COGNITIVE-MAP FORMATION OF BLIND PERSONS IN A VIRTUAL SOUND ENVIRONMENT

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ABSTRACT

This paper describes a new assistive technology for sightless persons based on a virtual auditory display (VAD). This system is intended to encourage its users to improve their map-forming skills and use them more efficiently while providing a safe virtual sound environment to virtually walk and navigate through. The VAD is a middle-ware software program called SiFASo (Simulative environment for acoustic 3D software), which is implemented on Windows XP (Microsoft Corp.). The system virtually realizes a sound maze through which a user navigates using a game controller instead of traveling physically. Two experiments were conducted to evaluate the practical effectiveness of this newly developed system. Firstly, it was examined whether participants were able to create corresponding tactile maps after walking through virtual sound mazes. Evaluation using bi-dimensional regression analyses and bi-dimensional correlation coefficients indicated that most participants were able to produce accurate cognitive maps. Secondly, an experiment to investigate whether the participants, after navigating through a virtual sound environment of an actual but unfamiliar building, could find their way on a real passage upon which the virtual environment was based. Results showed that three out of four participants were capable of completing the given tasks. This system is effective to promote the forming of cognitive maps or survey maps of users. For those reasons, it might be a useful tool for effectively training blind persons, thereby improving their orientation and mobility.

1. INTRODUCTION

Human beings can create mental maps or cognitive maps [1–5], which enable them to reach a desired destination in a familiar environment without external maps. Congenitally visually impaired persons are at a considerable disadvantage because they have little or no visual input, which plays an important role in the formation of cognitive maps. Walking is important for the formation of cognitive maps. During walking, sighted persons can form and reinforce memorization of a map with visual information of landmarks, heading, and self-velocity that are all added and organized or re-organized into a cognitive map. For those reasons, spatial experiences are crucial to form cognitive maps [6–8]. In addition, several recent studies report that spatial images can be developed and used by blind persons through the interaction with virtual environment through audio interfaces [9–11].

The authors have been developing a system to assist the formation of cognitive-maps. This system is intended to encourage its users to improve map-forming skills, and to do so more efficiently, while providing safe virtual sound environment to virtually walk and navigate through. The authors also conducted experiments and examined the practical effectiveness of the system.

2. DEVELOPMENT OF THE COGNITIVE-MAP FORMING SYSTEM

2.1. Outline of Virtual Auditory Display (VAD)

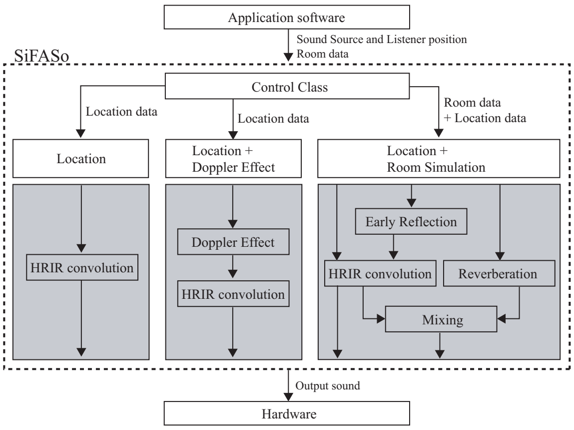


Figure 1: Specifications of VAD middle-ware “SiFASo”

The authors designed and developed a virtual auditory display (VAD) middle-ware program [12]. This system is called Simulative environment for acoustic 3D software (SiFASo) and is applied to a personal computer platform (Windows XP; Microsoft Corp.) . Figure 1 shows the specifications of SiFASo. Sound source signals are convolved with head-related transfer functions (HRTFs) to control sound localization. Users listen to processed sound through headphones, and a head tracking device is affixed to the head belt of the headphones so that it can be worn on the head. The tracking device sends data of the head movement to the computer to select appropriate HRTFs. The Doppler effect, first-order reflections in accordance with different wall materials, late reverberation, and air-absorption effect are also simulated, facilitating the development of various software programs. In the present study, a small 3-degree-of-freedom head tracker based on ultrasonic gyros (MDP-A3U9S; NEC-Tokin Corp.) was used.

