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

By Xiyue Wang, Seita Kayukawa, Hironobu Takagi, and Chieko Asakawa

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, choose exhibits that attracted them, and build 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 while traveling in the museum.

1. INTRODUCTION

Museums, as audience-centered institutions playing a range of educational and social roles, are now more than ever aware of the importance of delivering equality, diversity, and inclusion.[4] However, the museum's unique environment presents challenges to visually impaired visitors in accessing information prior to a visit. First, contemporary museums have distinctive architecture, internal design, and "inter-floor structures" (that is, stairs and walkways connecting the floors, see an example in Figure 1d) as a part of their exhibitions.[16] Blind visitors struggle with comprehending intricate "multidimensional information," including the building's shape, inter-floor structures, exhibit names, descriptions, sizes, and locations. Second, while some museums offer a straightforward layout with predetermined routes, most of them feature open arrangements of exhibits with potentially unclear routes.[5] In such museums, visitors typically explore and select exhibits based on their personal 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.

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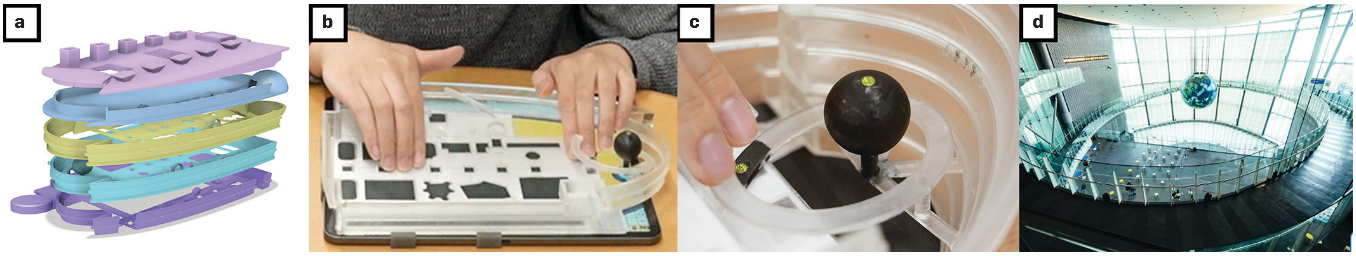
Accessible maps are the means for visually impaired visitors to learn about a site. Tactile maps are often available in public spaces and institutions to help the user build a mental map before going to a new place.[21] Since the effectiveness and understandability of a tactile map largely depend on the user's tactile skills and abilities,[17] three-dimensional (3D) maps with volumetric symbols and audio-tactile labels have been developed for ease of understanding and allowing autonomous map exploration. 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 is not a frequently visited place, blind visitors might feel it's particularly challenging to obtain information, orient themselves, and build a mental map. To bridge the gap between museums and

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 overlaid on an iPad app. (c) A user explores a structural attraction with fingers (a circular walkway named Oval Bridge that goes around a "globe-like" display named Geo-Cosmos). (d) The Oval Bridge and Geo-Cosmos in the museum.



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 (for example, 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?

Prior research developed single-floor plans[10,15] or reproduced external structures,[13] rarely addressing complex multi-floor settings like museums. Using a participatory and user-centered approach, we designed BentoMuseum, a 3D and layered museum map with audio-tactile interactions, to help blind users obtain information and understand the 3D attractions through tactile explorations (Figure 1).[a] The system contains two main elements: the 3D and layered floors (Figure 1a), which can be either interlocked to allow vertical exploration between floors (Figure 1c) or separated to support horizontal exploration of a single floor; and interactive touchpoints on the floor that allow audio feedback by touch (Figure 1b). When one floor is placed on a touch screen, information and tactile navigation with audio support can be triggered by tapping. Our innovation lies in the novel design of stackable 3D floors on a touch screen, which includes 3D and 2D attributes for providing comprehensive information that encompasses external and internal structures, exhibits, facilities, 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. They were encouraged to explore extensively, obtain information, select exhibits of personal interest, and construct mental maps. Participants expressed their map exploration styles and elaborated on their needs for information access. 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 about not getting lost, and led to a positive and inclusive museum experience.

