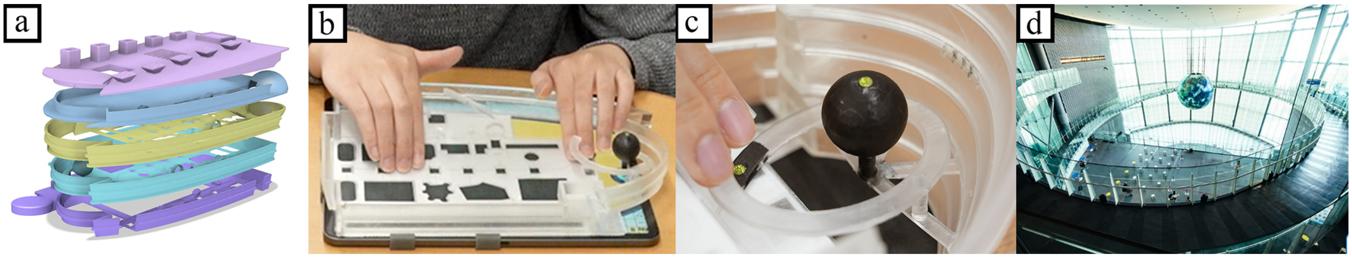

Figure 1: BentoMuseum, a 3D and layered design of a museum map that makes information accessible to visually impaired visitors. (a) All floors can be stacked or separated. (b) A user taps the interactive label, which responds with an audio guide when the floor is overlayed on an iPad app. (c) A user explores a structural attraction with fingers (a circular walkway named Oval Bridge which goes around a "globe-like" display named Geo-Cosmos). (d) The Oval Bridge and Geo-Cosmos in the museum.

ABSTRACT

Obtaining information before a visit is one of the priority needs and challenges for blind museum visitors. We propose BentoMuseum, a layered, stackable, and three-dimensional museum map that makes complex structural information accessible by allowing explorations on a floor and between floors. Touchpoints are embedded to provide audio-tactile interactions that allow a user to learn the museum's exhibits and navigation when one floor is placed on a touch screen. Using a tour design task, we invited 12 first-time blind visitors to explore the museum building, chose exhibits that attracted them, and built a mental map with exhibit names and directions. The results show that the system is useful in obtaining information that links geometric shapes, contents, and locations to then build a rough mental map. The connected floors and spatial structures motivated users to explore. Moreover, having a rough mental map enhanced orientation and confidence when traveling through the museum.

Author Version

CCS CONCEPTS

• **Human-centered computing** → **Accessibility systems and tools**; • **Hardware** → *Tactile and hand-based interfaces*; • **Social and professional topics** → *People with disabilities.*

KEYWORDS

information access, 3D structure, audio-tactile, touch screen

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1 INTRODUCTION

As audience-centered institutions with a range of educational and social roles, museums are, more than ever, aware of the importance of delivering equality, diversity, and inclusion, as well as their power to bring about positive change in society [13, 33, 34]. Increased attention is being paid to the development of equal access and multidimensional access, which not only refers to physical access but also to multi-sensory, intellectual, financial, emotional, cultural, educational as well as information access [2, 12, 24], all of which are important to the visually impaired community. At present, many barriers impede the attempts of people with visual impairments to visit a museum. Alongside exhibition accessibility and mobility assistance [2, 3], the limited provision of information and orientation before a visit can lead to a negative overall experience and emotional isolation [2, 10]. Nevertheless, making detailed and usable information available would create a welcoming and encouraging environment to blind visitors [30].

The museum's unique environment brings challenges to blind people in accessing information, different from other public spaces such as neighborhoods, parks, and hallways in a building. First, contemporary museums have distinctive architecture, internal design, and "inter-floor structures" (i.e., stairs and walkways connecting the floors, see an example in Fig. 1d) as a part of their exhibitions [31, 43]. Blind visitors have difficulty grasping the museum's complex "multidimensional information", such as the overall geometric shape of the building, the inter-floor structures, and each exhibit section's name, description, approximate shape and size, and location. Second, even though some museums have a minimal structure with a pre-defined route, more museums contain freely arranged exhibits that may or may not have clear route indication [14]. In such museums, visitors explore the museum and choose the exhibits they examine based on their interests. By encouraging such "free explorations", these museums effectively trigger a sighted visitor's curiosity, but conventional posted information may cause blind visitors access difficulties and orientation frustrations.

Accessible maps are the means for visually impaired visitors to learn about a site. Tactile maps are often available in public spaces and institutions to provide information and assist in navigation, with the aim of helping the user to build a mental map before going to a new place [45, 46]. Since the effectiveness and understandability of a tactile map largely depend on the user's tactile skills and abilities [38], three-dimensional (3D) maps with volumetric symbols have been developed for ease of understanding. Moreover, audio-tactile labels have been proposed for seamless and autonomous operation. The user is thus largely freed from either shifting attention between the map and the braille legend [25] or asking others for explanations [16]. The current 3D-printed audio-tactile maps show thrilling possibilities, but limitations persist. These maps usually present a simple one-floor layout, which is insufficient to support a structural mental map of a multidimensional museum.

Due to the fact that a museum contains a large amount of multidimensional information, and it is not a frequently visited place, blind visitors might feel it's particularly challenging to obtain information, orient themselves, and build a mental map. Consequently, they refuse to do this and give up the idea of a self-reliant visit. How can museums that have a complex 3D structure and freely arranged exhibitions provide information access to blind people before a visit? To bridge the gap between museums and blind visitors in terms of information access, and to investigate the suitable format of an accessible and inclusive museum map, the following research questions emerge:

- RQ1. How can we make the vast amount of needed information (e.g., architecture and interior structures, exhibits, facilities, locations, and route-finding) accessible and understandable on a museum map?
- RQ2. Is building a mental map possible and significant in the museum context?

Previous literature either developed floor plans in isolation [20, 29] or reproduced external structures [26, 50], in which complex multi-floor structures such as museums were rarely explored. Our core concept and innovation is the design of stackable 3D floors to capture the complex multidimensional nature of a museum. The multidimensional information includes the external and internal structures, exhibits and facilities, and their locations as well as route-finding. Using a participatory and user-centered approach, we designed BentoMuseum, a 3D and layered museum map with audio-tactile interactions, to support blind users in obtaining information and understanding the 3D attractions through tactile explorations (Fig. 1). The system contains two main elements: the 3D and layered floors (Fig. 1a), which can be either interlocked to allow vertical exploration between floors (Fig. 1c) or separated to support horizontal exploration of a single floor; interactive touchpoints on the floor that allow audio feedback by touch (Fig. 1b). When one floor is placed on a touch screen, different levels of information and tactile navigation with audio support can be triggered by tapping. Novel designs we propose include stackable floors, 3D and 2D attributes that represent different types of contents, and simulated navigation by tracing paths and intersections.

We invited 12 participants with severe vision impairment to be museum tour designers and instructed them to use the system as part of an authentic museum tour. We let them explore as much as possible, obtain information, choose exhibits of their interest, and try to build a mental map. Participants expressed their map exploration styles and elaborated on their needs for information access before, during, and after the tour. Our results suggest: (1) Using the system, the participants were able to actively obtain information that links shape, location, and content. Consequently, they were able to choose exhibits of interest and build a rough mental map. (2) Touching inter-floor structures motivated blind users to explore the museum map. Along with the navigation, it supported them in building a 3D mental map. (3) Building a rough mental map beforehand was beneficial for the subsequent visit. It provided orientation, enhanced the sense of safety and confidence that they would not get lost while traveling through the museum, and led to a positive and inclusive museum experience.

