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RESEARCH ARTICLE

Archi-TangiBlock: A Modular Block Based Tangible Media as a CAD Tool for Visually Impaired People

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ABSTRACT Tactile maps are crucial for orientation and mobility (O&M) training for visually impaired people (VIP) to gain spatial knowledge of their surroundings. However, existing tactile maps are limited in their ability to facilitate actively generating information, modifying, and sharing by VIP individuals, making it challenging for them and O&M specialists to create and customize maps independently. To address this issue, we propose Archi-TangiBlock (ATB), an accessible computer-aided design (CAD) tool for VIP. ATB comprises a modular block-based tangible user interface that modularizes architectural landmarks, a panel for plugging in block modules, and a computer interface. Visually impaired users can use ATB to create a 3D CAD model by constructing a space with the blocks, enabling active learning. We evaluated ATB with visually impaired participants, and our results demonstrate that ATB enables visually impaired users to easily build maps, achieving a remarkably low error rate of 1.2%, and to gain an understanding of the overall spatial layout at a rate twice as fast as compared to conventional tactile maps.

INDEX TERMS Tangible interface, computer-aided design, visually impaired people, tactile map.

I. INTRODUCTION

Tactile materials including tactile graphics and maps are commonly used as learning tools for visually impaired people (VIP). They play a significant role in education, particularly in STEM (science, technology, engineering, and mathematics) fields, as well as in Orientation and Mobility (O&M) training [1], [2], [3]. This approach is critical to addressing barriers to independent living among individuals with vision impairments, and tactile graphics are an essential tool in this process. Specifically, VIP face significant challenges when navigating indoor and outdoor environments in daily lives. The orientation and mobility in unfamiliar indoor spaces poses even greater difficulties compared to outdoor environments due to limited accessible cues such as signs, building maps, and prominent landmarks [4], [5]. Even within their familiar homes, VIP encounter cognitive strain and exert effort while transitioning from one location to another [6]. Due to these challenges, tactile maps are frequently employed to assist VIP in obtaining crucial information for their navigation.

Various methods to produce tactile maps have been used. Tactile maps, which consist of raised dots, lines, and braille, are created using various techniques such as a braille printer, braille embossers, swell papers, and thermoforming methods [7], [8]. These maps serve as aid tools for comprehending geographic instruction and orientation for VIP. In addition, architectural drawing based tactile maps are manufactured

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to provide indoor spatial information of the public building. These maps are designed to facilitate spatial awareness and navigation and include features such as protruding wall lines, tactile symbols (e.g., stairs, elevators, 'you are here'), and braille. However, these kinds of tactile maps have some drawbacks. Due to the relatively low height of the protrusions, it can be challenging to perceive the overall spatial layout and to distinguish between different types of symbols [9]. Moreover, a significant drawback of existing tactile maps is their lack of reconfigurability once they are produced, making it difficult to modify or update them in response to changes.

In order to overcome these limitations, researchers have explored the use of modular blocks to enable the reconfiguration of tactile maps. For example, Ottink et al. [10] implemented this approach by constructing a small city-scale tactile map, encompassing roads and buildings, using Lego building bricks and object item blocks within a 25 × 25 cm range of plate. Although the study did not involve an experiment on VIP and on the indoor environment, the tactile maps demonstrated a relatively accurate formation of cognitive maps. While the use of modular blocks allows for easy reconfiguration of tactile maps, it presents a limitation as the final output is volatile. That means, once all the blocks have been withdrawn and the initial empty state has been established, reproducing the exact previous configuration can only be achieved through user's memory or reliance on stored resources like photographs. Consequently, this approach restricts the tactile map to a single-use scenario, posing challenges in terms of portability, sharing, and reusability.

The limitations discussed above can be overcome through the advancements in computer-aided design (CAD) systems and 3D printing technology. The creation of tactile maps using 3D printing has become more common due to their ease of production, and it is utilized as a useful educational tool [11], [12]. Several studies [13], [14], [15], [16], [17], [18] presented tactile maps with protruding lines and textured area a little higher than braille to provide information of urban space or architectural space. In addition, some studies that enable to automatically generate 3d models for tactile maps had been presented. The Touch Mapper project [19], HaptoRender [20], and Gotzelmann and Pavkovic [16] offers automated downloadable street map models of point of interest based on web data. Even though these studies have improved the reconfigurability and accessibility of creating tactile maps for non-experts of CAD system, they are limited to outdoor spaces at the urban scale. More importantly, VIP are unable to directly produce tactile maps on their own.

Fundamentally, CAD simplifies collaborative endeavors and functions as a crucial communication instrument by enabling the sharing and modification of design information [21]. However, addressing the cognitive disparity between sighted individuals and VIP can presents a complex challenge. Cognitive variances, which include distinct preferences in frames of reference and navigation routes, exist in the mental maps of both VIP and sighted individuals [22]. Furthermore, effective verbal communication of spatial information between individuals with visual impairments and sighted individuals poses challenges due to the potential ambiguity and lack of clarity in verbal expressions, stemming from disparities in perceptual concepts [23], [24], [25]. Consequently, there is a demand for accessible CAD tools for the visually impaired, facilitating communication about spatial concepts to establish mutual understanding with sighted individuals through a shared spatial language.

Based on surveys and articles [26], [27], post-visual impairment occupational trends indicate a prevalence in massage work (29.7%), followed by simple labor and self-employment (16.2% each), and service work (13.5%). This constrained range highlights the challenges faced by visually impaired individuals in engaging with mainstream creative tasks. Recent surveys [28] reveal a growing interest in digital content creation among the visually impaired. However, the dominance of visual tasks in mainstream creativity poses significant barriers for VIP. Hence, ongoing research in diverse domains is dedicated to enhancing accessibility for VIP. Research endeavors involve the development of 2D CAD tools tailored for visually impaired individuals, enabling them to create graphics [29] and access engineering drawings [30]. A visually impaired researcher conducted a study on software capable of 3D modeling and 3D printing [31], reflecting an increasing demand for technology empowering direct interaction with CAD systems. Furthermore, independent creation not only fosters collaboration, democratizes creativity, and facilitates learning [32], [33], [34], but also underscores the importance of accessible CAD tools for boosting confidence, independence, and overall quality of life [35].