2.2. Specification of the cognitive map-forming system

In this section, the specification of the cognitive map-forming system is described:

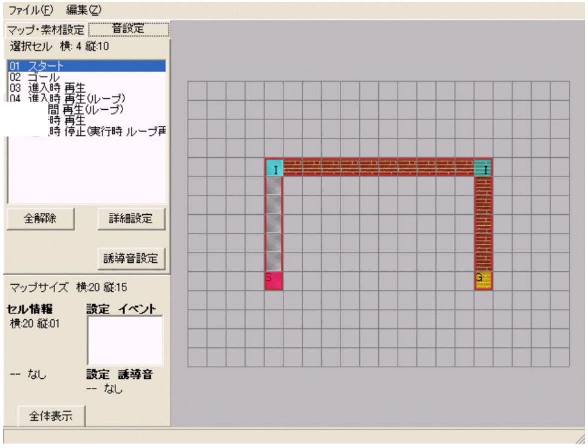
1. A user navigates through mazes of virtual sound environments using a game controller instead of traveling physically.
2. The user moves forward by pressing the forward button on the controller. The heading direction is determined only by the direction of user's head. Therefore, the user cannot change direction using the buttons on the controller. Figure 2 shows a participant walking through a maze. The user must turn his/her body to the right and then press the forward button if he/she wishes to turn right. To move backward, the user must turn around 180 degrees, then press the forward button. There is also a verbal confirmation "You have turned right" and "You have turned left" confirming the user's action that had been taken. The physical turning movement helps the user to perceive turning as a direction.
3. A maze is consisted of a series of cells. The user hears a footstep and moves one cell forward when the forward button is pressed. (A map editor to design mazes was also developed, as described later.)
4. A cell is a one meter cube with a floor, walls, and a ceiling. These dimensions are determined based on technical limitations of the present system.
5. A landmark (or soundmark) can be set at a cell. These lan marks include, but are not limited to, animal sounds such as dogs, cats, or sheep, and other daily sounds such as cars, motorcycles, audible traffic signals, and railway crossings. Since landmarks are represented by *.wav files (sampling rate: 44.1 kHz, bit depth: 16 bits), the variety of landmarks is not limited to the above mentioned items; The actual sound of a crowded street or that of a main street with shops can be recorded and then would provide good landmarks.
6. The landmarks can be used in two ways: in "trace mode", a user hears a landmark sound constantly, guiding him/her to the cell, and in "free style mode", a user encounters the landmark only when the user reaches the cell.
7. Both audible and tactile (vibrational) feedback is given to the user when a user accidentally hits a wall. A vibrator in the game controller vibrates for the tactile feedback.
8. The start and finish points can be set in mazes; a starting announcement and finishing fanfare can be also set accordingly.
9. The user's movement can be traced on a computer screen. This can be turned off according to preference.

Figure 2: A participant navigating through a maze of virtual sound environment

2.3. Specification of the Map Editor

The map editor is a Graphical User Interface (GUI) based application, making it easy for instructors and teachers at schools for the blind to produce maps to be used for training. Figure 3 shows a screen shot of the map editor. A map consists of a series of cells. These cells can be aligned to create a passage; alternatively, they can be agglomerated to create a room.

Although only limited to first-order sound reflection, reflections from the floor and walls can be simulated. Eight room-surface types provide different absorption coefficients: carpet, concrete, vinyl tile, wood, brick, plaster, non-reflective, and solid (non-absorption). One surface characteristic can be set for one cell. In this study, the direction in a maze is always expressed in terms with north, south, east and west. Up to 20 cells can be aligned for the east-west axis, and up to 15 cells can be aligned north-south.