2 BACKGROUND AND RELATED WORK

2.1 Museum Accessibility

Museums are not only institutions for the collection, preservation, and display of valued objects but also audience-centered spaces with a wide range of social roles and responsibilities [2, 6, 27, 48]. Sandell suggested that museums should contribute to social inclusion on individual, community, and society levels by supporting creativity and confidence; empowering independence, decision-making processes, and democratic structures; fostering acceptance and respect; and challenging stereotypes [41].

However, barriers exist when people with visual impairments attempt to visit a museum. It was noted that a blind person's visit experience begins even before entering the museum site [48]. The provision of information has been a priority need in terms of service accessibility [11, 23, 48]. A United Kingdom survey concluded that the basic accessibility information provided by a majority of museum websites could not address the access needs of blind or partially sighted persons who want to plan an independent visit [10]. Argyropoulos et al. found that complex museum architecture/interior design also hindered access to a museum. The overall inaccessibility led to a lack of motivation and negative emotions [2].

It was noted that providing haptic, touchable, and multi-sensory objects is one of the most anticipated and effective ways of improving museum accessibility [2, 9, 51]. In terms of accessing information and orienting visually impaired visitors, Vas et al. suggested presenting the museum space and exhibition through audio at the beginning of the visit [49]. Tactile maps and 3D models have also been developed to the needs of visually impaired visitors. Urbas et al. explored 3D printing techniques to develop physical floor plans to be mounted on the museum walls for touch [47]. Holloway et al. created 3D maps with distinct icons for an event, and they suggested that large maps require time to explore and thus should be made available before an event or at the entrance in a comfortable environment [26]. Leporini et al. pointed out that being able to explore and familiarize themselves with the structure and details of a large cultural site is crucial for orienting visually impaired people. This allows them to gain a global understanding and an overall impression [29].

2.2 Accessible Maps for the Visually Impaired

Maps that enable tactile explorations are designed for the visually impaired to learn the environment. One of the most common methods is tactile maps created with a set of accessibility guidelines [4, 35, 36]. Such maps represent features with raised lines, symbols, keys, and orientation [38, 55], often with the same elevation (around 0.5*mm*) on swell paper or a greater height difference (up to 2-3*cm*) when thermoformed [25, 39]. Most tactile maps are created for information provision in a digestible form that can be easily understood [39, 40, 55] and for mobility and navigation [25, 40, 46].

Although they are commonly used, tactile maps propose a set of challenges to visually impaired users. They are limited in creating 3D structures and a variety of heights [25]. The understandability of a tactile map also largely depends on the user's tactile ability [38, 40] and training in the skill of reading tactile graphics [1, 45, 46]. These maps also contain a relatively small amount of information, and normally a large area needs to be divided into different sections [38, 55]. Furthermore, the tactile maps need supplementary means to access the information, for example, a symbols glossary or legend [38].

To mitigate the understandability issues, research has explored maps with more distinct 3D structures. Voigt and Marten suggested the use of 3D models of buildings to facilitate spatial orientation and build a mental map [50]. Leporini et al. developed floor plans of indoor monuments of a cultural site to help both visually impaired and sighted people explore and familiarize themselves with elements before a visit [29]. Gual et al. found it was easier to memorize 3D volumetric symbols than 2D symbols [18]. Comparing two tactile maps, one with only 2D elements and the other also including volumetric symbols, Gual et al. found the use of 3D volumetric symbols significantly reduced both location-finding time and discrimination errors [19]. Holloway further compared the readability of different 3D icons on a map and proposed guidelines for icon design [26]. Pistofidis et al. tested a number of parameters related to 3D shape and haptic performance [37]. Holloway et al. compared 3D printed maps with tactile maps and found that 3D maps were preferred. The use of more easily understood icons and relative heights of map elements facilitated improved memory in short-term recall [25]. Gual et al. designed urban maps containing both volumetric attributes and relief attributes and demonstrated the value of the maps in terms of interpreting, memorizing, and understanding. However, they also found that the maps required verbal support to be used autonomously [20, 21].

2.3 Touch Sensing and Audio-Tactile Labels

Audio-tactile maps using touch sensing or buttons have been proposed to further support understanding in addition to the tactile sensations. Brock et al. designed an interactive map composed of a multitouch screen, a raised-line overlay, and audio output. Compared with tactile maps, they showed that replacing braille with audio-tactile interaction significantly improved efficiency and satisfaction [7]. Comparing tactile maps with interactive small-scale models (SSMs) for learning, Giraud et al. showed that the interactive SSMs improved both space and text memorization and were also adaptable to different situations and needs [16]. Several studies demonstrated that perceptible buttons that invoked different levels of audio content promoted an interactive, autonomous exploration [25, 29] and increased emotional engagement [52]. Utilizing printing technologies, automatic creation of 3D printable tactile graphics, and touch screens, research has developed the ability to instantly produce tactile-audio representations on a printed map by implementing the map on a touch screen [17, 44, 53].

The previous literature has built a strong foundation for developing 3D maps with audio-tactile labels. However, those works focused on one-floor settings with relatively small amounts of information. To the best of our knowledge, few research works have explored accessible maps for complex multi-floor structures. We fill this research gap by proposing stackable floor maps to access both the internal and external structures of an entire museum.

3 PARTICIPATORY SYSTEM DESIGN

The design concept is implemented in a science museum, Miraikan – The National Museum of Emerging Science and Innovation[1], with distinctive structure and symbolic interior attractions. It is a seven-floor building with a large-area atrium (with the 2nd, 4th, and 6th floors mainly atrium space) and structural attractions such as a series of escalators that directly connect all the floors (Fig. 3a), a walkway called Oval Bridge that goes around a "globe-like" display named the Geo-Cosmos (Fig. 1d)2n, and a Dome Theater with half of it inside the building and the other half extended into the exterior (Fig. 3b). It also lacks maps that can be perceived by touch.

We employed a participatory and user-driven methodology to design a map adapted to the museum. The design sessions include seven interviews with the blind designer (once in prototype 1, three times in prototype 2, and three times in preparing for the final design), one event that involved twenty blind museum visitors and three staff members, and one group meeting with those staff members.

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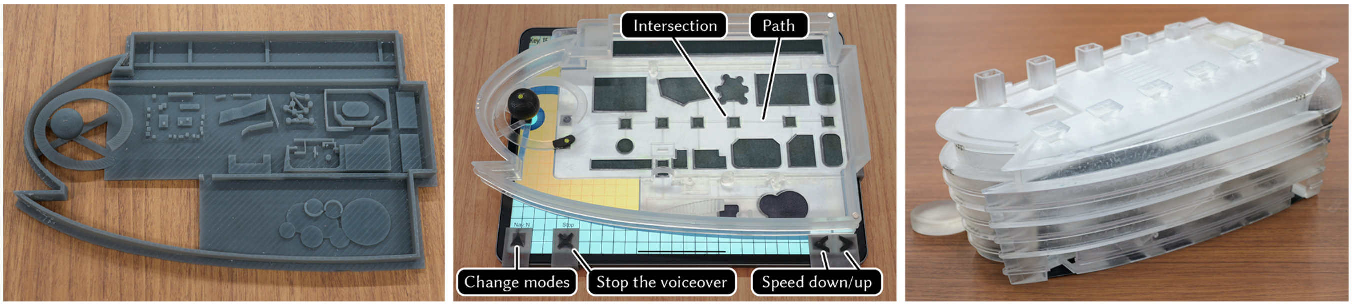
[1] https://www.miraikan.jst.go.jp/en/



(a) Prototype Design 1: Realistic Model

(b) Final Design: the 3rd Floor

(c) Final Design: the Fully Stacked Model

Figure 2: The printout of an early iteration and the final design. (a) The realistic model of the 3rd floor that was used in Prototype 1 to start the discussion (Section 3.2). (b) The 3rd floor of the final model, with simplified designs, audio-tactile labels painted in black, and control buttons on a touch screen. (c) The fully stacked final model that shows the external structure.