2. BACKGROUND AND RELATED WORK

2.1. Museum information accessibility.

For a visually impaired individual, the museum visit experience begins even before arriving at the location.[23] Addressing this, information provision has been recognized as a prioritized accessibility requirement.[11,23] A U.K. survey revealed that the majority of museum websites lack comprehensive accessibility information, leaving blind or partially sighted individuals unable to plan independent visits effectively.[3] Additionally, Argyropoulos et al. found that intricate museum architecture and interior design pose barriers to access, resulting in diminished motivation and negative emotions.[1] To address information access and orientation for visually impaired visitors, Vas et al. recommended introducing audio presentations of the museum space and exhibitions at the start of the visit.[24] Tactile maps and 3D models have also been proposed. Urbas et al. employed 3D printing to create physical floor plans for tactile exploration,[22] while Holloway et al. designed 3D maps with distinct icons, suggesting their availability for exploration before events.[13] Additionally, Leporini et al. emphasized the significance of allowing visually impaired individuals to explore and familiarize themselves with large cultural site layouts to gain an overall understanding.[15]

2.2. Accessible maps for the visually impaired.

Maps that enable tactile explorations are designed for the visually impaired to learn about the environment. Traditional tactile maps often use raised lines, symbols, and keys,[17] but they struggle to effectively depict 3D structures and varied heights.[12] Given that the understandability of tactile maps hinges on users' tactile sensitivity[17] and their proficiency in interpreting tactile graphics,[21] research has explored maps featuring distinct 3D structures to enhance comprehension. Leporini et al. developed indoor floor plans for a cultural site, aiding both visually impaired and sighted individuals in pre-visit exploration.[15] Gual et al. found it was easier to memorize 3D volumetric symbols over 2D symbols,[9] and Holloway et al. proposed design guidelines for 3D symbols.[13] Holloway et al. further compared 3D printed maps with tactile maps and found that 3D maps were preferred. Their use of easily understood icons and relative heights improved short-term memory recall.[12] Gual et al. designed urban maps with volumetric and relief attributes, proving their worth in interpretation and understanding. However, they also found that the maps required verbal support to be used autonomously.[10]

2.3. Touch sensing and audio-tactile labels.

Audio-tactile maps using touch sensing or buttons have been proposed to support understanding in addition to tactile sensations. Brock et al. introduced an interactive map with a multitouch screen, raised-line overlay, and audio output. Replacing braille with audio-tactile interaction significantly enhanced efficiency and satisfaction compared to tactile maps.[2] Comparing tactile maps and interactive small-scale models, Giraud et al. demonstrated that interactive models helped to improve space and text memorization.[7] It was also found that perceptible buttons triggering varied audio content facilitated interactive, self-guided exploration[12,15] and heightened emotional engagement.[25] Leveraging printing technologies, map data, and touch screens, researchers have made printed maps instantly interactive with audio feedback by overlaying the map on a touch screen.[8,20]

Previous research has built a strong foundation for de-

a The 3D data and code are available at https://bit.ly/4eId5b5.

veloping 3D maps featuring audio-tactile labels. Nonetheless, these efforts primarily concentrated on single-floor layouts with limited 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,[b] which has a distinctive structure and symbolic interior attractions. It is a seven-floor building with a large-area atrium (with the 2^{nd}, 4^{th}, and 6^{th} floors mainly atrium space) and structural attractions, such as a series of escalators that directly connect all the floors (Figure 3a), a walkway called Oval Bridge that goes around a "globe-like" display named the Geo-Cosmos (Figure 1d), and a Dome Theater with half of it inside the building and the other half extended into the exterior (Figure 3b). It also lacks maps that can be perceived by touch.

We used 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 20 blind museum visitors and three staff members, and one group meeting with those staff members.