Hence, a recent studies were conducted on a computer-aided design (CAD) tool that are accessible to VIP. Consequently, these research have enabled the independent production of 3D printed tactile maps. Several studies have developed software-based automated systems [35], [36], [37] that make the production of downloadable tactile maps accessible. However, due to the challenging software-based interfaces that VIP may encounter difficulties in manipulating intuitively and requirement of online street maps, alternative approaches have been developed that utilize tangible tools, which are more accessible and easier for VIP individuals to operate [38], [39], [40]. Siu et al. [41] devised 2.5D shape displays that enable VIP to engage in 3D modeling and receive prompt, tangible feedback. While it proves effective for revising and identifying existing 3D models, creating new 3D spatial structures presents a challenge for VIP, as it requires generating models through programming languages. Kamat et al. [42] developed a tangible construction kit that empowers VIP to create basic geometric virtual 3D models by utilizing 3D scanning technology to capture the 3D object manipulated by them. However, this system has limitations as it can only generate simple geometry and cannot construct spatial structures. Shi et al. [1] developed tangible user interface that enable VIP to directly modify maps with features such as scale adjustment, undo, delete, and voice label insertion. VIP can add braille and adjust textures with protruding lines or dots as well. However, this method requires pre-manufactured 3D printed tactile maps available on the web and offers limited customization options. Furthermore, these approaches do not provide users with the ability to freely create the map according to their specific needs or preferences.

To enable VIP to create tactile maps based on their own spatial interests and structures by themselves, there is a need for an accessible CAD tool, which is an efficient tool to create, reprocess, and share the spatial information. Therefore, we proposed Archi-TangiBlock (ATB), a novel type of tangible CAD interface designed to facilitate intuitive and effortless creation and modification of tactile maps, as well as enabling reconfigurability, storage, and sharing of created 3D models. In contrast to previous examples, ATB eliminates the necessity for prior preparations such as programming languages, pre-made 3D printed maps, and vision processing technology. Additionally, it liberates the constraints on manipulation and modification of spatial configuration. It consists of blocks that modularize architectural landmarks and have simple and intuitive shapes comprehensible to both sighted individuals and VIP, and base panel onto which the blocks can be plugged, for an intuitive manipulation method. It also includes software that visualizes the composition of blocks as they are placed on the panel. These tools overcome the limitations of existing tactile maps, which made for VIP only to touch and read unilaterally, enabling VIP to freely organize spaces and generate, modify, and reuse tactile maps as they wish. Furthermore, the development of an accessible CAD tool for VIP can contribute to promoting inclusive design practices and improving accessibility for all individuals with visual impairment.

This paper is organized as follows. Section II outlines the system design of our proposed ATB. Sections III and IV present different evaluations. Section III focuses on the accuracy of users' perception of space organized by ATB. Section IV examines users' ability to organize space effectively using ATB and discusses the validation of ATB for sharing and communication purposes among individuals with visual impairments. Section V covers the results of subjective satisfaction ratings, while Section VI discusses experimental findings, limitations, and future directions. Finally, Section VII presents the concluding remarks.

II. DESIGN OF ARCHI-TANGIBLOCK

A. SYSTEM OVERVIEW

ATB consists of three main parts: (1) block modules representing architectural elements of landmarks, (2) a panel for plugging the block modules in and connecting electric signal and power to the block modules, and (3) a 3D modeling software for creating 3D spaces of a structure with block modules and visualization (figure 1).

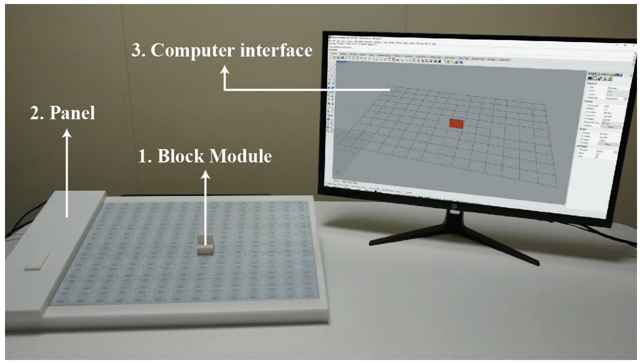


FIGURE 1. The entire system of ATB.

B. HARDWARE: BLOCK MODULE AND PANEL

The geometry of each block module is an important consideration for the efficacy of the ATB. Therefore, the elements of the building, which are used as important information in the process of O&M of VIP, are modularized and manufactured in the form of blocks. The block modules consist of various landmarks [43], [44], such as doors, stairs, elevators, women's restrooms (W), men's restrooms (M), and a 'you are here' (YAH) mark, serving as important tactile symbols employed in existing tactile maps (figure 2). The essential blocks, such as walls, right-angle walls, and T-shaped walls, are also designed to express indoor spatial structure. These function as basic modules when VIP design the space. When providing visual information to VIP, simplifying the information is important to make it easier to comprehend [38], [39]. Therefore, we designed the three-dimensional shape of each module simply and intuitively to be easily identified by touch [45].

The module includes block PCB (printed circuit board) inside to communicate with the panel (figure 2). When the block is plugged into the panel, information about its location (x and y coordinates on the panel) and type of module is transmitted to the main controller of the panel via inter-integrated circuit (I2C) communication. In addition, to enhance ease of use for VIP who may face difficulties in correctly plugging it in without assistance, magnets were inserted at the bottom corners of the module to facilitate attaching it to the corresponding position on the panel. The size of the block module is 28 mm (width) $\times$ 28 mm (depth) $\times$ 35 mm (height).

The main role of the panel is to transfer the data received from the modules to the PC to build 3D models of the space. It includes: (1) the main controller (STM32F407VGT discovery board, STMicroelectronics, Switzerland) that receives data from block modules and sends them to the PC using a USB communication protocol, and (2) the exterior case into which the blocks are plugged. The number of blocks that can be plugged into it is 14 horizontally, 10 vertically, and 140 totally. To facilitate easy positioning for block placement, we designed a 0.6mm protruding guide line on the upper face of the panel. Furthermore, magnets were strategically

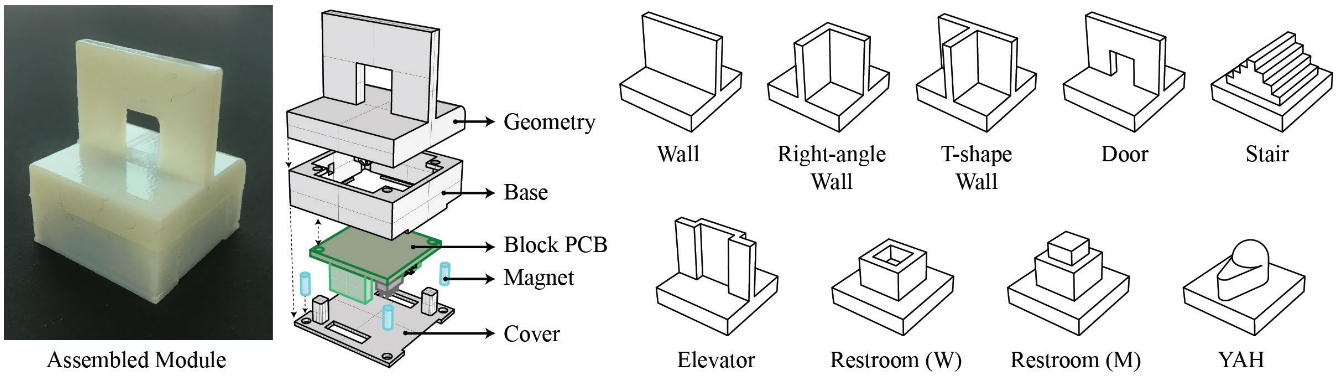


FIGURE 2. Assembled and each parts of block module and several types of modules having different shape respectively.

