Health, 2016, 8, 487-494
Published Online March 2016 in SciRes. http://www.scirp.org/journal/health
http://dx.doi.org/10.4236/health.2016.85052

Comparison of Developmental Stages in Relation to Way Finding Behavior in an Immersive Virtual Reality Space

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Received 26 February 2016; accepted 27 March 2016; published 30 March 2016

Abstract

To establish a proper evaluation method for spatial cognitive deficits and a form of developmental disorder, we have used an immersive virtual reality (VR) device to develop a game that involves actually walking through a VR space to search for a target object. In this paper, we presented the results of control experiment with 22 healthy elementary school students as participants. The complexity of the VR space was controlled according to the number of pillars present and whether an overall view was possible (controlled by the height of the pillars). For each set of conditions, 24 trials were performed, and the route and time taken to search for the target were recorded. The starting point was changed in each subsequent trial. Results showed that the search time decreased as the number of trials increase, suggesting a process whereby a cognitive map was formed. We also compared the present results to results from our previous experiment with university students using the same experimental conditions, and we discussed the influence of developmental stage on spatial cognition.

Keywords

Virtual Reality, Way Finding, Developmental Disability, Spatial Cognition

1. Introduction

Research has been conducted to establish a proper evaluation method for spatial cognitive deficits and a form of

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How to cite this paper: Watanabe, H., Okumura, T. and Wakamiya, E. (2016) Comparison of Developmental Stages in Relation to Way Finding Behavior in an Immersive Virtual Reality Space. *Health*, **8**, 487-494.
http://dx.doi.org/10.4236/health.2016.85052

developmental disorder [1] [2]. Unlike other spatial cognitive disorders, topographical disorientation is distinctive in that it becomes apparent when individuals with the disorder walk around a wide area [3] [4]. Cognitive phenomena in topographical disorientation include difficulty grasping the positional relationship between two separate locations, and forming a bird's-eye cognitive map of an overall region based on the route taken.

To quantitatively examine these kinds of clinical observations, we have used an immersive virtual reality (VR) device to develop a game (hereinafter, VR test) that involves actually walking through a VR space to search for a target object, thereby enabling parameters such as search time and walking distance to be measured. This method is expected to be useful for elucidating the relationship between search behavior and a wide range of spatial factors, such as size of the space, presence or absence of landmarks, and position of the initial viewpoint, as well as the characteristics of the cognitive maps formed. Here, we reported the results of a control experiment that was conducted using the VR test with healthy elementary school students as participants. We discuss trends in the search time required to find the target, and we compare the results with our previously reported results for healthy university students performing the same task [1].

2. Methods

2.1. Participants

Participants were 22 elementary school students aged ≥10 years who had normal or corrected to normal (glasses or contact lenses) visual acuity and normal stereoscopic acuity (mean age, 11.4 years; SD, 0.5 years; 13 boys and 9 girls). They were recruited through educational committee nearby the first author's institute. On the day of the test, we verified that the participants were fit to take part in the experiment by measuring their vision and stereoscopic acuity using a Landolt ring chart from 5 m, a Yamachi's chart for near point distance (30 cm, HP-1233, Handaya Co., Ltd.), and a Stereo Fly Test (Stereo Optical Co., Inc.). Participants had no prior knowledge of the maps used in the experiment and were not told the specific purpose of the experiment. The study protocol was approved by the Ergonomics Committee of the National Institute of Advanced Industrial Science and Technology (AIST). Written informed consent to participate in the study was obtained from a parent or guardian of each participant, and the participants gave written informed assent to participate.

2.2. Pretest Examinations

Prior to the experiment using the VR test, we conducted the following examinations: (1) a question sheet on medical history and physical condition on the day of the test; (2) Raven's Colored Progressive Matrices [5]; (3) Test of Visual Perceptual Skill (TVPS-3) [6]; and (4) Topographical orientation questionnaire for children (TOQ- C). Of these, the tasks in (2) involve selecting the option that matches the missing part of a standard pattern, while the tasks in (3) involve selecting a standard figure from several similar figures. Both of these tests are used as methods for evaluating visual reasoning and developmental stages of visual perception. Similarly, (4) is a questionnaire for children answered by parents, developed referring to an adult version [7] to assess (on a 5-point scale) subjective awareness of one's sense of direction.

2.3. VR Space Way Finding Experiment

Here, we describe the details of the experiment where participants navigated through a VR space in search of a hidden target.