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

One of the designers, P0, is a blind adult female, 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."*[c] This was the initial attribute of the map we hoped to investigate: a 3D model that contains internal structures.

b https://www.miraikan.jst.go.jp/en/

c All communication with participants was in their native language. This paper presents any translated content in the form of *"translated content."*

3.2. Prototype 1: Feedback of a realistic model.

An initial map design took the form of a realistic 3D print of the museum floor (Figure 2a). We sliced the 3D model into floors and encapsulated the detailed information, such as the walls and tables. 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 (that is, 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:

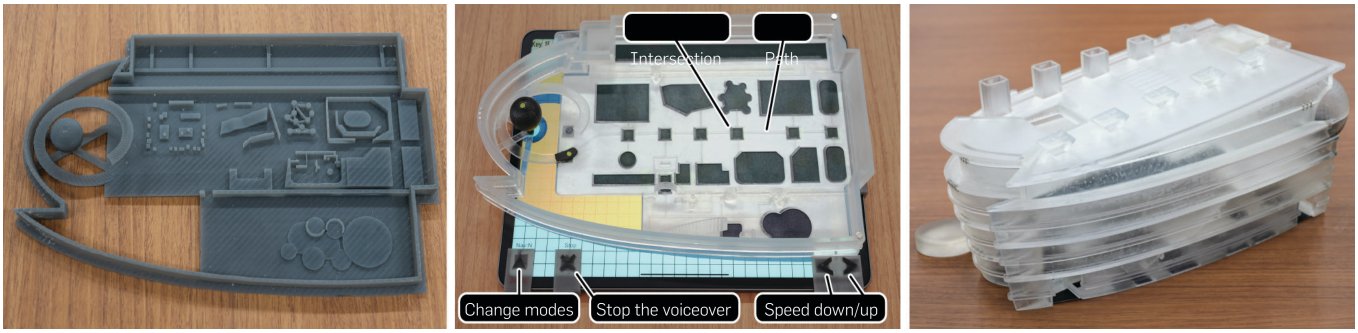
- **Facilities:** In addition to exhibits, basic map elements such as restrooms, elevators, and escalators also needed to be included.
- **Orientation and navigation:** The map should support identifying the entrance, main route, and how to move around. These elements support the development of a "mental map," which is crucial for blind people.

The feedback highlighted that the 3D map effectively conveyed structural characteristics, while the tactile map preserved scanning, aligning with prior findings.[12] This motivated our focus on 3D maps, while harnessing the strengths of both 3D volumetric and 2D relief attributes.

3.3. Prototype 2: 3D floors and audio-tactile interactions.

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

Figure 2. The printout of an early iteration and the final design.



(a) Prototype design 1: Realistic model **(b) Final design: The 3rd floor** **(c) Final design: The fully stacked model**

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 its representation on one floor (right). (d) Eight symbols that represent museum facilities.

(a) Escalators **(b) Dome Theater** **(c) One exhibit area** **(d) Eight symbols**

▸ **Structural attractions** include inter-floor structures and symbolic spatial structures (Figure 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 (Figure 3a); (2) simplifying prominent walls into 1mm-tall and 3mm-wide cuboids; and (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.[6] Floors can be partially stacked to simulate how to walk between them (Figure 3a) or fully stacked to show a facade (Figure 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 they took (Figure 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 (Figure 3d), with design guidelines from previous work.[9,13] For facilities that take a large space (for example, 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** indicates a route on open ground. According to the actual layout and flow, we defined a main path 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 (Figure 2b).

▸ The **intersection** is represented as a 10mm × 10mm hollowed square located at the crossing of the paths, which is distinguishably smaller than the exhibit areas (Figure 2b).

Interactions. 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 (for example, Geo-Cosmos in Figure 1c), the audio-tactile label was implemented by redirecting touch from the screen to the 3D surface using conductive ink, following touch-screen redirection technical practices.[19] 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 Figure 1c). To tactually distinguish hollowed interactable areas from the atrium, we attached a paper with textures on the back of the floor (Figure 2b). An app that processes touch and provides voiceover information was developed in Unity. We adopted a double tap as the recognized touch from the previous work[2] to prevent accidental triggering during the exploration. Two modes were developed to serve the needs of free exploration and route-finding:

▸ In **Exploration mode**, double-tapping a touchable area triggers the audio explanations.