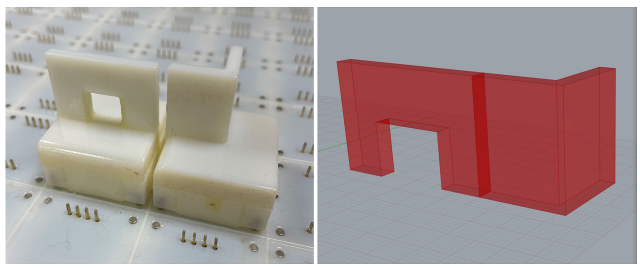


FIGURE 3. The computer interface interacting with the panel and block modules. The 'Door' and 'Right-angle Wall' modules (left) are visualized in interface (right).

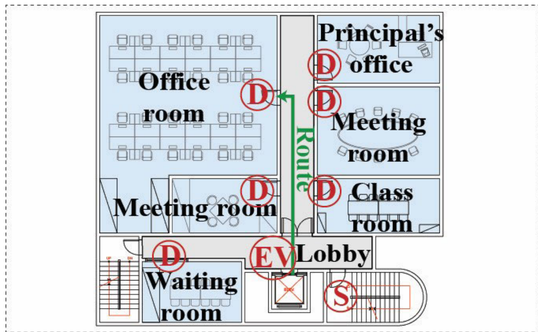


FIGURE 4. A representative example of familiar space for participant A.

inserted at locations that correspond to the four corners of the block, enabling effortless attachment. The panel size is 450 mm wide, 310 mm long, and 30 mm high, and its weight is 2,530 g.

C. 3D MODELING SOFTWARE

The main function of 3D modeling software as a computer interface is to build the 3d model of the space based on data received from the panel (figure 3). Each time a block module is inserted onto the panel, a corresponding 3D model is automatically generated, and the 3D model file (Rhino 3-D Model,.3dm file) of the entire spatial structure is finalized as the user configures it. Subsequently, all block models are merged and converted into a 3D printable stereo lithography file format (STL). This approach enables the creation of a CAD file and subsequent conversion to an STL file, allowing for the production of a 3D printed tactile map. The platform used to create 3D geometry is Rhino3d (Robert McNeel & Associates, USA). Its interface was developed as an add-on software to Grasshopper, which is an internal parametric design tool in Rhino3D.

III. EVALUATION 1: EFFICACY OF THE ATB

In order to assess the effectiveness of the device, experiments were conducted with totally VIP participants. This experimental study was planned to investigate the perceptual accuracy of VIP participants in perceiving the ATB space and their comprehension of its overall spatial structure. Additionally, we aimed to examine the extent to which the shape of the block module in the ATB corresponded to the participants' spatial mental map. By conducting these evaluations, we can determine the efficacy of the ATB as a communication medium when VIP assume the role of the receiver.

A. PARTICIPANTS

Referring to previous studies that recruited 4 to 8 subjects [46], [47], this study involved five totally VIP participants (1 female and 4 males), aged between 19 and 59 years old, with a mean age of 39.4 (SD = 16.3). Two participants were congenitally VIP while others were acquired VIP. All participants demonstrated familiarity with braille, and three of them had prior experience to the existing tactile map. The participants did not report any known sensorimotor disorders and none of them had prior experience with our proposed ATB used in this study. This experiment was approved by the Institutional Review Board of Korea Institute of Science and Technology (KIST-202306-HR-007).

B. PROCEDURE

The study evaluated the level of coincidence between the mental maps formed by participants and the space

TABLE 1. The information of pre-configured ATB space describing respective familiar space of each participants and unknown space to all. ('R': room, 'S': stairs, 'EV': elevator, 'LC': lobby and corridor, 'D': door, 'T': restroom, 'L': living room, 'KD': kitchen and dining room).

Participants	A	B	C	D	E	Unknown space
Location	Welfare center	House	Seoul National School for the Blind	Welfare center	Seoul National School for the Blind	Laboratory in KIST
Spatial structure (no. of rooms)	5 R, 1 S, 1 EV, 1 LC	3 R, 2 T, 1 L, 1 KD	5 R, 2 T, 1 S, 1 EV, 1 LC	5 R, 1 S, 1 EV, 1 LC	5 R, 1 T, 1 S, 1 EV, 1 LC	5 R, 2 T, 1 EV, 1 S, 1 LC
No and Type of Landmark	6 D, 1 EV, 1 S	4 D, 2 T	6 D, 2 T, 2 S, 1 EV	6 D, 1 EV, 1 S	6 D, 1 T, 2 S, 1 EV	6 D, 2 T, 1 EV, 1S
Area	372 m^2	144 m^2	438 m^2	372 m^2	432 m^2	440 m^2
Scale	1/100	1/50	1/100	1/100	1/100	1/100

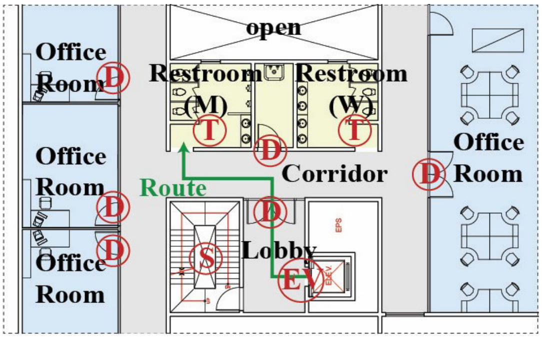


FIGURE 5. A plan digram of unknown space for all participants.

constructed by ATB. The researcher provided pre-configured ATB spaces to the participants and allowed them to touch and perceive the spaces. Each participant was provided with a familiar and unknown space, respectively. The familiar spaces were provided to assess the ATB's ability to effectively represent pre-existing mental maps of VIP in terms of shape and organization. The unknown spaces were presented to evaluate VIP's capacity to accurately form mental maps of unfamiliar environments by perceiving the spatial information conveyed through the ATB.