Device: The test images were projected using the CAVE immersive VR device (University of Illinois) from a 4000 lm projector (NP-M402XJD; NEC) onto 3 m × 3 m screens placed to the front, left and right of the subject, as well as on the floor. Participants viewed these images through polarized glasses (using a circular polarization method). Non-contact measurement of the participant's head position was performed with a motion capture system (Bonita 10, Vicon) at a sampling rate of 120 Hz. This position information was sent to the CAVE system via an Ethernet connection. Rendering distortions due to the position of the participant's head were corrected based on this information, and this information was recorded to measure the paths taken by participants as they walked through the space.

Task: The task was for the participant to find a target (a teapot rendered by computer graphics) hidden in one of several pillars arranged on the floor of the CAVE environment, by walking through the VR space and placing his or her head inside the pillars. We prepared two pillar configurations (Map A and Map B), consisting of either four or eight pillars in each case. The top row of **Figure 1** shows the two possibilities for Map A, while the bot-

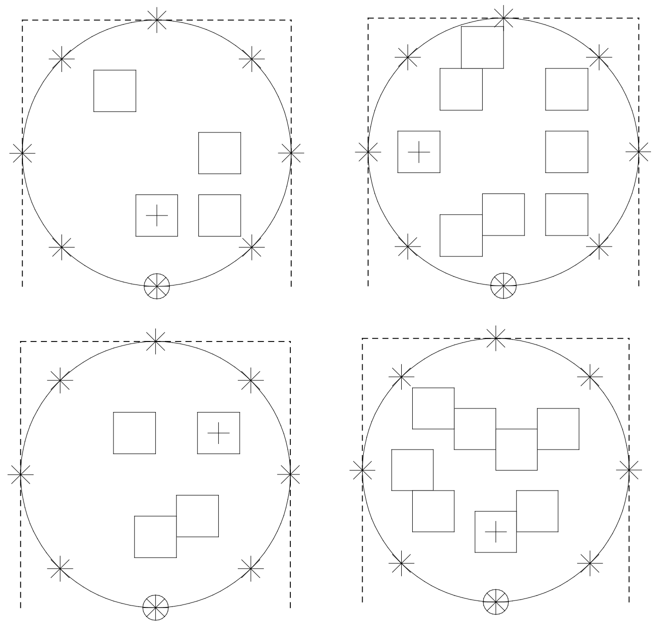

Figure 1. Pillar arrangements used in the VR test (top row: Map A; bottom row: Map B).

tom row shows the two for Map B. The pillar marked "+" contains the target. By setting the height of all pillars to either 1.5 m or 3 m, we prepared two viewing conditions: one where an overall view of the entire map was possible, and another where it was not **Figure 2**. **Figure 3** shows an example of the test conditions with the four-pillar version of Map A when an overall view was possible.

Procedure: Participants were randomly assigned to one of two groups. For one group an overall view was possible for Map A but not for Map B, and for the other group the opposite was the case. For both groups, the order in which maps were presented was randomized, but for both maps, the four-pillar tests were conducted before the eight-pillar tests. For each combination of map and number of pillars, 24 trials were performed. The map orientation at the start of each trial was changed according to the following method. Namely, for each trial the entire map was rotated through either 0˚, 45˚, 90˚, 135˚, 180˚, 225˚, 270˚ or 315˚ about the vertical axis passing through the center of the floor before being presented. In **Figure 1**, each asterisk around the perimeter indicates a relative starting point. The pillar containing the target was always the same but its position changed because of the rotation. The procedure for each trial is as follows. The room is darkened and the participant stands waiting at the starting position (the center of the perimeter of the CAVE floor area, marked by the circles in the lower central parts of each diagram in **Figure 1**). In the first trial, a beep sounds and the map is presented with a rotation angle of 0˚. The participant then walks freely through the map and searches for the pillar containing the target. Participants are instructed that they may not pass through the inside of pillars while searching, and that they should search for the target by placing only their head inside the pillars. As soon as the participant finds the target, the entire map disappears, and the participant is instructed to return to the starting position once again. For the second and subsequent tests, the map is displayed with one of the eight rotation angles above, with each angle being used three times in random order, and the participant searches for the pillar where the target was found in the first trial. Participants completed all 24 trials with an average time of about 15 min, and then rested for about 30 min before conducting another set of trials with a different map or a different number of pillars. Totally, thus, the experiment time did not exceed four hours for one participant with rest and all data was collected within one month.

3. Results

3.1. Pretest Results and VR Space Way Finding Test

Mean scores for Raven's Colored Progressive Matrices, and the Visual Discrimination and Visual Memory

Figure 2. Conceptual diagram of whether an overall view is possible (left) or not (right).