▸ In **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 start, which is the location in the exhibit intersected 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 reaching the destination.

The final floors are approximately 32cm × 20cm × 13cm stacked, and 2.5cm-tall 1.5mm-thick each floor (Figure 2c), which was at a 1/400 scale of the actual museum. 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 three 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:

▸ 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 (for example, universe, earth, life), and accessibility info (for example, *"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 (for example, *"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 were clipped onto the iPad and can be triggered using a double-tap (Figure 2b).

▸ In 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; and (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 same science museum to investigate our research questions and evaluate the effectiveness of our proposed system. The staff who joined the final design process (Section 11) 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 toward 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) ranging in age from 24 to 71 years old (mean = 53.8, SD = 13.1). They were recruited via an e-newsletter for people with visual impairments and were compensated $75 plus travel expenses for their time. All of them were first-time visitors who held minimal preset knowledge about the museum where the study took place. Six participants were frequent museum visitors who visited other museums more than once a year (P2, P5, P7–P9, P11). Three visited other museums every two to three years (P1, P3, P4), and three rarely visited a museum (P6, P10, P12). All of them had experience with tactile materials, including tactile graphics (P2, P4–P12) and 3D models (P1–P11).

4.2. Task and procedure.

4.2.1. Structural exploration.

We first introduced the stacked BentoMuseum, its orientation, and external structures. We then encouraged participants to disassemble the floors to experience the "Bento Box" characteristics. The subsequent reassembly process incorporated touch exploration of inter-floor elements, such as escalators and the Oval Bridge. Finally, participants were primed with a list of 10 icons (eight from Figure 3d, plus the escalator and wall). This phase took 10 minutes.

4.2.2. Training phase.

A training phase was conducted to familiarize participants with the audio-tactile interactions. The first-floor map in Exploration mode was presented on the touch screen. Steps included: (1) double-tap one exhibit to hear its name; (2) double-tap for further details; (3) double-tap an intersection for surrounding information; (4) explore to find the guest room; (5) adjust voiceover speed using speed button; (6) stop audio using stop button; (7) switch to Navigation mode using navigation button; and (8) set special exhibit zone as goal, guest room as start, and then trace the route following the audio guide. This phase also took about 10 minutes.

4.2.3. 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 six (equivalent to a two-hour

Figure 4. Questionnaire results of the overall experience of our system (Q1–Q3).

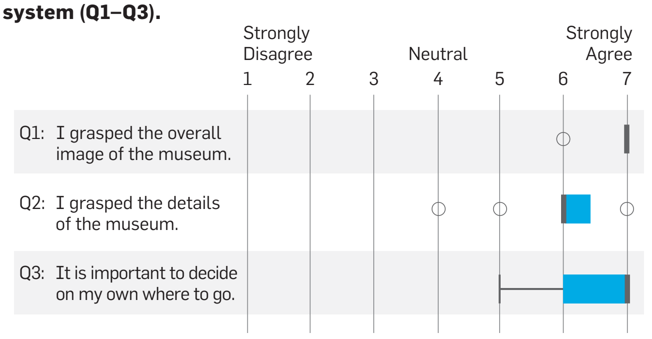
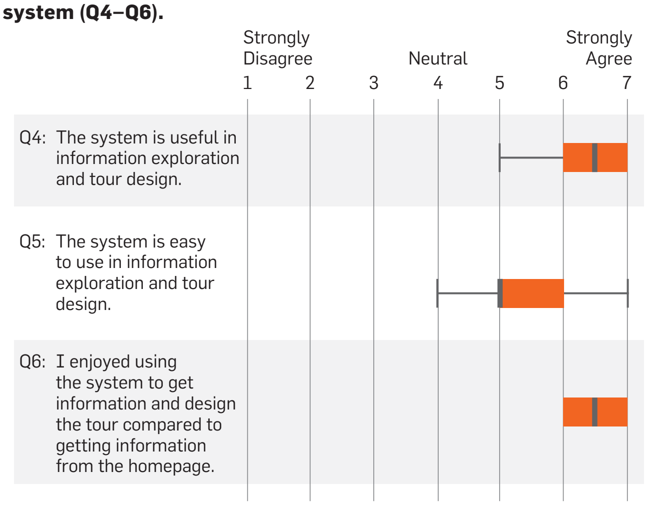