The methodology employed in prior studies [46], [47], involving the question of participants regarding spatial information to assess the accuracy of their responses, was adopted for evaluating the efficacy of constructing a mental map after exploring a pre-provided tactile map. Following their familiarization with the provided ATB spaces, participants were directed to verbally express details of the spatial environment while simultaneously engaging in tactile exploration of the ATB through touch. The principal objective of this verbal description task was to assess the level of similarity between the spatial representation pre-constructed by the ATB and participants' mental maps. At this stage, participants had developed enough familiarity to articulate descriptions based on the cognitive map they had constructed in their minds. This situation may introduce the potential challenge of discerning between information obtained through tactile manipulation of the ATB and that which is already embedded in their mental map. To ensure precision, participants were instructed to physically grab and point to the corresponding blocks of ATB while providing their explanations. Subsequent to task completion, each participant was queried about the fidelity of the ATB in representing their individual mental map and received feedback accordingly.

1) TASK 1: EXPLORE WITH FAMILIAR SPACE

In this task, participants were asked to explore the composition of a space that was constructed by the researcher using ATB (figure 4 describes an example of familiar space 'Welfare center' given to participant A and D). The architectural space of a welfare center, a house, and a Seoul National School for the VIP were respectively applied to the constructed ATB space to generate familiar spaces for the participants (see Table 1). The spaces were configured on an approximately 1/100 scale, considering the size of the representable ATB relative to the area of the actual space. In the case of participant B, because the actual area of the house was smaller than half of that for the other participants, approximately a 1/50 scale was applied. Participants were given their respective walking routes (depicted in figure 4 as green arrow lines), which are frequently used in daily life for each of them, and were required to verbally describe the sequential steps.

2) TASK 2: EXPLORE WITH UNKNOWN SPACE

Similar to the task 1, all subjects were provided with the same unknown space. For a fair comparative evaluation, a space with a similar area, spatial structure, and spatial complexity to the 'familiar' space was selected as an 'unknown' space (see figure 5 and table 1). It was a scaled model approximately at a 1/100 scale. The verbal walking route from the elevator to the restroom corresponding to the participants' gender, where many people usually move, was provided to participants, and was described in figure 5.

C. METRICS

To assess the efficiency of understanding the spatial structure of the ATB space, the time participants took to comprehend the entire configuration, as arranged by the experimenter, was recorded for evaluation.

1) COINCIDENCE RATE

We conducted a quantitative evaluation from a cognitive perspective to assess the degree of correspondence between the space represented in the ATB and the verbal descriptions (VD) of mental maps. It includes 'Spatial Structure,' a fundamental component in the analysis of architectural space [48], [49], [50], and the 'Landmark (LM) module' and 'Orientation and Mobility (O&M) Sequence,' both of which are associated with VIP's principles of ambulation [51], as a means of externalizing their mental map.

The 'Spatial Structure,' which relates to the number of rooms defined with walls, was compared to the ATB space as a reference. The 'Landmark (LM) module' was measured by the number of landmark block modules that participants recognized in the ATB space. Note that the 'Wall' module (including T-shaped and right-angle walls) is excluded from the 'LM module', as it primarily functions as a guide to connect important spatial points not specific geographic location. For the O&M Sequence, we asked participants to explain a route they had taken using the ambulation principle of VIP, including main points (landmark, information point) and directional information from the starting point to the destination [52]. The coincidence rate for all metrics was determined by calculating the ratio of the number of elements expressed by the participants to the total number of elements required to accurately describe the actual space.

D. RESULTS

1) TASK 1: EXPLORE WITH FAMILIAR SPACE

The VD of the space by all subjects confirmed that the 'spatial structure' and 'LM module' of ATB were described uniformly. For the 'O&M sequence', four subjects used egocentric reference frames while one used an allocentric reference frame [53]. The average time taken to identify the space using an ATB was 2 minutes and 14 seconds (see table 2). As an example of 'O&M sequence' result, the VD of subject E about the route (teachers' room → meeting room) was as follows, *'1. Get out of the teachers' room door → 2. turn right → 3. and go straight along the wall, passing the principal's office, go straight through the lobby → 4. to the wall → 5. turn right → (6. turn to the left) → 7. to find and enter the meeting room door'*. It had a coincidence rate of 85.7 %, with only one orientation information which is in parentheses omitted. Despite this, subject E acknowledged that the ATB closely expressed the space in comparison to the actual place.

2) TASK 2: EXPLORE WITH UNKNOWN SPACE

Subject A was unable to complete the task due to personal scheduling constraints, and as a result, was excluded from the evaluation for this task. The VD of the space by all subjects confirmed that the 'spatial structure' and 'LM module' of ATB were described uniformly as well in this task. The task was completed on average in 2 minutes and 24 seconds, with subject E showing remarkable comprehension of the spatial structure in just 1 minute and 6 seconds (see Table 2). Although the coincidence rate of 'O&M sequence' was different for each participants, all participants successfully completed the verbal O&M tasks in the ATB-generated spaces.

IV. EVALUATION 2: USABILITY OF THE ATB

The efficacy of this device was verified by the first evaluation explained above. The aim of this experiment is to assess how easily the participants can utilize the ATB as a CAD tool independently. To evaluate its performance, participants were assigned three distinct tasks representing application scenarios: 'modify' and 'generate,' which encompass fundamental functions of CAD [54], and 'share,' as a communication function of CAD [55], [56]. They were asked to construct a space using the ATB for each task. The resulting designs were compared to a reference space to evaluate the usability of the tool. Through these evaluations, we can also determine the efficacy of ATB as a spatial communication medium between VIP and the sighted individuals, and between VIP. The same subjects who participated in the previous evaluation were recruited for this experiment. This experiment was approved by the Institutional Review Board of Korea Institute of Science and Technology (KIST-202306-HR-007).

A. PROCEDURE

1) TASK 1: MODIFY

This task is aimed to evaluate usability of the 'modify' as a basic CAD function, which allows users to edit and revise designs previously created. The spatial layout of ATB constructed in the previous task (Task 1 of the evaluation 1: 'Explore with familiar space') was given to the participants. They were instructed to modify areas, where they encountered difficulty navigating in the corresponding familiar space or identified discrepancies with their mental map, within the provided ATB space (see Figure 6(a)).

2) TASK 2: GENERATE

As an important function of CAD tool, this generate task is aimed to evaluate usability to represent the mental map in user's mind. The participants were instructed to generate a ATB space of a place they were familiar with independently, because completely new spatial design couldn't be evaluated without a comparable reference. Assuming that their mental maps matched the real world because it was a familiar space to the subjects, the generated ATB space was compared with the real-world space to evaluate how accurately and efficiently VIP could describe the space with ATB.

3) TASK 3: SHARE

The objective of this task is to assess the feasibility of 'sharing' the 3D model generated by a visually impaired individual in the preceding task as a 3D printed tactile map among VIP. The spatial configuration adopted as the shared tactile map among participants was based on subject A's model (Rhino 3-D Model, .3dm file) of a previous 'generate' task (figure 7 (a), (c) and table 4), which was found to be the most suitable in terms of complexity. The space represented

TABLE 2. The result of the evaluation 1 perceiving the ATB space for each participant. The numerator in parentheses in the coincidence rate of 'O&M sequence' represents the number of verbally matched paths reported by the subject, while the denominator represents the total number of paths required to describe the corresponding route. (CR: coincidence rate).