選択セル 横: 4 縦:10

マップサイズ 横:20 縦:15

セル情報 横:20 縦:01

-- なし

設定 イベント

設定 誘導音 -- なし

Figure 3: Map Editor

3. EXPERIMENT 1: COGNITIVE MAP-FORMING AND TACTILE MAP EVALUATION

An experiment was conducted to examine whether the cognitive map-forming system is effective as an assistive technology. This experiment examined whether the participants can produce tactile maps after navigating through mazes created with the system.

3.1. Method for Creating a Tactile Map

A white-board with soft bar magnets shown in figure 4 was used to draw tactile maps. Magnets are easy to feel and to apply or remove when users wish to make a correction in their own work. In addition, small magnetic figures (1–2 cm by 1–2 cm by 1–2 cm) were used to represent audible landmarks such as animals or vehicles on maps. They can be attached to the board and are easily detected by touch.

Figure 4: White-board, bar magnets and magnetic figures

3.2. Tasks

Two tasks were given to participants: a landmark-locating task and a map-drawing task. In this experimental setting, all cell surfaces were set to concrete.

Task1: Landmark-locating

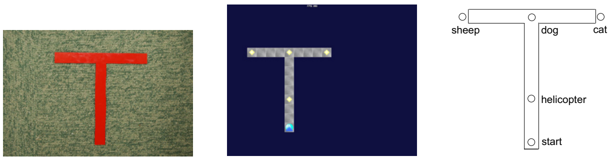


Figure 5: Route 1; a (left); Tactile map without landmarks, b (middle); Visual representation of sound maze, c (right); Example of map completed by a participant

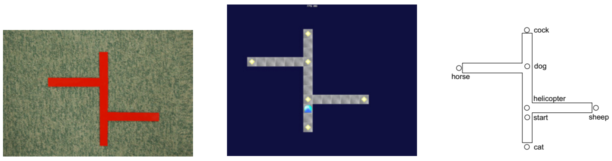


Figure 6: Route 2; a (left); Tactile map without landmarks, b (middle); Visual representation of sound maze, c (right); Example of map completed by a participant

Participants were given a tactile map of a maze without landmarks to facilitate memorization of the route. Two routes shown in Figs. 5a and 6a were used. They were then asked to navigate through the virtual sound maze to locate several landmarks, as shown in Figs. 5b and 6b. The participants were asked to memorize the locations of all landmarks, then complete the map by placing magnetic figures in correct places for these landmarks. Figure 5c and 6c show examples of the map completed by participants for, respectively, Figs. 5b and 6b. The landmarks were shown to participants by use of ”free style mode.” Although 10 min was given to participants for the navigation in a maze, the navigation finished as soon as the participant reached all the landmarks, even if it was accomplished in less than 10 min. Then, immediately after the navigation, participants were asked to locate landmarks as they had memorized them. An experimenter verified the location of landmarks after a participant completed the task.

Task2: Map-drawing

Participants were asked to navigate a virtual sound maze with several landmarks. Two routes shown in Figs. 7a and 8a were used. The landmarks were shown to participants by use of ”free style mode.” While navigating the sound maze, they were asked to draw the map of the sound maze by locating soft magnet bars and figures representing landmarks on a white-board. The participants were allowed to freely travel the virtual sound maze and draw the tactile map back and forth. The time for the task was unrestricted. Figures 7b and 8b show examples of the maps drawn by participants for, respectively, the virtual sound maze shown in Figs. 7a and 8a. Whether participants were able to create corresponding tactile maps after walking through virtual sound mazes was first qualitatively evaluated by experimenters. Then, results were quantitatively evaluated by using bi-dimensional regression analysis and bi-dimensional correlation coefficients.