Figure 5. Questionnaire results of the overall usability of our system (Q4–Q6).



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 recorded the session on video and audio 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 from among five defined levels:

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.

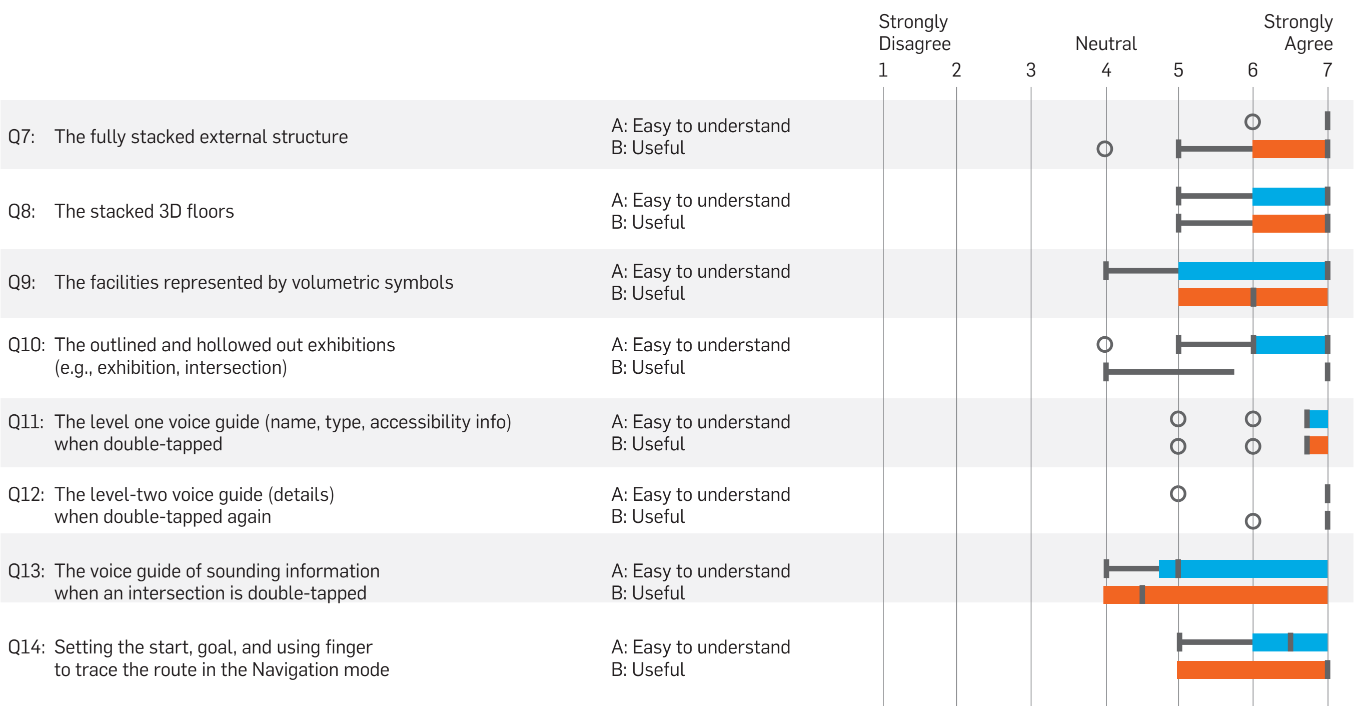
Level 5: Remember all of the exhibits they chose and the location of each exhibit.