3.1 Motivation: "What if I can open the model and get information about the floors?"

One of the designers, P0, is an adult female who has complete blindness, as well as being an interaction designer and researcher. After being presented a 3D model of the museum, she expressed the need to understand the interior: *"I have heard about the symbolic globe-like display and the Oval Bridge around it. But it's so hard to imagine them just through descriptions. I wish I could open the model and touch them"*[2]. This was the initial attribute of the map we hoped to investigate: a 3D model that contains internal structures.

3.2 Prototype 1: Feedback of a Realistic Model

An early version of the map was a realistic 3D print of the museum floor (Fig. 2a). We sliced the 3D model into floors and encapsulated the detailed information such as the walls and tables at each exhibit to a $24cm \times 14.5cm \times 1.2cm$ miniature floor. A tactile map resembling the 3D map's layout was developed and printed on swell paper for comparison. During a two-day event called *Inclusion Week*, two maps along with other 3D prints were explored in the wild by 20 blind visitors, for 5 to 10 minutes each person. From their comments, we learned the following needs to satisfy in developing an understandable map:

- **Content:** Simplified and categorized forms were needed. Users highly praised the understandable form of the Oval Bridge on the 3D map but also pointed out that the detailed depictions of exhibits were not digestible.
- **Tactile exploration:** A relatively smooth surface without acute edges was preferred. Small and pointy objects (i.e., walls and tables) on the 3D map hindered hand scanning.
- **Explanations:** Automated audio-tactile interactions were desired. Both maps were not understandable unless the museum staff gave explanations.

The two maps were then tested by P0 during a 30-minute interview. Further requirements were confirmed based on her knowledge of the museum and expertise in design:

- **Facilities:** While the current maps were highly focused on the exhibits, the basic map elements such as restrooms, elevators, and escalators also needed to be included.
- **Orientation and navigation:** The map should support identifying the entrance, main route, each exhibit, and how to move around the space. These elements support the development of a "mental map," which is crucial for blind people.

The feedback revealed that the 3D map was good at delivering structural impressions while the tactile map preserved scanning, thus confirming the previous research [25]. Previous literature suggested 3D maps with audio-tactile labels offer clear advantages, including understandability, memorization, and effectiveness, all of which are important for museums. Nevertheless, we did not find a clear advantage to using the tactile map for the museum, so we were motivated to focus on 3D maps. We utilize the advantages of both volumetric attributes and relief attributes, learning from previous practices [18, 19, 25, 26, 29] while making our own design innovations and adaptations.

3.3 Prototype 2: 3D Floors and Audio-tactile Interactions

Based on the feedback, we categorized the museum's multidimensional information into the following three types of information, and we provided design criteria for each of them:

- **Structural attractions** include inter-floor structures and symbolic spatial structures (Fig. 1c, 1d, 3a, 3b). Our design choices include: (1) Simplifying structures into primary forms with understandable relative scales. For example, the parallel escalators and stairs were made simpler into one slope with textures (Fig. 3a). (2) Simplifying prominent walls into $1mm$ tall and $3mm$ wide cuboids. (3) Embedding magnets to support easy stacking and lining up of floors, which has proved to be effective in developing 3D objects for the blind [15]. Floors can be partially stacked to simulate how to walk between them (Fig. 3a) or fully stacked to show a facade (Fig. 2c).
- The **exhibits** included booths, wall-divided spaces, and artifacts placed in open spaces. Our design choice was to simplify them into outlines that were proportional to the real space

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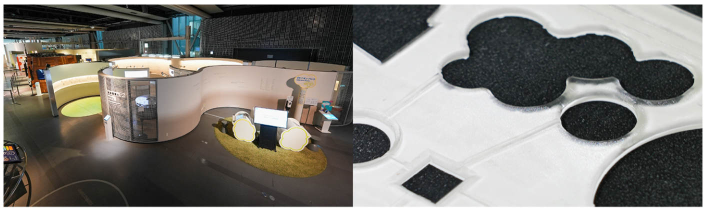
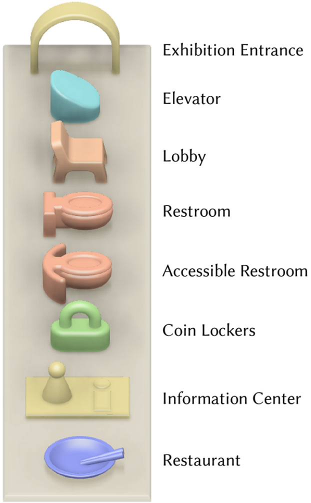
[2] All communication with the participants was in their native language. In this paper, we present any translated content in the form of *"translated content."*

(a) Escalators

(b) Dome Theater



(c) One Exhibit Area



(d) Eight Symbols

Figure 3: Designs for different types of information. (a) The escalators and stairs run parallel in the museum (left) and their representations on several floors (right). (b) The Dome Theater (left) and its representations on several floors (right). (c) One exhibit area (left) and it's representation on one floor (right). (d) Eight symbols that represent museum facilities.

they took (Fig. 3c). This design supports clear separation, differentiation, and scanning. The outlined shape was hollowed to enable audio-tactile interaction (described later).

- The **facilities** in the museum were summarized into eight frequent items. We represented them using volumetric symbols (Fig. 3d), with design guidelines from previous work [18, 19, 26]. For those facilities that take a large space (e.g., lobby and restaurant), their outlines were hollowed out to show the area and enable touch interaction.

To support orientation and navigation on the map, we further defined paths and intersections to indicate how the user can travel.

- The **path** is similar to the tactile paving [32], which suggests a route on open ground. According to the actual layout and flow, we defined a main path in the center of the exhibition space and sub-paths as routes that connect each exhibit's entrance to the main path. All of the paths are represented by $1mm$ wide embossed lines (Fig. 2b).
- The **intersection** is represented as a $10mm \times 10mm$ hollowed square located at the crossing of the paths, which is distinguishably smaller than the exhibit areas (Fig. 2b).

To automate the explanations with different levels of detail, we implemented audio-tactile labels using capacitive sensing on a touch screen. A 12.9-inch iPad Pro was used as a platform to sense touch. When a floor is placed on it, a touch can be sensed directly on the hollowed exhibits. On a structural attraction with a geometric shape (Oval Bridge, Geo-Cosmos, Dome Theater), the audio-tactile label was implemented by redirecting touch from the screen to the surface of the shape using conductive ink, following touch screen redirection technical guidelines [42, 54]. A $3.5mm$ wide tube was cut out in the geometric shape, filled with the conductive ink, and had its top and bottom painted with conductive ink. We also pasted a $4mm$ wide circular tactile sticker at the center to indicate the touchpoint (see an example in Fig. 1c). To tactually distinguish hollowed interactable exhibits from the atrium, we attached a paper with textures on the back of the floor (Fig. 2b). An app that processes touch and provides voiceover information was developed in Unity. As learned from the previous work [7] and through our own testing, we mainly adopted a double tap as the recognized touch to prevent accidental triggering during the exploration. Two modes were developed to serve the needs of free exploration and route-finding:

- In the **Exploration mode**, double-tapping a touchable area triggers the audio explanations.
- In the **Navigation mode**, the user double-taps two exhibits to select the destination and the start. A route with a start, destination, and a number of intersections in-between is generated. Next, The user is instructed to move a finger to the entrance of the start place, which is the location in the exhibit reached by the path. Once the user moves there (without any tapping), she is directed to trace the path to the next location of the route until she reaches the destination.