	Participants	A	B	C	D	E	Average
Task 1	Time	47 s	1 m 7 s	4 m 17 s	3 m 17 s	1 m 55 s	**2 m 17 s**
	Route of verbal O&M	Elevator → Office room	Kitchen → Room	Laundry room → Class room	Elevator → Office room	Teacher's room → Meeting room	-
	CR of 'O&M sequence'	100 % (7/7)	100 % (5/5)	86 % (6/7)	86 % (6/7)	83 % (5/6)	**91 %**
Task 2	Time	-	2 m 15 s	2 m 59 s	3 m 16 s	1 m 6 s	**2 m 24 s**
	Route of verbal O&M	-	Elevator → Restroom				-
	CR of 'O&M sequence'	-	100 % (8/8)	87.5 % (7/8)	75 % (6/8)	100 % (8/8)	**90.6 %**

(a) (b)

FIGURE 6. The example result of 'modify' task for participant E. (a) is the space given to the participant E and (b) is the modified space.

the interior of a single apartment and was unknown to all participants. The scale of the map was modified into 1:4 to make it portable enough to fit in a pocket, and 3D modeling file was converted to a stereo lithography file format (STL) to be 3D printed. Participants were instructed to first perceive the space of 3D printed tactile map through palpation and to construct a space using the ATB to match the shared map as a reference. The constructed ATB space was compared with the shared tactile map to evaluate how accurately and efficiently VIP individuals could transcribe the spatial structure from the 3D printed map onto the ATB.

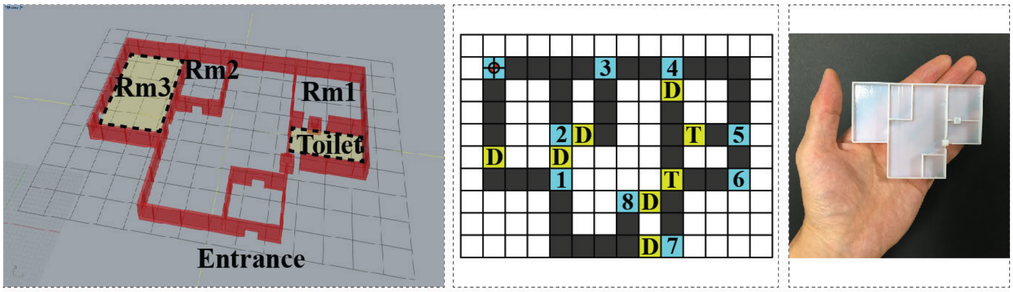
B. METRICS

1) EFFICIENCY

This metric is for evaluating participants' ability to use the device in terms of placing ATB's block module easily and correctly on the panel from an efficiency perspective. Two measures were employed: 1) participants were observed to determine if they placed the block modules in the correct positions on the male connector of the panel, and the number of 'Positioning Errors' was recorded when the modules were inserted into incorrect positions. 2) Placement of inappropriate block module while constructing spaces resulted in 'Constructing Errors', which were also counted. For instance, the use of a straight or right-angle wall instead of a T-shaped wall to separate two consecutive rooms was deemed a 'Constructing Error'. Additionally, the number of block modules used and the time required for participants to complete the grasping and construction of a space were measured. These metrics were utilized equally in all the three tasks.

2) COINCIDENCE RATE

A quantitative approach was employed to evaluate participants' cognitive performance across three metrics for both 'generate' and 'share' tasks. For the 'modify' task, it was excluded from metric evaluation due to its reliance on participants' subjective judgment and absence of objective reference for comparison. The 'LM module' and 'Spatial Structure' align with the descriptions provided in section III. The concept of 'Spatial Ratio' has recently been introduced as an essential component in architectural space analysis [48], [49], [50]. It serves as an additional metric to assess the perceived distance ratio between detailed spatial elements



(a) (b) (c)

FIGURE 7. **(a) Reference space provided to the subjects, (b) Feature point based image converted from (a) with the LM module, (c) 3D printed tactile map based on 3D CAD data from (a).**

TABLE 3. **The result of 'modify' task related to 'efficiency' perspectives for each participant.**

Participants	A	B	C	D	E	Average
Time	-	3 m 2 s	-	6 m 4 s	1 m 7 s	3 m 24 s
Number of modules used	-	3	-	8	8	6.3
Positioning Error	-	0	-	0	0	0
Constructing Error	-	0	-	5	1	2

and the overall spatial context. Given the inherent challenge of accurate distance perception in individuals with visual impairment [52], [57], [58], this metric was exclusively employed in the 'share' task, where the reference space is entirely comparable. These metrics were calculated as a ratio of the extent to which participants' constructed spaces matched the reference space they were compared to.

Explaining the details of the 'Spatial Ratio' metric, it is employed to assess the degree of matching in terms of the ratio of each room's size in the overall spatial structure, comparing the participant's ATB space with the reference space. The Manhattan distance comparison method [59], [60], aligning with the design features of ATB where blocks are formed within a grid of uniform width and height, was employed to effectively measure image similarity [61]. Specific feature points, defining the size of each room, were selected in both the participant's ATB space and the reference space. The origin was established as the feature point located at the top left corner (see Figure 7 (b)). A value of '1' was assigned to feature points and other black pixels, signifying wall block modules, while the remaining vacant white pixels were designated a value of '0,' resulting in the creation of a binary image. Utilizing binary images derived from both the reference and user-configured spaces, the initial representation of similarity is expressed as a normalized value through the quantification of the Manhattan distance method, as depicted in equation [62], [63]:

$$D_n = \sum_{i=1}^{K} \frac{|ui - vi|}{K}, S_d = (1 - D_n) \cdot 100 \tag{1}$$

where D_n represents the normalized Manhattan distance, K denotes the total number of pixels in the binary image converted based on feature points, and ui and vi represent the binary values associated with each pixel in the reference and user-constructed spaces, respectively. The variable S_d, converted to a percentage, indicates the level of similarity between two images. In result analysis, a value approaching 100 indicates a greater similarity between the reference and ATB spaces.