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

4.2.4. Conducting the tour.

To validate the mental map in a real-world setting and gather insights, participants were invited to take a 15-minute walkthrough of their designed tours with a museum guide. Elaborated guidance of a chosen exhibit was included to provide a brief museum experience. Participants concentrated on traveling and validating their mental map, and they were allowed to fully explore the museum after the study.

Figure 6. 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.



4.2.5. 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 Figure 4); (2) rating overall system usability (Q4–Q6 in Figure 5); (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 Figure 6); and (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 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. Performance of information access.

5.1.1. Overall experience.
All participants successfully finished the tour design task within the allowed time (45 minutes). Ratings related to information access through the task are summarized in Figure 4 (Q1–Q3). The participants strongly agreed that by using the system they could get an overall image of the museum (Q1, median = 7). They also agreed that they were able to grasp the details of the museum (Q2, median = 6). All participants agreed (Q3, 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: *"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)

5.1.2. User exploration styles.
Analyzing double-tap log data during Exploration mode, we observed varied hand-movement styles while participants explored the floor. Despite participants' tactile familiarity, three (P8, P9, P12) under-explored the floor, tapping only a few exhibits. Three (P3, P5, P11) over-explored, tapping most exhibits but traversing the map randomly with long distances between taps. The remaining participants showed a typical in-between style and built a relatively circular and systematic pattern. An ideal style emerged in P4's exploration of one floor. After exploring one exhibit, P4 shifted to the closest one, showcasing a "circular and complete" scanning strategy, cited as one of the most efficient methods for map exploration.[12]

5.2. Performance of mental map building.

Among 12 participants, nine (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 (for example, *"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 Navigation mode of the proposed system were effective for building a 3D mental map (see Section 5.3.1 and Section 5.3.2). Participants noted an improvement in orientation (P2, P6, P9, P10) and greater 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: *"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)

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

5.3. System usability.

5.3.1. Overall usability.
Figure 5 summarizes the results of three ratings related to usability (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 effective and enjoyable: *"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: *"The best thing is that I could explore independently without asking for help."* (P11)

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

5.3.2. Usability of 3D and layered floors.
The results of ratings related to 3D and layered floors are summarized in Figure 6 (Q7.A–Q10.B). In general, all 3D and layered floor-related elements were rated as understandable and useful (median $\geq$ 6). The fully stacked 3D building (Q7) and partially stacked 3D interlocking floors (Q8) received especially positive ratings (median = 7). 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 Box" characteristics, which motivated them to learn structural details: *"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)

Participants commented that touching the structural attraction's geometric shape on the model was the best way to understand its actual structure (P2, P7, P12): *"It would be impossible to understand the structure of the Oval Bridge without the 3D model."* (P7) As a result, all participants included the Oval Bridge in the tours they designed.

About the outlined exhibits (Q10), 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: *"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 about the shape from the voice guide."* (P4)

The volumetric symbols (Q9) were understandable but not perceived as especially useful due to the fact that the task was designing a tour. However, participants recognized their importance during an actual visit (P4). Participants also noted that facilities, especially the restroom and front desk, possibly needed touch interactions for more information (P4, P10, P11): *"I want to know more about the ticketing 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, magnets' lockup support, and maintained model orientation. Nevertheless, some participants noted that although inter-floor structures (for example, the Oval Bridge and escalators) were evident on the bottom floor, it was difficult to locate where they were connected on the top floor from that floor alone (P1, P3, P6).

5.3.3. Usability of audio-tactile interface.
The results of ratings related to audio-tactile interactions are summarized in Figure 6 (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 $\geq$ 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): *"Thanks to the Navigation mode, I could learn relative locations and build a mental map."* (P1) Nevertheless, the need for Navigation mode might depend on the tactile and orientation ability: *"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). Regarding usefulness, one participant (P8) commented that the information could be accessed by touching the exhibits, and another (P6) suggested it could instead inform what area hasn't been explored.

5.3.4. 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 on the train (P4).