The final floors are created with a stacked area of approximately $32cm \times 20cm \times 13cm$ stacked, and $2.5cm$ tall, $1.5mm$ thick each floor (Fig. 2c), which was at a 1/400 scale of the actual museum (see specific sizes and details in Fig. 4). This is the largest size that can fit onto an iPad to support audio-tactile exploration. It is designed in Autodesk Fusion 360, and printed with Formlabs Form 3L SLA 3D printer, using Clear Resin material.

3.4 Final Design: Content and Customization

We then conducted a 1.5-hour group meeting with 3 museum staff members, who are not only proficient as museum guides but also experienced in guiding blind users. We decided to include the following contents:

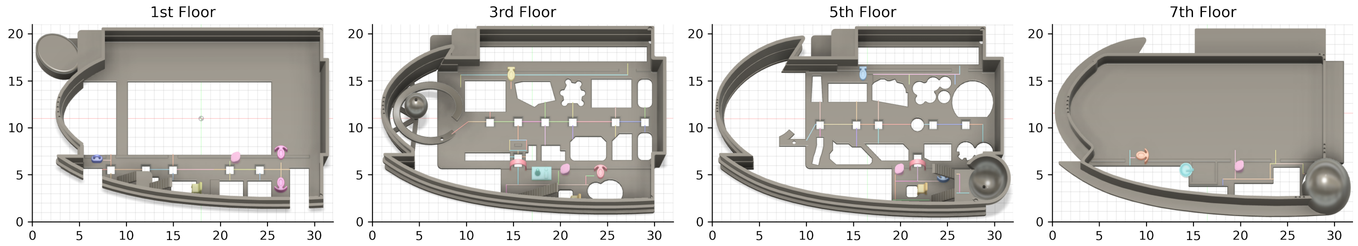


Figure 4: The layout of all the 3D floors. The x and y axes are in *cm*. Different colors marked the floors, facilities, and paths.

- The **audio guide for the 3D structure or the exhibit**, which speaks at one of two levels of detail in turn when tapped. The first level contains name, keyword (e.g., universe, earth, life), and accessibility info (e.g., *"Over there, you can touch a 3D model of the rocket engine."*) The second level contains a 15-second description about it.
- The **audio guide for an intersection**, which speaks the surrounding information when tapped (e.g., *"This intersection is connected to an earth-type exhibit on the top and a universe-type exhibit on the bottom. Eight exhibits are on the left. Five are on the right."*)

The following updates were made to enable user customization:

- Three physical buttons (stop the voiceover, modify the speed, and change Exploration/Navigation mode) were developed. They are clipped onto the iPad and can be triggered at any time using a double-tap (Fig. 2b).
- In the Navigation mode, the route explanation style can be switched between the turn-by-turn (default) and the north-up navigation.

In summary, all elements in our proposed map are as follows: (1) the 3D and layered floors, which include inter-floor structural attractions, the outlined exhibits, and facilities shown by volumetric symbols; (2) the audio-tactile interactions, which include the two-level audio guide of exhibits, an audio guide at the intersections, and navigation by tracing the paths and intersections.

4 USER STUDY

We conducted a user study at the science museum[1] to investigate our research questions and evaluate the effectiveness of our proposed system. The staff who joined the final design process (Section 3.4) stressed that visitors came with different interests and expectations. A fixed task and a rigorous evaluation of the performance might discourage the participants, who are also important stakeholders. We came to agree that a tour design task should be flexible to reflect different user styles and support curiosity and autonomy, which are the museum's important social roles. We included a tour after the map exploration to help visitors generate feedback towards a real museum visit. Each individual study took two to three hours in an order of tour design, conducting the tour, and post-tour interview.

4.1 Participants

We recruited 12 blind participants (male = 5, female = 7) with ages ranging from 24 to 71 years old (mean = 53.8, SD = 13.1), as listed in Table 1. They were recruited via an e-newsletter for people with visual impairments, and compensated $75 plus travel expenses for their time. All of them were first-time visitors who held minimal preset knowledge about this museum where the study took place. Six participants were frequent museum visitors who visited other museums more than once a year. Three visited other museums every two to three years, and three rarely visited a museum. All of them had experience with tactile materials, including tactile graphics (P2, P4–P12) and 3D models (P1–P11).

Table 1: Demographic information of the participants.

ID	Age	Blind since	Navigation Aid	Visiting other Museums
P1	58	41	Guide Dog	Once every 2–3 years
P2	49	45	White Cane	2–3 times/year
P3	63	50	Guide Dog	Once every 2–3 years
P4	60	45	White Cane	Once every 2–3 years
P5	42	32	White Cane	2–3 times/year
P6	49	16	White Cane	Never
P7	57	53	White Cane	2–3 times/year
P8	24	3	White Cane	Once/year
P9	71	60	White Cane	2–3 times/year
P10	43	3	White Cane	A few times
P11	61	56	White Cane	4 times/year
P12	68	35	Guide Dog	Never

4.2 Task and Procedure

4.2.1 Pre-Interview. The first part of the study, tour design, took place in a guest room located on the first floor of the museum. Before presenting them the system, we conducted a roughly 10-minute pre-tour interview, hearing about their tactile experience and previous preparations before going to other museums.

4.2.2 Structural Exploration. Next, we presented the fully stacked BentoMuseum 3D model and allowed the participant to explore freely by touch as we introduced the basic external structures. We informed participants that the museum had the shape of a boat, and the front "bow" should be kept on the left-hand side for a consistent orientation. We then introduced the "Bento Box" characteristics and encouraged the participant to take the floors apart one by one. Next, the floors were stacked back one by one, and we encouraged the participant to touch the inter-floor structures (e.g., escalators and Oval Bridge) to learn how floors are connected. Finally, the participants were primed with a list of 10 icons (eight in Fig. 3d, escalator and wall), which is separately prepared on a sheet. This phase took roughly 10 minutes.

4.2.3 Training Phase. A training phase was conducted to familiarize participants with the audio-tactile interactions. The participant was shown the 1st floor map on the touch screen in Exploration mode. The following steps were taken: (1) double-tap the special exhibit zone to listen to the name; (2) double-tap it again to hear the details; (3) double-tap the intersection to hear information of surroundings; (4) find the guest room by double-tapping; (5) double-tap the speed buttons to adjust voiceover speed; (6) double-tap the cancel button to stop the audio; (7) double-tap the navigation button to change to the Navigation mode; (8) double-tap to set the special exhibit zone as the goal and the guest room as the start, and trace the route following the audio guide. This entire process took around 10 minutes.

4.2.4 Tour Design Task. A loosely structured tour design task was conducted. The individual participant was asked to imagine the following real-world scenario: The system is placed at the entrance of the museum, and they are using this system to select the exhibits of interest and design a unique tour for themselves. With the help of the staff, they can place any floor on the touch screen. From a total of 28 exhibits, they were asked to select 6 (equivalent to a two-hour tour) and to try to build a mental map with routes connecting the spots within 45 minutes. Considering the real-world scenario, they were also free to take notes. During the task, a researcher was taking notes of the selected spots for later evaluation. We video and audio recorded the session and saved app log data for later analysis.