C. RESULTS

1) EFFICIENCY

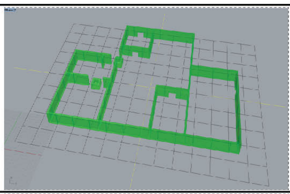
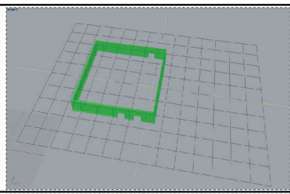
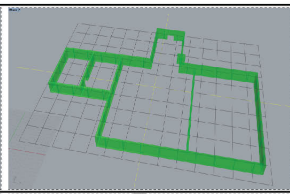
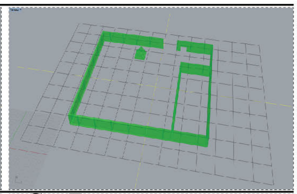
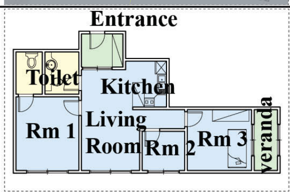
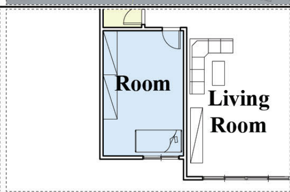
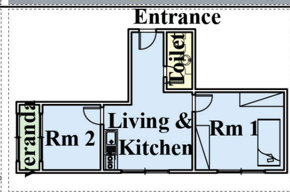
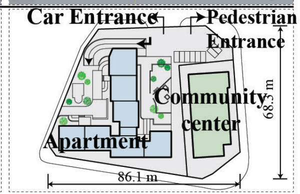
a: MODIFY

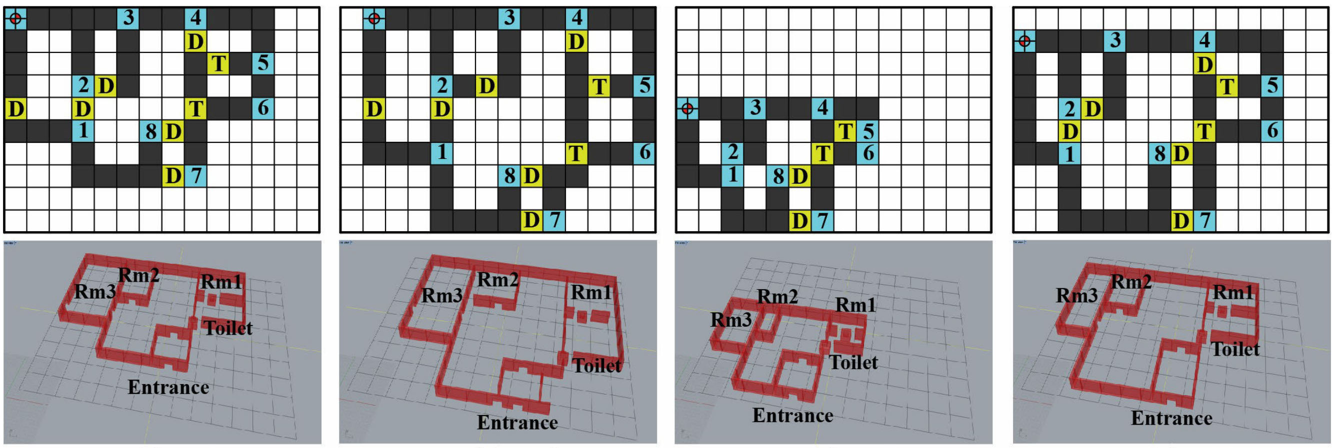
The 'modify' task was completed by three of the subjects, while the remaining two lacked the motivation or resources to participate in the 'modify' task (an example result is shown in the figure 6 (b)). On average, the subjects made zero 'Positioning Errors' and two 'Constructing Errors' (table 3).

b: GENERATE

Participant D, the eldest and congenitally VIP, possessed limited familiarity with tactile materials and lacked prior experience in articulating mental maps using tools such as the ATB. Consequently, the execution of this task posed notable challenges, leading to discontinuation, and hence, this participant was excluded from the experimental findings. The difficulty level of the spaces constructed by the participants varied, but the spent time for construction with 42 block modules was consistently 8 minutes and 34 seconds in average. Given the constraints due to the small number of participants, generalizing the statistical analysis may be challenging. However, the results imply that 11.4 seconds per module can be considered as a unit time to express the mental map. The frequency of errors was also analyzed, and the average number of 'positioning errors' and 'constructing errors' were 0.25 and 1.5 times, respectively. Based on the average number of modules used, the probability of error occurrence was very small, at 0.005 % and 0.03 % for 'positioning errors' and 'constructing errors' respectively (table 5).

TABLE 4. The result of 'generate' task constructing their own familiar space for each participant and specific information about each space.

Participants	A	B	C	E
Place	Home	Room in the house	Home	Residential area
Scale (approximate)	1:50	1:30	1:25	1:300
TM space				
Reference (actual space)				



participant B participant C participant D participant E

FIGURE 8. The ATB space of each participant as results of 'share' task.

TABLE 5. The result of 'generate' task related to 'efficiency' perspectives for each participant.

Participants	A	B	C	D	E	Average
LM module	88.9 %	100 %	100 %	-	42.9 %	**83 %**
Spatial Structure	100 %	100 %	100 %	-	50 %	**87.5 %**
Time	16 m 36 s	3 m 22 s	8 m 53 s	-	5 m 27 s	**8 m 34 s**
Number of modules used	55	24	53	-	36	**42**
Unit time for model construction	18.1	8.4	10.1	-	9.1	**11.4**
Positioning Error	0	0	1	-	0	**0.25**
Occurence rate of positioning error	0	0	0.02	-	0	**0.005**
Constructing Error	3	0	3	-	0	**1.5**
Occurence rate of constructing error	0.05	0	0.06	-	0	**0.03**

TABLE 6. The result of 'share' task (constructing the unknown space for all participant) related to 'efficiency' perspectives.

Participants	A	B	C	D	E	Average
LM module	-	100 %	100 %	50 %	88 %	**84.5 %**
Spatial Structure	-	100 %	100 %	100 %	100 %	**100 %**
Spatial Ratio	-	86.4 %	65 %	64.3 %	78.6 %	**73.6 %**
Time	-	23 m 21 s	10 m 45 s	26 m 18 s	11 m	**17 m 51 s**
Number of modules used	-	52	62	35	55	**51**
Unit time for model construction	-	26.9	10.4	45	12	**23.5**
Positioning Error	-	0	3	0	0	**0.75**
Occurence rate of positioning error	-	0	4.8	0	0	**1.2**
Constructing Error	-	0	9	4	1	**3.5**
Occurence rate of constructing error	-	0	14.5	11.4	1.8	**6.9**

c: SHARE

Subject A was excluded because the experiment was based on the space constructed by him. On average, participants completed this task in 17 minutes and 51 seconds, utilizing 51 block modules (see table 6). The construction of each module took an average of 23.5 seconds. Regarding the

TABLE 7. Results of the questionnaire on a 5-point Likert scale.