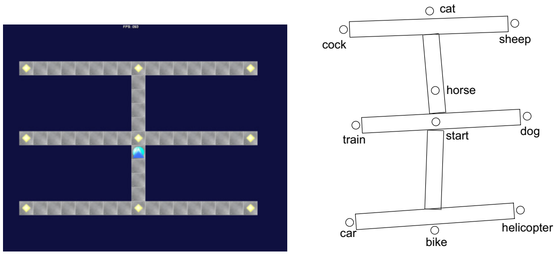


Figure 7: Route 3; a (left); Visual representation of sound maze, b (right); Example of map completed by a participant

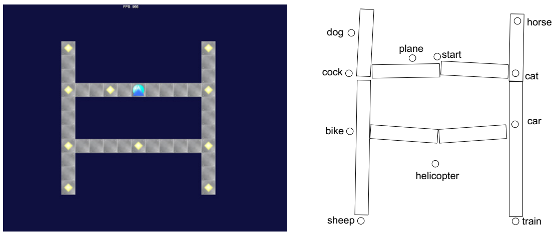


Figure 8: Route 4; a (left); Visual representation of sound maze, b (right); Example of map completed by a participant

3.3. Participants of the Experiment

Of the eight participants, four (CMR, CSM, CTH and CKR) were congenitally blind adults and four (SYN, SGK, SMS and SOM) were blindfolded sighted adults. Of the four blind participants, one was female; the rest were male. All the sighted participants were female. Prefixed by a C denote congenitally blind participants, and prefixed by an S designate sighted participants. At the start of the experiment, a participant stood facing north in both virtual and real terms. A desk was placed in front, just north of a participant and participants were instructed to feel free to find the desk for directional reference purposes when they were disoriented during navigating the maze. Participants were asked to remain standing during navigation and, when they wished to make a turn in the maze, changed their body direction toward the direction to proceed and pressed the forward button on a game controller to move ahead.

3.4. Results and Discussion

Task1: Landmark-locating

In the landmark-locating task, one sighted participant confused the placement of a dog and a sheep. However, the remainder of the participants made no mistakes. On route 1, the task was completed by congenitally blind participants anywhere from 57 s to 180 s, with an average of 107 s; whereas the sighted participants needed 56 s to 229 s, with an average of 155 s, to complete the task. There was no statistically significant difference between blind persons and the sighted participants in terms of how long it took them to complete the task. On the other hand, both groups took significantly longer on route 2 ($F_{(1,6)}$=29.84, p<.01). This might be understandable because route 2 was more complex than route 1: the number of landmarks was increased from 4 to 6 with two intersections, whereas only one intersection was found on route 1. Figure 9 shows the time each participant took in the landmark-locating task.

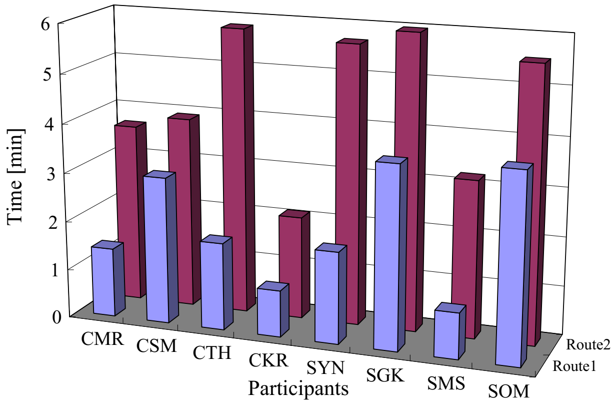


Figure 9: Time for seeking landmarks

Task2: Map-drawing

Figures 10 and 11 show examples of the maps drawn by two participants. All participants drew geometrically accurate maps.

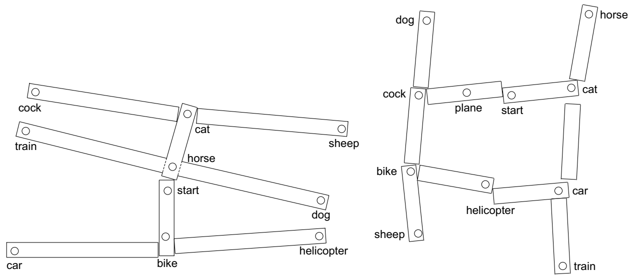


Figure 10: Examples of maps by participant SMS; route3 (left) and route4 (right)