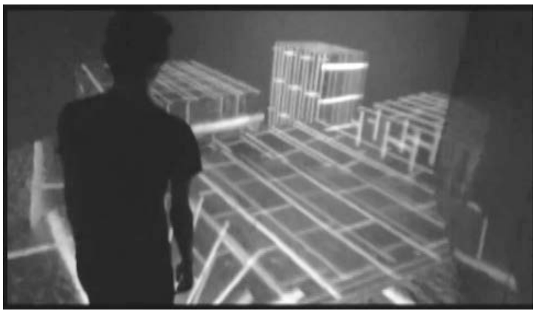

Figure 3. Example of the display during the VR space way finding test.

components of TVPS-3 were 32.14 (SD, 3.48), 10.50 (SD, 3.39) and 13.00 (SD, 2.09) respectively. Comparing these results to those of our earlier study (Watanabe *et al*., 2015) targeting healthy university students with the same stimulus as in this experiment, t-tests showed no significant differences in the measurements (Raven's Colored Progressive Matrices: $F(1, 52) = 0.406$, n.s.; TVPS-3 Visual Discrimination task: $F(1, 52) = 1.320$, n.s; TVPS-3 Visual Memory task: $F(1,52) = 0.056$, n.s).

For the TOQ-C, subjective perceptions of sense of direction were graded by summing the raw scores [7]. The results of the questionnaire were grouped into five categories so that higher scores in a particular category indicate a subjective feeling of not being good at that aspect. The categories, mean scores and standard deviations were as follows: ability to form a cognitive map (mean, 14.95; SD, 7.57), ability to use landmarks (mean, 3.36; SD, 2.63), ability to solve problems by oneself (mean, 3.00; SD, 1.41), sense of direction (mean, 0.95; SD, 1.09), and application strategy (mean, 9.05; SD, 3.20). A one-way analysis of variance (ANOVA) taking these categories as within-subject factors found the categories to be significant main effects ($F(4, 84) = 51.371$, $p < 0.001$). Ryan's multiple comparison test suggested that the ability to form a cognitive map was the most significant category, and that of the other four categories, application strategy was the most significant.

3.2. VR Space Way Finding Test

Turning to the results of the VR test, we analyzed the search time with respect to the number of trials. Mean search time versus the number of trials for Map A and Map B is shown in **Figure 4** for the case when an overall view was possible and in **Figure 5** for the case when it was not possible. The symbols ○ and × in each graph indicate trials with four or eight pillars, respectively. The results of four-way ANOVA are shown below, taking the map type (A or B) and the possibility of an overall view (yes or no) as inter-group factors, and the number of pillars (four or eight) and number of trials as intra-group factors.

Significant main effects were found for possibility of an overall view ($F(1, 40)=7.29$, $p < 0.05$), number of pillars ($F(1, 40) = 88.64$, $p < 0.001$), and number of trials ($F(23, 820) = 14.86$, $p < 0.001$). In contrast, no significant main effect was found for map type ($F(1, 40) = 0.189$, not significant). Also, a significant interaction was found between number of pillars and possibility of an overall view ($F(1,40) = 23.258$, $p < 0.001$). A simple main effect test found that when there were eight pillars, the search time was longer when an overall view was not possible than when it was possible ($F(1, 80) = 22.496$, $p < 0.001$).

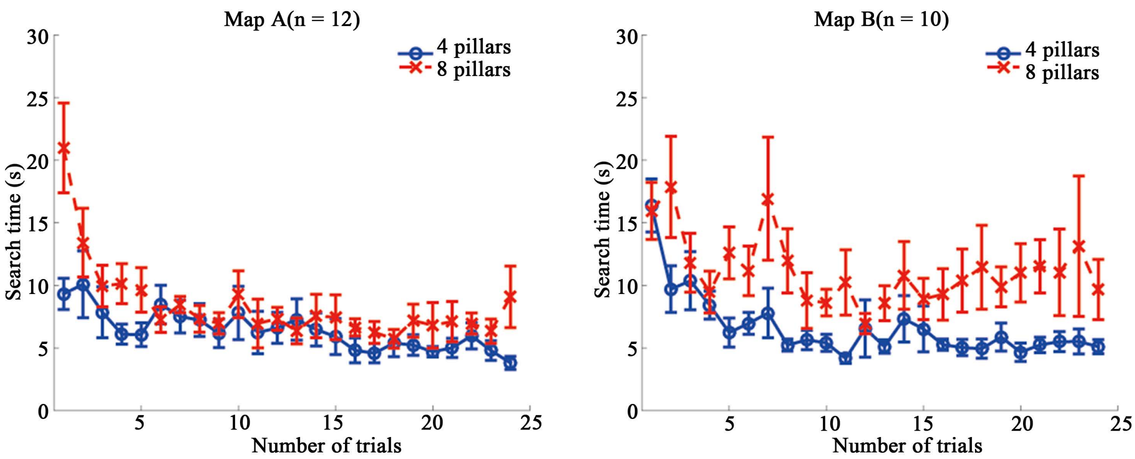

Figure 4. Search time trends for Map A (left) and Map B (right) when an overall view was possible.