Participants also raised hopes and made suggestions about what the system could offer, such as conversational agents and question-answering (P5, P11), and multiple audio languages to accommodate not only the visually impaired but also foreigners and children (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, outperforming the baseline of accessing information by reading a Web page. It helped the participants to build knowledge that integrates the structural information, location, and contents. The multi-sensory method was noted to be more helpful than using either a tactile map or an audio guide alone, and all features were proved to be easy to understand and useful. The innovative "Bento Box" characteristics of the map and inter-floor structures were commented as being curiosity-arousing, understandable, and enjoyable. The system also empowered users for independent exploration and decision making, both considered invaluable[18] toward the social inclusion of the museum.

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 5.1.2). Navigation mode was beneficial for drawing location relationships on a floor, and the touchable inter-floor structures helped them to connect floors and build a 3D mental map.

However, unlike frequently visited locations where Orientation and Mobility (O&M) training is conducted, visitors in our study showed reluctance to construct a more detailed mental map of the museum. When we asked participants' 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. Second, it gave them a sense of safety and the confidence that they will not get lost. This confidence is an objective of navigation for the visually impaired in an unfamiliar environment, which supports autonomy and self-reliance.[14] Through user responses, we infer that the rough mental map is significant in improving the museum experience.

6.2. Limitations and next step toward universal access.

Several usability issues have arisen in the system's design, but they can be improved through further refinement: (1) enlarge touch areas (for example, intersections) for different finger sizes, (2) enhance 3D details for clear inter-floor structure transitions on the top floor, and (3) optimize audio content by using the intersection to inform users of unexplored areas. Some participants struggled with double-tap input due to unintentional touches during explorations. More intuitive touch interactions, such as gesture or force recognition, should be explored.

To integrate the system into museums, the display and communication methods need further exploration: (1) Self-serve floor-changing. Investigate user-initiated floor changes, ensuring clear labels, verbal cues, and tactile indications. (2) Automated instructions. Automate instructions for learning the external structure and overall system to reduce the need for staff expertise. (3) Time- and interest-based instructions. Log data of movement styles reveal that the most efficient style was uncommon (Section 5.1.1). Given the diverse tactile skills, time allowance, and interests, customizable guidance needs to be investigated to support efficient exploration.

Participants also expressed interest in the conversational possibilities of the map, and they anticipated its usefulness for others. Indeed, it can potentially connect and share information between different stakeholders—blind visitors, museum staff members and service providers, domestic visitors, foreign visitors, and other visitors with disabilities—to create universal access. The map could connect different services to expand accessibility throughout any user's visit.

6.3. Generalizability and lessons learned.

Participants suggested applying the methods to locations that troubled them, attracted them, or required their confidence (Section 5.3.3). While currently applied to a single museum, our method's generality extends to diverse locations, particularly those with irregular structures. We suggest the following design considerations in applying our method: (1) Categorize a building's complex data into three types: structural attractions, exhibits (or informative attractions), and facilities. Shape them as 3D, 2D relief, and volumetric symbols, respectively. (2) Make floors stackable: inter-floor 3D elements can be understood by touch when floors are stacked or seperated. (3) Include audio labels for points of interest and ensure they can be recognized by touch. This design employs cost-effective resources: 3D printers, touch screens, and conductive ink.

Another lesson we learned is the value of instruction, guidance and encouragement when introducing a complex map to new visitors. Guiding users through inter-floor structures via touch increased their engagement and appreciation. Without such guidance, key structural elements could be missed amid the numerous 3D and 2D features. Incorporating methods for communicating the map's contents and motivating users is integral to effective map design.

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 connecting it with other assistive technologies to support autonomous museum exploration. C

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

Seita Kayukawa (seita.kayukawa@ibm.com), IBM Research-Tokyo, Japan.

Hironobu Takagi (takagih@jp.ibm.com), IBM Research-Tokyo, Japan.

Chieko Asakawa (chiekoa@us.ibm.com), Miraikan-The National Museum of Emerging Science and Innovation, Tokyo, Japan.