When time was up or the participant was finished, they were asked to orally explain the (1) name and (2) orientation and location of each spot. Based on their explanations after the task and during the tour, we determined which level of mental map they possessed. In this study, we defined five levels of the mental map:

- Level 1: Hardly remember any exhibits they chose.
- Level 2: Remember some of the exhibits they chose.
- Level 3: Remember all of the exhibits they chose.
- Level 4: Remember all of the exhibits they chose and which floor each exhibit is on.
- Level 5: Remember all of the exhibits they chose and the location of each exhibit.

We also asked the participants to give a self-evaluation of what level of the mental map was needed.

4.2.5 Conducting the Tour. To validate their mental map in a real-world setting and gather feedback on the important factors before visiting the exhibitions, we invited the participant to experience the designed tour. We shortened the two-hour tour to approximately 15 minutes, the time allotted for walking over the designed tour with a museum guide and listening to elaborated guidance of a chosen exhibit to get a taste of the museum. We encouraged participants to concentrate on validating their mental map, and they were allowed to fully explore the museum after the study.

4.2.6 Post-Tour Interview. A roughly 30-minute interview was conducted after the participant was settled back in the guest room. The interview included two forms: a seven-point Likert rating, from strongly disagree ($score = 1$) to strongly agree ($score = 7$), and free responses. Four sections composed the interview: (1) rating the overall experience of using the system (Q1–Q3 in Fig. 5); (2) rating the overall system usability (Q4–Q6 in Fig. 8); (3) rating the 3D floors and audio-tactile interactions, which were further divided into eight specific elements in terms of A. understandability and B. usefulness (Q7.A–Q14.B in Fig. 9); (4) free responses about using the map prior to the visit, the strengths and limitations of the system, applications, and other findings after the tour. For all of the ratings, we asked participants to consider or imagine accessing information by audio means, such as reading a homepage when preparing for a visit, as a baseline ($score = 4$).

5 RESULTS

5.1 Preparations before Going to the Museums

Eight out of nine who had visited museums said they would gather information ahead of time through web pages and other means. The information they hoped to collect included exhibit information (all), floor information (P2, P3, P7, P8, P10, P11), the detailed route to get to the exhibits (P7, P8, P11), and facility information such as restaurants (P4, P5) and opening hours (P5). Two participants said it was difficult to acquire information they needed through web pages, so they made calls (P5, P7).

5.2 Performance of Information Access

5.2.1 Overall Experience. All participants successfully finished the tour design task within the allowed time (45 minutes). The ratings related to information access through the task are summarized in Fig. 5 (Q1–Q3). The participants strongly agreed that by using the system they could get an overall image of the museum (median = 7). They also agreed that they were able to grasp the details of the museum (median = 6). All participants agreed (median = 7) that it is important to decide on their own where to go. Participants were excited about having good control of information and being able to design the tour independently based on their own interests:

> A1: *"The museum visits are precious parts of my life. I really don't want to miss anything interesting. Thus I want both independent exploration and recommendations."* P9
>
> A2: *"It might be nice if there were a recommended course, but I would still like to explore it myself. There is a sense of security to control where I go."* P11

5.2.2 User Exploration Styles. By analyzing the double-tap log data during the Exploration mode, we identified several hand movement styles when the participants were exploring the floor. Research has found that touch readers were taught to first systematically scan in a circular pattern, and this effective scan strategy was used with both tactile map and 3D models [25]. We were interested in learning whether did they naturally perform this exploration strategy. Although all participants had tactile experience, we identified that three participants (P8, P9, P12) under-explored the floor (see example in Fig. 6a). They only touched some of the exhibits, and no circular pattern was formed. Three participants (P3, P5, P11) over-explored the floor (see example in Fig. 6b). Their tapping covered most exhibits, but their fingers traveled randomly by long distances

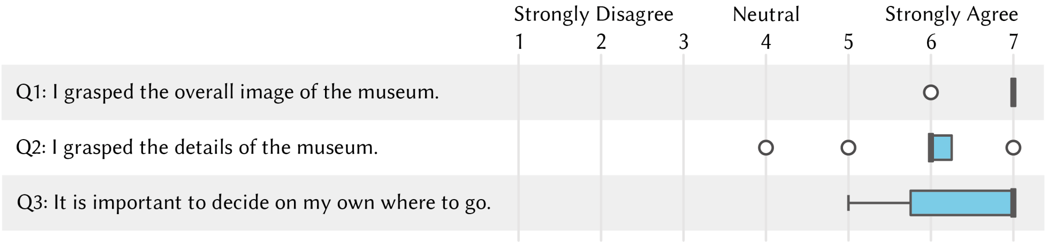
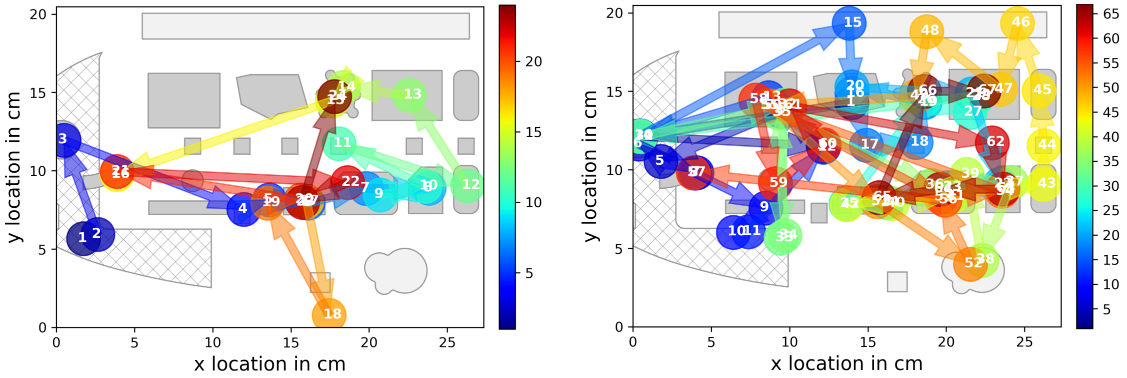
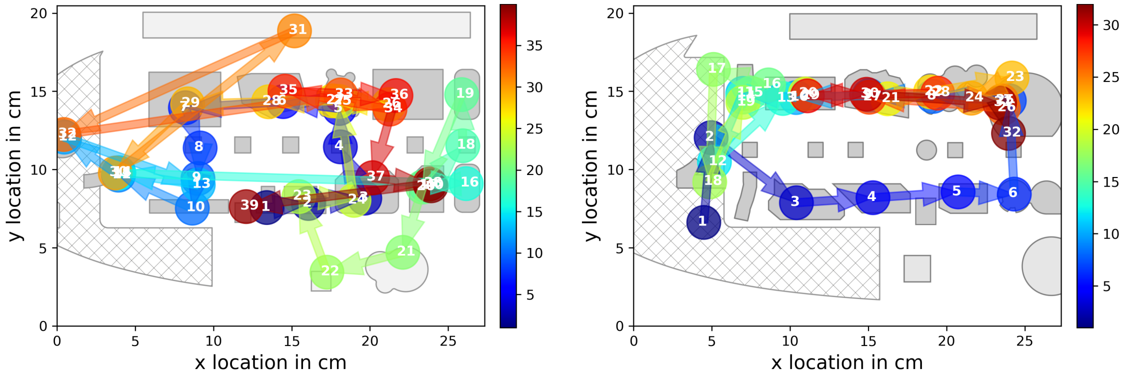


Figure 5: Questionnaire results of the overall experience of our system (Q1–Q3).