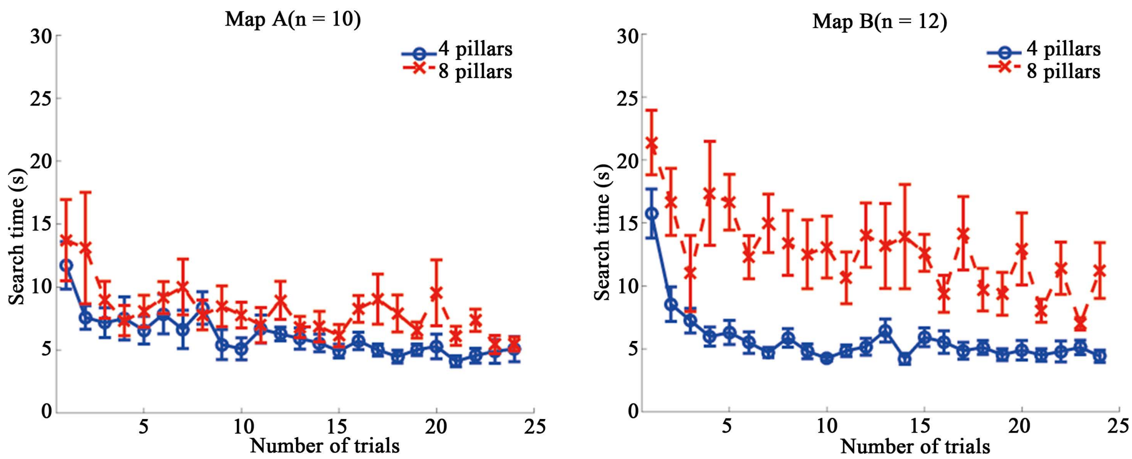

Figure 5. Search time trends for Map A (left) and Map B (right) when an overall view was not possible.

These results are reasonable in that they indicate an effect of task complexity on search time and the presence of a learning effect.

4. Discussion

Pretest results suggest that the participants in this study had typical development for their age. Moreover, for the navigation task within the VR space, the results indicate that the degree of difficulty due to the number of pillars and the possibility of an overall view affected the search time and that learning effect was evident. In contrast, the map type did not affect performance.

Next, we discuss the influence of developmental stage on search ability by comparing the present results to our results from a previous experiment with healthy university students under the same test conditions [1]. **Figure 6** and **Figure 7** show the search time trends for the search task performed by university students using same maps as in this experiment, and under conditions where an overall view was either possible or not possible [1].

Table 1 shows a summary of the comparison between the results of this study and our previous results. Note that the inequalities in the table refer to the duration of the search time.

The comparison between the two studies indicates that consistent results were obtained for the main effects. On the other hand, comparing the sub-effect tests reveals differences between the two experiments with respect to the following points: (1) When there were 4 pillars, the search time for the elementary school students was affected by whether an overall view was possible, while for the university students there was no difference, and (2) When there were 8 pillars and an overall view was not possible, the search time was different for each map among university students but not among elementary school.