Participants	A	B	C	D	E	Average
Frequent usage	-	4	3	3	5	**3.75**
Ease	-	5	5	5	5	**5**
Independent usage	-	4	5	5	5	**4.75**
Learnability	-	4	5	3	5	**4.25**
Discernability	-	4	4	4	5	**4.25**
Average	-	**4.2**	**4.4**	**4**	**5**	**4.4**

errors, the average 'Positioning error' was found to be 0.75, with an average occurrence rate of 1.2 %, while the average 'Constructing error' was 3.5, with an average occurrence rate of 6.9 %. These results demonstrate the efficiency of the ATB as a tool for facilitating spatial expression for VIP and for sharing the 3D tactile map as a final output of the CAD tool-created 3D model.

2) COINCIDENCE RATE

a: GENERATE

For the 'LM module', the average coincidence rate was 83 %, and details are described in table 5. Subject E showed the lowest coincidence rate due to the absence of block modules describing an outdoor environment, while the results of the other subjects showed a high degree of coincidence with the actual space. The 'Spatial Structure' of four subjects was also found to be coincident with the actual place, except for subject E who constructed an outdoor space but could not complete it due to the same reason as in the 'LM module'.

b: SHARE

The average coincidence rate of the 'LM module' used was 84.5 %, and details are described in table 6. Excluding Subject D, who had the lowest rate, the remaining three subjects had an average coincidence rate of 96 %, indicating a high degree of coincidence. This high coincidence rate was due to only one LM module 'constructing error'. Regarding the 'Spatial Structure' aspect, all subjects constructed a space with 6 rooms and 2 bathrooms, which coincidentally matched the reference space (see figure 8).

As for 'Spatial Ratio', even though there were slight discrepancies between the reference space and the spaces constructed by the subjects, the average coincidence rate was 73.6 %, as shown in figure 8 and table 6. Participant C configured a space notably larger than the reference, whereas Participant D, in contrast, constructed a space that was overall smaller. Although some participants showed varying distance ratios at specific feature points, their overall space constructions closely aligned with the reference. The results suggest that the ATB was an efficient tool not only for sharing and reusing tactile maps designed by other users but also for facilitating active learning, with a low rate of error occurrence.

TABLE 8. Results of the questionnaire on a SUS. Each item is followed, 1) I think that I would like to use this system frequently. 2) I found the system unnecessarily complex. 3) I thought the system was easy to use. 4) I think that I would need the support of a technical person to be able to use this system. 5) I found the various functions in this system were well integrated. 6)I thought there was too much inconsistency in this system. 7) I would imagine that most people would learn to use this system very quickly. 8) I found the system very cumbersome to use. 9) I felt very confident using the system. 10) I needed to learn a lot of things before I could get going with this system.

Participants	A	B	C	D	E	Average
1)	-	4	3	3	5	**3.75**
2)	-	1	1	1	1	**1**
3)	-	5	5	5	5	**5**
4)	-	4	5	5	5	**4.75**
5)	-	3	4	3	5	**3.75**
6)	-	1	1	1	1	**1**
7)	-	4	4	3	5	**4**
8)	-	5	4	5	4	**4.5**
9)	-	5	5	5	5	**5**
10)	-	4	5	3	5	**4.25**
SUS Score	-	**65**	**62.5**	**60**	**72.5**	**65**

V. SATISFACTION

A. QUESTIONNAIRE

To assess user satisfaction with the ATB, participants were asked to rate the system on a 5-point Likert scale based on five aspects, including the intuitiveness of the block module's shape and the ease of use. Participants also rated the level of difficulty they experienced while using the ATB on a 5-point Likert scale (1 = strongly disagree; 5 = strongly agree). In addition, the System Usability Scale (SUS) was used to evaluate the usability of the system [64]. The results showed an average Likert scale score of 4.4 and SUS score of 65 indicating a moderately good level of user satisfaction with the ATB (Table 7 and 8).

B. PARTICIPANTS' FEEDBACK

Upon completion of various tasks and questionnaires, participants were asked to provide feedback on the modular block-based ATB and suggest improvements. Participants expressed high levels of satisfaction and found using ATB to be as enjoyable as playing a game.

Participants shared feedback that highlighted key observations. They mentioned that the 3D block modules within the ATB were more distinguishable and conveyed spatial information more effectively when compared to conventional 2D tactile maps. The latter often presented an excess of information in a one-sided manner. A participant expressed that traditional tactile maps require a passive reception of predetermined information, necessitating individuals to await the crafting of a personalized map. In contrast, the ATB shows promise in allowing users to quickly obtain customized maps that cater to their immediate needs. Participants appreciated the accessibility and adaptability of the ATB, enabling them to autonomously construct spaces as needed and customize them according to their preferences. A participant noted, "Through the creation of my personal living space, I gained a deeper understanding of spatial cognition, leading to an improvement in my self-esteem." Furthermore, in the context of the device's perceived usability, participants conveyed, "Rearranging furniture within the household has posed considerable challenges for many visually impaired individuals. Nonetheless, with the ATB, it appears feasible to actively participate in planning furniture arrangements that were previously deemed impractical." Moreover, participants indicated their capability to establish connections between each block module and tangible architectural elements once they understood their respective functions.

Participants provided valuable recommendations for improvements, acknowledging that finding the 'Stair' and 'Restroom' modules was relatively straightforward. However, they pointed out challenges in grasping specific details, such as the orientation of stairs or the internal arrangement of the restroom. As a potential resolution, participants proposed the incorporation of specialized block modules to communicate precise details. Additionally, they recommended elevating the height of prominent modules such as 'Door,' 'EV,' 'Stair,' and 'Restroom' to prevent users from inadvertently missing these vital landmarks during rapid examinations of the space using the ATB.

VI. DISCUSSION

A. EFFICIENCY OF PERCEIVING ATB

The research [9] showed that it took approximately 15 minutes for VIP to form a mental map of a spatial structure covering an area of about 1,200 m^2 by physically palpating an existing tactile map. Under the assumption of proportionality between the area of the space and the time required for mental map formation, it is expected that 400 m^2 will take approximately 5 minutes. Consequently, utilizing ATB is anticipated to yield further reduction in the required time for mental map formation.

In contrast, when utilizing ATB, the formation of a mental map can be considered significantly more efficient and effective, taking 2 minutes and 24 seconds, which is approximately half the time, even for unknown spaces. These results affirm that ATB outperforms the existing tactile map in facilitating the acquisition of spatial information about unfamiliar environments for the formation of a mental map.

Consequently, it can be confirmed that the block modules of ATB have a suitable geometric form that facilitates efficient recognition of landmarks within the space, and the composition method of ATB enables easy comprehension of the entire spatial structure, which represents an area of approximately 400 m^2 when scaled at about 1/100.