(a) Under-exploration (P8, 3rd floor) **(b) Over-exploration (P3, 3rd floor)**

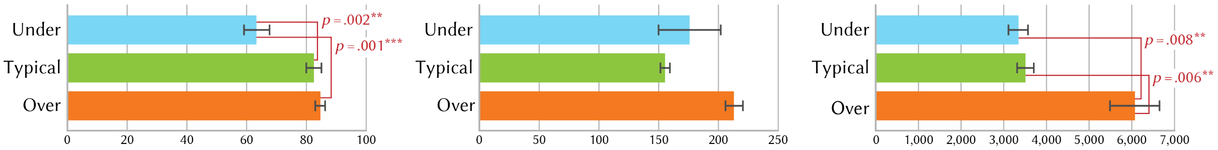


(c) Typical (P4, 3rd Floor) **(d) Ideal (P4, 5th floor)**

Figure 6: Different exploration styles. The location of first level touches and their sequences during the Exploration mode are plotted on a 2D floor map. The arrow indicates the consequence, and the color shows the touch order.

on the map. A clear, circular pattern was hardly observed. The rest of the participants showed a typical style (see example in Fig. 6c). Even though they had slightly long traveling, they were able to build a relatively circular and systematic pattern. In latter exploration, one participant (P4) also showed an ideal style (see example in Fig. 6d) with a very systematic circular pattern. After one exhibit was explored, he moved to the closest exhibit. This style exhibited the "circular and complete" scanning strategy, which was noted as one of the most efficient strategies for exploring a map [25].

We next analyzed the relationship between the identified styles and the quantitative performance, and the latter was used to identify exploration effectiveness on tactile graphics [5]. These quantitative measures include coverage percentage of the exhibitions, tap counts (perceived as a more reliable indication of time in our case compared to the clock time), and exploration distance. We computed a Univariate ANOVA with a Bonferroni Pairwise post-hoc test to compare the results. Mean coverage for under-exploration was significantly lower than those for typical ($p < .01$) and over-exploration ($p < .001$) (Fig. 7a). There was no significant difference among the three styles in terms of tap count (Fig. 7b). Mean exploration distance for over-exploration was significantly higher than those for typical ($p < .01$) and under-exploration ($p < .01$) (Fig. 7c). The results show



(a) Coverage (%) (b) Tap Count (c) Exploration Distance (cm)

Figure 7: Mean (a) coverage, (b) tap count, and (c) exploration distance for the typical, over-explored and under-explored groups. p: p-value of the Univariate ANOVA with a Bonferroni Pairwise post-hoc test (*** and ** indicate the 0.001 and 0.01 levels of significance, respectively).

that among all the styles, those participants who hold a typical style are having high coverage and short exploration distance, which indicated relatively efficient explorations.

5.3 Performance of Mental Map Building

Among twelve participants, nine participants (75%) remembered all the exhibits they chose and their locations (level 5), two (16.7%) remembered the exhibitions and their corresponding floors (level 4), and one (8.3%) remembered a part of the chosen exhibits (level 2). Level 5 participants could explain the general location of each exhibit (e.g., *"Exhibit A is on the upper-left side of the 5th floor* or *"Exhibit B is located to the left as you exit Exhibit C*), and we determined that they had built a "rough" mental map.

All participants noted that there could be a clear difference between with and without a mental map, and some commented that 3D and layered floors and the Navigation mode of the proposed system were effective for building a 3D mental map (see Section 5.4.2 and Section 5.4.3). The participants noted that there was an improvement in orientation (P2, P6, P9, P10) and confidence that they were safe and would not get lost (P7–P9, P11) with a rough mental map during the visit, compared to their previous museum experiences without a mental map.

> A3: *" Without the mental map, I didn't understand where I was walking. Controlling where I was going using the map, I walked with a sense of accomplishment, and everywhere I went became a lot more fun."* P2
>
> A4: *" Without a rough mental map, it just feels like being pulled around and it's simply boring and tiring."* P9
>
> A5: *" If I don't have a mental map [before following a course], I don't remember where I went, I don't know how long I will walk. Now when I notice where I am, I can calculate back from the mental map, and I feel a completely different level of security."* P8
>
> A6: *" It feels safe to decide where I go, understand the relative locations, and have a structure of the museum in my mind. It makes the tour and the discussion easier. I might make mistakes about the route, but I can soon integrate the new information and easily correct my map."* P7

On the other hand, all participants contented themselves with the current level of the mental map they built. The participants thought building a higher level of mental map, which means remembering the route clearly, would be unnecessary for the following reasons: (1) the museum is not a frequently visited place (P4); (2) there is too much intellectual information to remember (P9, P11, P12); and (3) they felt the complex environment is not yet ready to allow them to travel alone (P1, P5, P6).

> A7: *"It was easier to remember the routes than the exhibit names. I wish the names could be replaced with another format, such as numbers."* P9

5.4 System Usability

5.4.1 Overall Usability. The results of three ratings related to usability are summarized in Fig. 8 (Q4–Q6).

All participants agreed that the system was useful (Q4, median = 6.5) and enjoyable compared with getting information from the homepage (Q6, median = 6.5). In particular, seven participants (P1, P3, P4, P5, P7, P10, P12) commented that linking geometric or outlined shape, location, and content using the 3D model and audio-tactile labels was both effective and enjoyable.

> A8: *"I'm not good at building mental maps, but I somehow managed to do it by touching and listening."* P1
>
> A9: *"Processing the audio-tactile information, I could understand the content and arrangement of the exhibit booths."* P10
>
> A10: *"Compared to merely reading the homepage, touching and listening made me excited about the following trip."* P4

Three participants (P2, P11, P12) were also excited about the independence they obtained in the exploration.

> A11: *"The best thing is that I could explore independently without asking for help."* P11

The participants other than P12 leaned toward giving a rating that the system was easy to use (score equal to or greater than 5). Six participants commented that the double-tap was not easy at first (P2, P4, P6, P8, P9, P12), which influenced their score on Q5. The participants pointed out that there was a learning curve, and it largely depended on the user's proficiency with mobile devices and voiceover controls.

> A12: *"I wasn't used to double-tapping and didn't know where I could tap at first. But I got proficient after I spent more time with it."* P6

Three participants hoped to use a more explicit and seamless touch to trigger the audio (P2, P6, P8), although they acknowledged that a single-tap would trigger unnecessary sounds (P2, P8).

> A13: *"The double-tap also reacted to other fingers during exploration. I think touch with a stronger force is better than double-tap. It would respond to more conscious movements."* P6

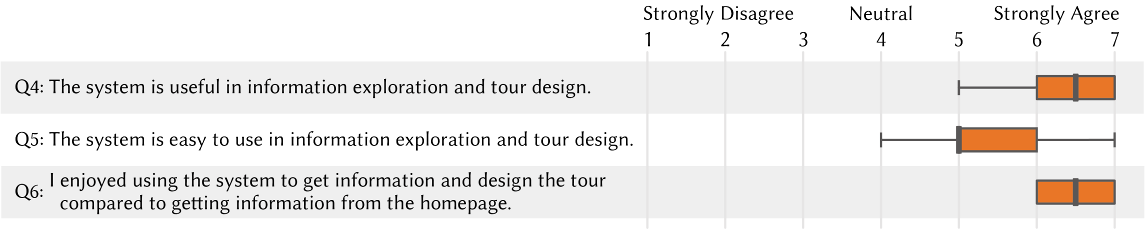


Figure 8: Questionnaire results of the overall usability of our system (Q4–Q6).