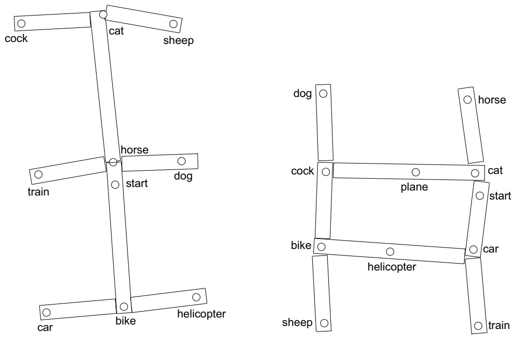


Figure 11: Examples of maps by participant CMR; route3 (left) and route4 (right)

Figure 12 shows the respective times taken by participants to complete routes 3 and 4. A statistical test showed no significant differences between the time it took the congenitally blind persons and the sighted participants to complete the tasks. However, both groups took significantly longer on route 4 than on route 3 ($F_{(1,6)}$=11.61, p<.05). A reason must be the structure of shape of the maze for route 4; the passage of the maze forms a square ambulatory. The participants would have had difficulty to recognize this ambulatory unless they kept track of the location of the landmarks as well as their heading direction while they made turns. Without recognizing that, they would have been around in circles without grasping the entire picture. Another reason might be that the number of landmarks increased from 10 on route 3 to 11 on route 4.

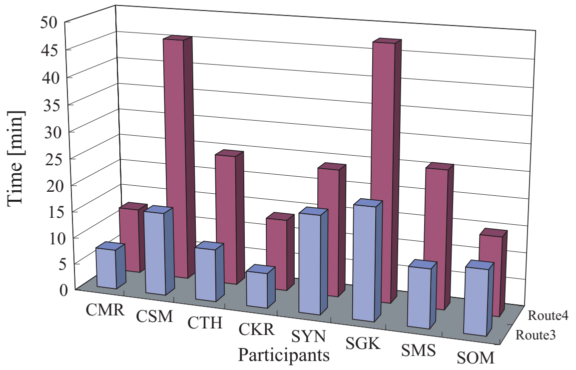


Figure 12: Time for making maps

3.5. Quantitative Evaluation of Drawn Tactile Maps

Maps drawn by the participants were evaluated quantitatively using bi-dimensional regression analysis developed by Tobler [13]. This analysis is based on bivariate unidimensional regression for least squares and is a good tool for dealing with a bi-dimensional variate [14]. For a point i (u_i, v_i) on an external map, and a point corresponding on a cognitive map is (x_i, y_i), the Euclidean regression equation is as follows (Eq. 1):

$$\begin{pmatrix} u_i \\ v_i \end{pmatrix} = \begin{pmatrix} a_1 & -a_2 \\ a_2 & a_1 \end{pmatrix} \begin{pmatrix} x_i \\ y_i \end{pmatrix} + \begin{pmatrix} b_1 \\ b_2 \end{pmatrix} + \begin{pmatrix} e_i \\ f_i \end{pmatrix} \quad , \qquad (1)$$

where e_i and f_i indicate residual matrices, a_1, a_2, b_1, and b_2 indicate regression coefficients, and n indicates the number of target points. The Euclid regression analysis estimates the regression coefficients that produce the sum of squares of the element of a residual matrix minimum based on the least-squares method. Setting $c = \sqrt{a_1^2 + a_2^2}$, Eq. 1 can be transform into the following equation (Eq. 2):

$$\begin{pmatrix} u_i \\ v_i \end{pmatrix} = c \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} x_i \\ y_i \end{pmatrix} + \begin{pmatrix} b_1 \\ b_2 \end{pmatrix} + \begin{pmatrix} e_i \\ f_i \end{pmatrix} \quad , \qquad (2)$$