B. EFFICIENCY OF MANIPULATING ATB

Regarding the 'Positioning Error (PE)', out of all the participants, subject C was the only one to exhibit the error, and this happened only once in the 'generate' task and three times in the 'share' task. The error probability in each task was low, with values of 0.02 % and 4.8 % respectively, when compared to the number of block modules used. Nevertheless, subject C was able to correct these errors through repeated construction attempts. Importantly, no other participants, including those who were congenitally VIP, experienced any 'Positioning error', indicating that the block modules could be easily plugged into the correct positions on the panel. In the future, the utilization of alternative connectors with integrated magnets and connection pins such as magnetic pogo pin connector would significantly reduce this error.

Regarding the 'Constructing Error (CE)', a total of 20 errors were observed across the 'generate' and 'share' tasks. In the 'generate' task, the occurrence rate was less than 1 % due to participants' familiarity with the space. However, in the 'share' task, the occurrence rate was relatively higher at 6.9 % due to the unfamiliarity with the unknown space. Specifically focusing on the errors observed in the 'share' task, there were 5 instances where the 'wall' module was mistakenly used instead of configuring the 'door' module. This suggests that participants may have encountered difficulty in identifying the smaller-sized door, due to the utilization of a scaled-down 3D printed tactile map. Regarding the remaining errors, the majority involved the misuse of the standard wall module instead of the 'T-shaped wall' or 'right-angle wall'. Upon examining the ATB space created by the participants, it can be determined that there are no issues with their ability to construct the spatial structure. However, this observation can be attributed to the narrow spacing between the modules at the vertical intersections of the walls, which creates a misperception of being connected. These issues could be addressed by enhancing the geometry of the respective modules, such as enlarging the door's size or increasing the height of the T-shaped and right-angle walls.

In terms of the time taken to complete a task, the ability to form mental maps and engage in spatial construction is inferred to vary depending on prior visual experience. Regarding the 'share' task in Evaluation 2, participants B and D, who were born VIP, took an average of 24 minutes and 49.5 seconds. This was 13 minutes and 57 seconds longer than participants C and E, who acquired their VIP and had an average completion time of 10 minutes and 52.5 seconds (table 6). Additionally, the oldest participant, D, took the longest time to construct the space. Upon examining the low performance results of participant D in both the 'modify' and 'share' tasks as well, it is conjectured that spatial perception and construction ability might be related to tactile sensations in the finger. However, by engaging in educational activities focused on familiarizing individuals with various spatial structures and providing hands-on experience in constructing spaces using ATB, it is anticipated that the disparity resulting from prior visual experience can be minimized.

C. BLOCK MODULE

In the initial phase of tactile exploration, four out of five participants mistakenly perceived the 'Stair' module as resembling a pyramid or a roof, misinterpreting its intended meaning. To address this issue, it is required to redesign the 'stair' module, employing a geometry that distinctly conveys the concept of ascending or descending. Moreover, for improved differentiation of key landmarks such as 'Door,' 'EV,' 'Stair,' and 'Restroom,' it is advised to raise the height of these modules in comparison to the 'Wall' modules. Concerning the 'Restroom' module, while it primarily offers location information for the restroom, there is potential for enhancement by introducing additional modules depicting specific details, such as a toilet and a sink. This comprehensive incorporation of module features would contribute to an enhanced understanding of the spatial arrangement within the restroom.

The current iteration of the ATB primarily emphasizes enabling spatial representation at a 1:100 scale. However, effectively communicating intricate details can pose a significant challenge due to the limitations imposed by the restricted size of the panel. Thus, diversifying the range of modules and panel specifications is necessary to expand the capability for multi-scale spatial representation. Moreover, the design of additional modules representing outdoor environments is essential to address the current limitations confined to indoor spaces. Expanding the ATB in this manner aims to alleviate its current limitations and offer valuable support to visually impaired individuals navigating outdoor spaces.

D. SPATIAL LEARNING

The outcomes of our experiments provide strong evidence supporting the effectiveness of the ATB as a valuable tool for obtaining spatial information. Notably, evaluation 1 demonstrated the feasibility of passive learning, where exposure to spaces created by sighted individuals was sufficient. In contrast, it was observed that active learning was achievable through the user test in evaluation 1, as visually impaired participants independently constructed spatial representations. Nevertheless, enhancing the efficacy of the ATB as an aid for active spatial learning necessitates the incorporation of suitable interactive elements, such as sound notifications or haptic feedback. Incorporating feedback mechanisms to rectify errors holds the potential to markedly diminish the time needed for spatial construction tasks, thereby elevating the overall usability of the ATB as an effective learning tool.

VII. CONCLUSION

We proposed a novel block-based tangible media, ArchiTangiBlock, which enables VIP to construct and express their own spatial designs in CAD system, as well as create tactile maps. We designed block modules that represent and modularize architectural elements, which are important factors in the process of O&M, to improve the efficiency of recognition. Another part of the ATB, a computer interface, was developed to visualize the space as VIP constructed on the panel with modules.

We first investigated whether an ATB could express a space coincidently with mental map of the user to identify the efficacy of the ATB. The findings from evaluation 1 demonstrated that the ATB effectively described the space in accordance with the VIP's mental map. Moreover, VIP users exhibited faster mental map formation for unknown spaces when using the ATB compared to existing tactile maps. This confirms that the geometric design of block modules and spatial composition method employed in the ATB facilitated a more intuitive grasp of the entire space.

Subsequently, we conducted experiments to identify the functionality and usability of the ATB as a computer-aided design tool in the tasks of constructing spaces. Based on the findings from the 'modify' and 'generate' tasks in evaluation 2, it was established that VIPs could efficiently and accurately construct a spatial representation nearly coincident with the actual space using ATB. Conducting the 'share' task revealed that VIP could effectively and accurately comprehend the spatial structure and communicate about it with each other by reusing the tactile maps generated by the ATB. Furthermore, user satisfaction with the ATB was assessed to be high, as indicated by the responses from the questionnaire on a 5-point Likert scale and the valuable feedback provided by the participants.

Finally, it is significant to mention that the evaluation of user satisfaction with the ATB resulted in favorable ratings, as indicated by responses on a 5-point Likert scale in the questionnaire and the feedback conveyed by the participants. Participants expressed enjoyment in the process of directly constructing space using the ATB, drawing parallels to engaging in a game. There was feedback suggesting that it would be effective for spatial cognitive learning as well. Furthermore, a notably positive impact was noted concerning the boost in self-esteem when participants directly expressed their spatial knowledge. These results not only affirm the device's functionality but also underscore its effectiveness as a practical tool for individuals with visual impairments.

For future studies, our plan is to modify the shape of specific modules and extend their functionality to enable detailed representation of indoor architectural spaces. Furthermore, we will design an additional module capable of representing outdoor spaces and modules that can depict information across multiple scales. Finally, we will further study to assess the effectiveness of ATB when incorporating suitable interactions, such as sound notifications or haptic feedback.

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