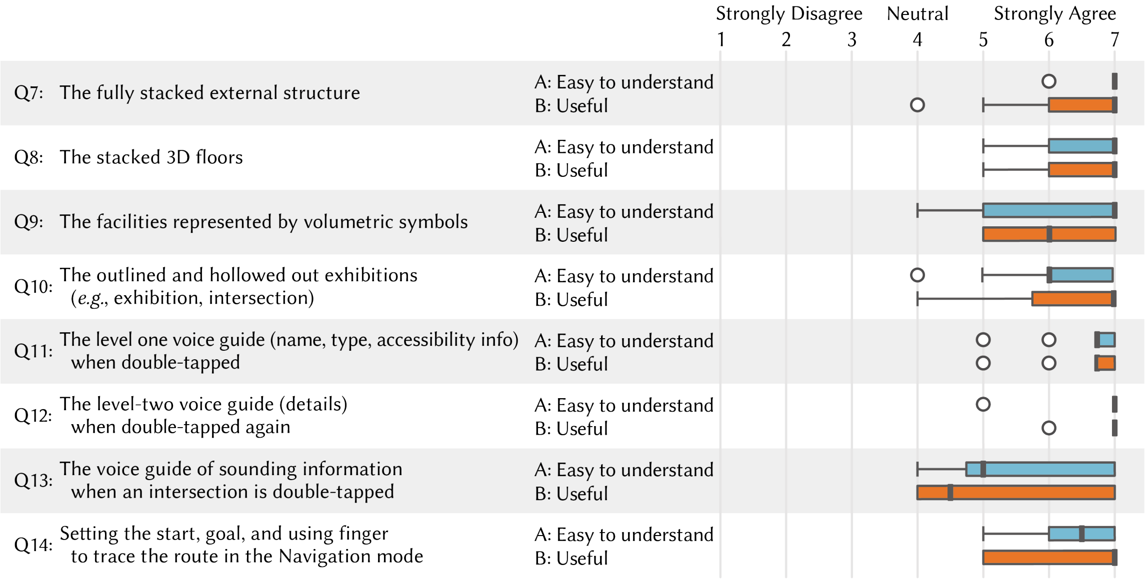


Figure 9: Questionnaire results of the usability of 3D and layered floor-related elements (Q7–Q10) and audio-tactile interface-related elements (Q11–Q14). A: [The element] is easy to understand, and B: [It] is useful in exploration and tour design.

5.4.2 Usability of 3D and Layered Floors. The results of ratings related to 3D and layered floors are summarized in Fig. 9 (Q7.A–Q10.B). In general, all 3D and layered floor-related elements were rated as understandable and useful (median >= 6). The fully stacked 3D building (Q7) and partially stacked 3D interlocking floors (Q8) received especially positive ratings (median = 7). The participants felt it was especially beneficial and enjoyable to be able to stack and touch structural attractions in the building, such as the Oval Bridge, the Dome Theater, the atrium, and the series of long escalators (P2, P4–P8, P10). They noted that they were attracted by the "Bento" characteristics, which motivated them to learn structural details.

> A14: *"When building a mental map before, I could only make a flat map for one floor. But using this system, I had a stronger impression of 3D movement. I was so excited to walk [with a finger] in the 3D space."* P4
>
> A15: *"By exploring the structures in order, such as the entrance and escalator, I feel like I was walking in the museum. It gave me the sense of being immersed into the museum."* P6
>
> A16: *"The building can be separated, and it is easy to understand the details. In the case of a tactile map, it is difficult to understand how to move from floor to floor."* P8

Participants commented that touching the structural attraction's geometric shape on the model was the best way to understand its actual structure (P2, P12). As a result, all of the participants chose the Oval Bridge to be a part of the tour they designed.

> A17: *"It would be impossible to understand the structure of the Oval Bridge without the 3D model."* P7

About the outlined exhibits, not every participant associated them with the actual size and outline of the exhibition area. However, when they noticed the association, they were very positive about this kind of information being provided.

> A18: *"One exhibit was a narrow and long chamber. When I went in, I was like 'That's it!' I remembered the shape clearly with my fingers. The impression would not be that strong if I had only heard from the voice guide that it was narrow and long."* P4

The volumetric symbols were understandable but not perceived as especially useful due to the fact that the task was designing a tour. They acknowledged that even though it was not very much used, it would be absolutely important in the actual visit (P4). Participants also noted that facilities, especially the restroom and front desk, possibly needed touch interactions (P4, P10, P11).

> A19: *"I want to know more about the ticketing information and where the flush button is in the restroom."* P11

The study did not find particular challenges in stacking and orienting the floors due to the model's irregular shape, the magnets' support of a specific lockup, and the maintained model orientation. However, some participants reported difficulties in recognizing separable 3D structures. They noted that even though the inter-floor structures (e.g., Oval Bridge and escalators) on the bottom floor were self-explanatory, it was difficult to locate them on the top floor alone (P1, P3, P6).

5.4.3 Usability of Audio-tactile Interface. The results of ratings related to audio-tactile interactions are summarized in Fig. 9 (Q11.A–Q14.B). The exhibition's two-level audio information (Q11 and Q12) and Navigation mode (Q14) were rated as understandable and useful (median >= 6.5). After obtaining information, all participants included at least one exhibit with accessible content in their tour. Two participants (P4, P11) chose the north-up navigation style, and the rest used the default turn-by-turn style. Participants mentioned that the navigation was helpful for them to develop the route in their minds (P1–P4, P7, P11) and that using a finger to trace the route was an enjoyable experience (P1, P3, P4, P7, P10).

> A20: *"Thanks to the Navigation mode, I could learn relative locations and build a mental map."* P1
>
> A21: *"It was fun to grasp the location relationship by tracing the route with a finger."* P3

Nevertheless, the need for the Navigation mode might depend on the tactile and orientation ability:

> A22: *"I don't need the Navigation mode now because the layout is easy. I can understand and remember it just by touch."* P8

Participants somehow agreed that double-tapping the intersection was easy (Q13.A, median = 5) and useful (Q13.B, median = 4.5). Four participants reported that the intersection was small for a double-tap (P5, P7, P9, P10). In terms of usefulness, we received a variety of comments and suggestions.

> A23: *"I can touch the exhibit to learn the needed information, thus I didn't use the intersection."* P8
>
> A24: *"I might have touched a number of exhibits, but I don't know which are untouched. I hope the system tells me what area hasn't been explored. Probably it is best at an intersection."* P6

5.4.4 Free Comments and Suggestions. Participants freely expressed where they wanted to use the system. The answers are categorized as follows: locations containing many points of interest, such as museums (P2, P5, P6, P7, P9, P11), amusement parks (P5, P11, P12), and department stores (P5, P9, P11); large and complex places, such as convention halls (P6) and airports (P2, P10); and frequently visited places, such as train stations (P3, P8, P10, P11), hospitals (P1, P11), city halls (P4, P11), schools (P4, P6), and in the train (P4).

Participants also raised a variety of hopes and suggestions of what the system could offer.