where b_1 and b_2 respectively indicate the translations along the horizontal and vertical axis, c indicates the scaling factor and θ indicates the amount of rotation counter-clockwise. Then, the correlation between an external map and corresponding cognitive map can be evaluated using the correlation coefficient derived from the Euclidean regression transformation, as described below. Here, the coordinate of point i on an external map is (u_i, v_i); its barycentric coordinate is $(\bar{u}_i, \bar{v}_i)$, and the superposed point using least squares is $(\hat{u}_i, \hat{v}_i)$. Then, the dimensional correlation coefficient is expressed as follows:

$$R = \sqrt{1 - \frac{\sum_{i=1}^{n}(u_i - \hat{u}_i)^2 + \sum_{i=1}^{n}(v_i - \hat{v}_i)^2}{\sum_{i=1}^{n}(u_i - \bar{u}_i)^2 + \sum_{i=1}^{n}(v_i - \bar{v}_i)^2}} \quad . \qquad (3)$$

The maps created by the map editor and those drawn by the participants were digitized. Then horizontal and vertical coordinates were obtained by regarding the starting point as the origin to evaluate the results of the map-drawing task using bi-dimensional regression analysis. Bi-dimensional regression was applied to calculate the bi-dimensional correlation coefficients. Only the completed parts of the maps that were analyzed for the maps were not completed; this was for the maps drawn by the congenitally blind participant CTH and the sighted participant SYN. Figure 13 shows the correlation coefficient of each participant for each route.

All participants showed correlation coefficients greater than 0.85. These high correlations suggest that this system is effective to assist the formation of cognitive maps. The correlation coefficient for CMR on route 3 was low, because the tactile map drawn was vertically (north-south) longer than the original map created by the map editor (Fig. 11). Overall, however, drawn maps were mostly accurate in their form in terms of alignment of landmarks, distances among landmarks, and relations of passages.

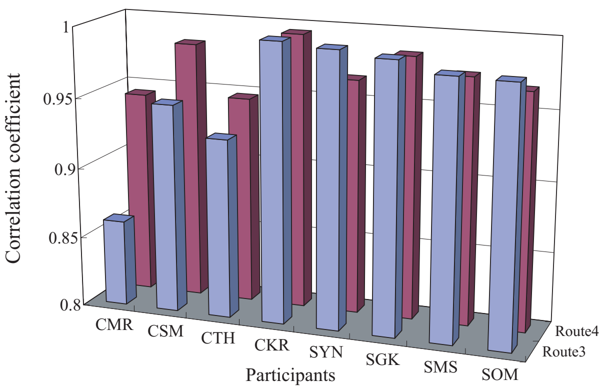


Figure 13: Bi-dimensional correlation coefficient of each participant on each route

4. EXPERIMENT 2: COGNITIVE MAP FORMING FOR ACTUAL BUILDING

The result of experiment 1 indicates that cognitive maps can be formed correctly after navigation through the virtual sound environment. This experiment examines whether the training in virtual sound maps is applicable to traveling in the real world.

4.1. Procedure

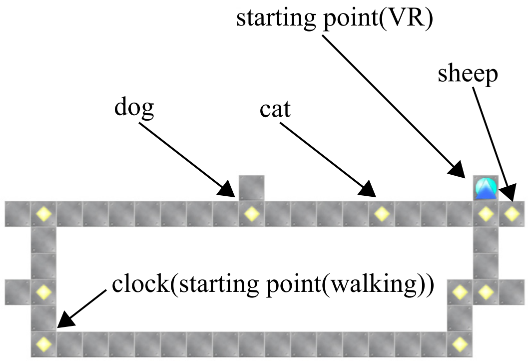


Figure 14: Visual representation of sound maze based on hallway floors of an actual building

A maze was designed based on corridors of an actual building (Fig. 14). Participants first freely navigated through the virtual sound maze up to 20 min to learn the map of the maze. Then, after navigating through the virtual sound maze, without drawing any (tactile) maps, they were asked to walk in the real corridor as instructed. The participants were the same four congenitally blind adults who had participated in the previous experiment. At the beginning of the real walking, they were guided to the landmark clock where they had started the virtual navigation. Then the following four tasks were given to them:

task 1 Go to the landmark dog,

task 2 Go to the sheep without encountering the cat,

task 3 Go to the dog taking the shortest route, and

task 4 Go back to the clock taking the shortest route.

This experiment aims at examining whether the participants were able to create cognitive maps of so-called survey-map type after navigating the virtual sound maze. That is, they were given different starting points in virtual and real environments. Moreover, in task 2, they were required to make a mental picture of the floor plan and the relative locations of the dog, cat and sheep. Therefore, if all these tasks are well completed, it can be regarded that cognitive maps are formed as survey maps. During these tasks, for safety assurance, participants walked with a sighted guide and when participants changed their heading directions, they were asked to give vocal commands to a sighted guide.

4.2. Result and Discussion

Tab. 1 shows the evaluation of walking tasks by the experimenter for each participant. Here, ◎ is marked when a participant was able to find the way to an instructed destination without wandering at all, ○ is marked when a participant wandered but reached an instructed destination in the end, and △ is marked when a participant was able to reach an instructed destination with some verbal assistance, or was able to reach an instructed destination however missed the starting point. On the other hand, × is marked when a participant was unable to find the way to an instructed destination. Figure 15 shows distances walked for each task by each participant. "Correct distance" indicates the length of the shortest way to reach the instructed destination.

Table 1: Evaluation of walking tasks

Participants（gender）	task 1	task 2	task 3	task 4
CSM（M）	○	○	◎	○
CTH（M）	◎	△	◎	◎
CKR（M）	○	◎	◎	◎
CMR（F）	×	×	×	△

CSM in tasks 1 and 2 and CKR in task 1 wandered around before reaching the destinations. In contrast, CTH went straight to the destination in task 1 but became disoriented in task 2. After asking for verbal assistance, CTH completed tasks 3 and 4. The verbal orientation assistance in task 2 might have helped CTH to complete tasks 3 and 4. Finally, CMR did not reach the correct destinations in tasks 1 through 3. Later, CMR reached the clock in task 4, but from a different starting point than planned.

The results suggest that only CSM and CKR were able to produce survey maps. After the experiment, experimenters asked both CSM and CKR why they wandered around before reaching the destination in task 1. CSM was confused by some alignment effect because the starting point of the real environment (the clock) was different from that of the virtual environment. Nevertheless, while walking in the real environment, he might have been reminded of the mental map and correctly aligned it to the actual floor plan. Moreover, CKR answered that he walked from one end of the corridor to the other end to find out the map scale, which was not given to the participants.