> A25: *"I want to bring the system with me, and let it explain things to me just like a tour guide. Like 'We arrived here. It is about...' I hope we can hold a discussion in-depth about the exhibition. It would also be nice to tell me where it is crowded and where it isn't."* P5
>
> A26: *"The museum has a shop, right? I want to learn what are popular souvenirs. I also want to know the restaurant menu. I want to hear a lot of options in this museum!"* P11
>
> A27: *"I want to use it at the entrance when I come again. But it's not only for the visually impaired. Foreigners, children, it can be useful for everybody!"* P12

6 DISCUSSION

6.1 RQs: Effectiveness in Information Provision and Mental Map Building

6.1.1 RQ1. How can we make the vast amount of needed information accessible and understandable on a museum map? While contemporary museums contain a massive amount of multidimensional information, through the participatory design with stakeholders we categorized the needed information into structural information (layered and stackable), exhibition (name, detailed description, and accessibility), facilities, and their locations on the map.

Our proposed method, BentoMuseum, has been proved effective in obtaining the above types of information (Section 5.4.1, Q1 and Q2). It helped the participants to build knowledge that integrates the structural information, location, and contents. All of the ratings of the purposed system outperformed the baseline of accessing information by reading a web page, the current prevalent method. The multi-sensory method was noted to be more helpful than using either a tactile map or an audio guide alone (A8 and A9). Participants especially praised the innovative "Bento Box" characteristics of the map as being curiosity-arousing, enjoyable and understandable (Section 5.4.2, Q7 and Q8). Enabling the users to travel from one floor to another by touch when the map is stacked gave them a sense of immersion (A14 and A15). It also made the structural attraction's geometric shape, especially those crossing several floors, accessible and understandable in a concrete way (A16 and A17).

Aside from the provision of information, we also found a set of advantages that BentoMuseum contributes toward the social inclusion of the museum. It empowers users to achieve independent exploration and decision-making, which are reported to be valuable (Section 5.2.1, A1 and A2) [41]. At the end of the study, participants showed their gratitude for the museum becoming more accessible and inclusive. Frequent museum visitors (P5, P11) ideated further customization (Section 5.4.4, A25 and A26), and those who rarely visited a museum (P12) expressed the desire to come again for an in-depth exploration (A27). The findings indicate that the system can help to bridge the understanding between the blind visitors and the information provider and contribute to the social role of museums, that is, to welcome blind visitors and challenge stereotypes.

6.1.2 RQ2. Is building a mental map possible and significant in the museum context? The results from a non-rigorous five-level evaluation show that most participants could build a rough mental map using our system (level 5 in Section 5.3). The proposed system was helpful in the following ways: In addition to the other elements that allowed them to explore the exhibits of interest, Navigation mode was beneficial for drawing location relationships on a floor (A20 and A21), and the touchable inter-floor structures helped them to connect floors and build a 3D mental map (A14–A16). Different from frequently visited places where Orientation and Mobility (O&M)

training has been conducted, the visitors exhibited resistance to building a detailed mental map of the museum (Section 5.3). The results demonstrate the ability of our system to help build the current type of rough mental map (A20 and A21) and indicate its ability to support route memorization (A7). Even though creating and maintaining a finer mental map imposes a cognitive load in addition to information access and tour design, it is necessary for visually impaired people's independence [22]. A future work is to rigorously measure spatial memory to support O&M training.

On the other hand, when we asked participants' thoughts and impressions about the mental map after the museum tour, all of them explicitly stated that the current rough mental map was beneficial for their tour. First, it supported their orientation, which made their tour meaningful (A3 and A4). Second, it gave them a sense of safety and the confidence that they will not get lost (A5 and A6). This confidence is an objective of navigation for the visually impaired in an unfamiliar environment, which supports autonomy and self-reliance [8, 28]. Through such comments, we infer that the rough mental map is significant in improving the museum experience.

6.2 Limitations and Next Steps

Some usability issues are related to system design, which can be addressed by further improvement: (1) Enlarge the small touch area (e.g., the intersections) to fit different finger sizes. (2) Refine 3D details to make clear, inter-floor structures available on both top and bottom floors. (3) Refine the audio content. The audio-tactile information at the intersection was noted as not useful (A23); instead, it can be used to report the exhibit coverage as P6 suggested (A24). Some participants also found double-tap difficult. This input method was used to prevent unintentional touches but might be unnatural when all fingers are used for exploration. Seamless touch interactions with less learning effort (e.g., force recognition suggested by P6 in A13) need to be further investigated.

To make the system a part of the museum facility, the display and communication methods need to be further examined: (1) Self-serve floor-changing. The participants did not confuse the order of the floors because we handed them each floor upon request. We also instructed the participants to keep the same orientation. To order and orient the floors in the wild by the users themselves, clear labels, verbal instructions, and tactile indications need to be tested. (2) Automated instructions. Our study proved that instructions delivered by museum staff (Section 4.2.2 and Section 4.2.3) were beneficial to understanding the external structure and learning the system. Automating those instructions is needed to reduce the staff expertise for system operation. (3) Time and interest-based instructions for efficiency. The tour design task took approximately 45 minutes, which was a considerable amount of time that not every visitor can afford. Our log data show that the movement styles were linked to efficiency, and the most efficient style was not performed naturally (Section 5.2.2). Since museum visitors might have varied tactile skills and needs, customizable instructions that support an efficient exploration need to be investigated.

6.3 Generalizability and Lesson Learned

Many participants hoped that the method would become available in museums. Interestingly, they also suggested applying the methods to other locations that troubled them, attracted them, or required their confidence (Section 5.4.4).

Even though the design method is currently implemented in one particular museum, it could be generalized to a variety of locations, especially buildings with irregular external or internal structures and complex information. We suggest the following design considerations in applying our method: (1) Categorize the complex information of a building into three types: structural attractions, exhibits (or informative attractions), and facilities. Simplify the shape of each type into 3D elements, 2D relief elements, and volumetric symbols on the floor, respectively. (2) Make floors stackable and ensure the inter-floor 3D elements can be understood by touch when floors are stacked. (3) Add audio labels to the points of interest and ensure they can be recognized by touch. Such a design can be implemented with relatively inexpensive materials: 3D printers, touch screens, and conductive ink.

Through our study of introducing an entire museum to first-time visitors, another important lesson we learned was that instruction, guidance, and encouragement could motivate the users and promote effective information provision when presenting a complex map. In our study, we instructed the users to travel through inter-floor structures using fingers and consequently learned they especially enjoyed these structures. If we failed to do so, some participants might overlook them due to the large number of 3D and 2D elements on each floor. The methods to communicate the map and motivate the users should be a part of the map design.

6.4 Toward Universal Access

Participants showed an interest in having the BentoMuseum as an "ask-me-anything" box (A25 and A26). Further investigations (e.g., conversational agent) should be made to fulfill individual needs while maintaining simple operation. Some participants also expected it to support the needs of those beyond themselves (A27). Indeed, it can potentially share information between different stakeholders: the blind visitors, museum staff members and service providers, domestic visitors, foreign visitors, and other visitors with disabilities to create universal access. For example, the information that is now decoded to audio might be presented in sign language to support hearing impaired visitors in gaining information access. Different services can be connected through the map to extend access throughout the visit.

7 CONCLUSION

This work investigated how a museum with a massive amount of multidimensional information could provide accessible maps to blind visitors. We designed 3D and layered museum maps for each floor of a science museum which can be stacked or placed on a touch screen to learn different levels of detail. An authentic tour design task with 12 blind first-time museum visitors showed our system's effectiveness in obtaining information and building a rough mental map. Through user feedback, we learned the potential of our system to contribute to a positive and inclusive museum experience. Our next steps include expanding this design method to other museums and attractions, making it smarter to support different needs, and making it available along with other means of assistive technologies to support autonomous museum exploration.

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