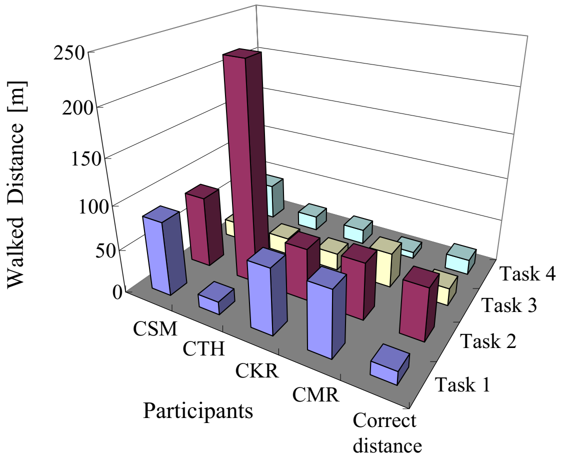


Figure 15: Walked distance by each participant

Why could not CMR complete the tasks in this experiment, even though he showed no marked difficulties in the map-drawing task in experiment 1? At least three possible reasons exist. First, CMR might have failed to perceive the map during virtual sound map navigation. Secondly, CMR might have failed to memorize the map sufficiently; the question then arises: Why did CMR succeed in the map-drawing task in experiment 1, but not in experiment 2? A salient difference between these two experiments was the drawing of the tactile maps. In the map-drawing task, participants drew tactile maps while navigating through the mazes; this procedure might have reinforced the formation of cognitive maps. The results suggest that the combination of navigation of (virtual) spaces and drawing of maps can be very effective to form good and robust cognitive maps. The third reason is that CMR might have failed to use the cognitive map. After the experiment, CMR found difficulty walking with a sighted guide because a guide dog is CMR's chosen method of mobility. It is noteworthy that CMR is the only one who has a guide dog: the other blind participants do not walk with guide dogs. The possible influence of the use of a guide dog on the acuity of spatial cognition in orientation and mobility, including formation of cognitive maps, seems to pose an interesting problem for future study.

After the experiments, a few participants gave a similar opinion: they became disoriented by physically turning right or left repeatedly in a virtual environment. This disorientation might be attributable to mental rotation of incomplete maps under formation. Use of other directional buttons on a game controller would solve this problem. Theoretically, physical experience, typically by walking, is a key to the formation of cognitive maps. However, repeated rotation without any real moving or walking might have promoted such confusion. An idea would be to give users the choice of changing direction by body movement or by using game controller buttons. Anyway, the navigation method in a virtual sound environment seems to pose another interesting problem for future examinations.

4.3. Issues for Future Investigation

Overall, experimental results showed that after a blind person navigates through an unfamiliar environment a cognitive map can be formed as a survey map with the help of this system based on a Virtual Auditory Display. However, through the present study several interesting future issues as well as problems to be solved have arisen:

1. This system was originally planned as an assistive tool to train orientation and mobility for the adventitious blind and pupils of schools for the blind. It is necessary to examine its applicability to those people.
2. The present map editor is not capable of producing a map larger than 20 cells by 15 cells. A capability to create larger maps must be made available to realize a helpful tool in an actual training setting.
3. The cell is only a regular hexahedron with one cubic meter volume. This must be improved to create more realistic passages, rooms and spaces.
4. The VAD middle-ware we developed can render moving sound sources. Therefore, effective use of this capability is a key to create a more realistic virtual world. Some examples are good localization and cognition of the sound of traffic, which are important skills that can give blind pupils better mobility.
5. The present study demonstrated the practical effectiveness of the use of VAD on the formation of cognitive maps. However, further study is necessary to determine whether the virtual sound map is more effective than the use of a traditional tactile map, including the development of effective methods of navigating in virtual sound maps.
6. For future application, orientation and mobility training for vertical directions must be examined because good orientation for train station platforms and staircases are important for increasing mobility in daily life. Development of systematic course-ware that is fitted to specific users must also be important.

5. CONCLUSION

A new assistive technology based on a virtual auditory display (VAD) was designed to assist and train blind persons in the formation of cognitive maps. Its effectiveness was examined using two experiments. First, it was examined whether participants were able to create corresponding tactile maps after walking through virtual sound mazes. Evaluation using bi-dimensional regression analysis and bi-dimensional correlation coefficient indicates that most participants were able to produce accurate cognitive maps. Secondly, experiments were conducted to investigate whether the participants, after navigating through a virtual sound environment of an actual but unfamiliar building, were able to find their way on the real passage that was modeled after the virtual environment. Results show that three out of four participants were able to complete given tasks. This result demonstrates that the use of this system promotes the formation of cognitive maps of users. These results confirm the practical effectiveness of our assistive technology for blind persons. This system might be an effective tool for orientation and mobility training for blind persons.

6. ACKNOWLEDGMENTS

A part of this research was supported by a Ministry of Education, Culture, Sports, Science, and Technology Grant-in-Aid for Exploratory Research, 14658054, from 2002 to 2004 , 17650263, from 2005 to 2007 and Consortium R&D Projects for Regional Revitalization of Ministry of Economy Trade and Industry from 2003 to 2004. The authors would like to thank Mr. K. Saito and Mr. M. Toyoda for their assistance during this study.

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