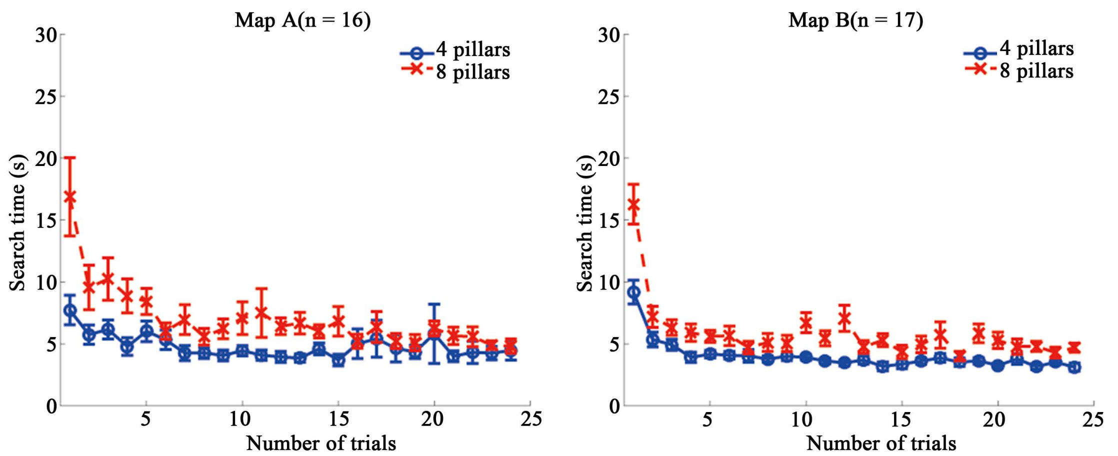

Figure 6. Search time trends for Map A (left) and Map B (right) when an overall view was possible, with university students as participants (reproduced with permission from Watanabe *et al*., 2015).

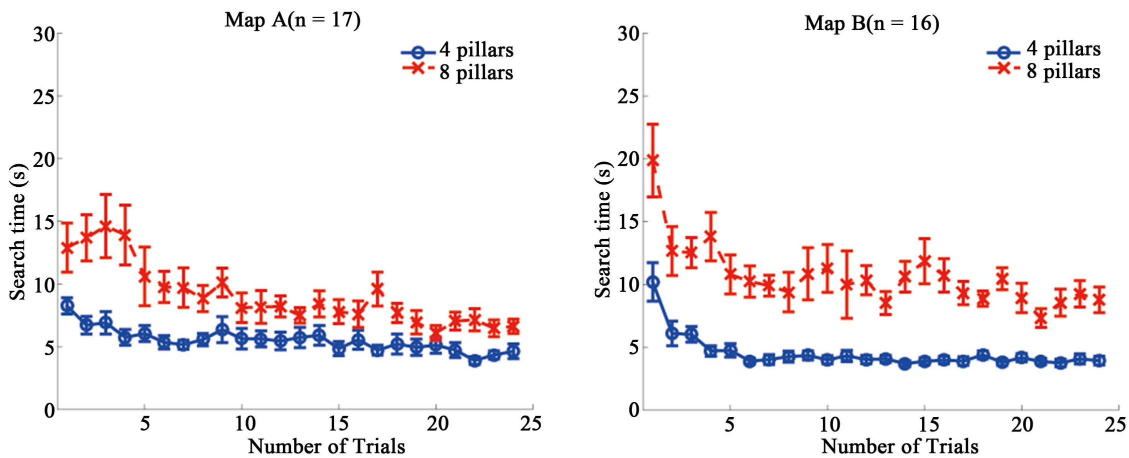

Figure 7. Search time trends for Map A (left) and Map B (right) when an overall view was not possible, with university students as participants (reproduced with permission from Watanabe *et al*., 2015).

Table 1. Comparison between tests with elementary school students and university students*.

	This study	Watanabe *et al*., (2015)
Subjects	Elementary school students	University students
N	22	33
Main effects		
Map	n.s.	n.s.
Possibility of overall view	No > Yes	No > Yes
Number of pillars	8 > 4	8 > 4
Number of trials	$P < 0.001$	$P < 0.001$
Sub-effect test		
4 pillars	Overall view not possible > possible	n.s.
8 pillars	Overall view not possible > possible	Overall view not possible > possible
8 pillars, overall view not possible	n.s.	Map B > Map A

*All results shown in the table were statistically (ANOVA) significant ($p < 0.05$) except described as "n.s. (non-significant)".

It is interesting that whereas the elementary school students consistently took longer to search when an overall view was not possible, the university students were affected by only whether an overall view was possible when there were 8 pillars. Another result worth noting is that the map conditions (the arrangement of the pillars) had different effects on search times for university student participants only when there were eight pillars and an overall view was not possible.

These differences in the results may suggest an influence of developmental stage on the process of forming a cognitive map, or on the way that cognitive maps are used. A cognitive map is formed by recalling the positions of pillars arranged within a space, and it has been pointed out that cognitive maps can be classified into two types: route maps and survey maps [8] [9]. The former is a sequential cognitive map from the perspective of the person moving through the space, while the latter involves grasping positional relationships with a perspective that looks down on the space, by positioning oneself outside of it [10].

In most cases, both the university students and the elementary school students who participated in our studies reported in the posttest interview that they felt Map B with eight pillars was more difficult than Map A with eight pillars. This was likely due to the lack of visual distinctiveness resulting from the symmetry of the pillar arrangement in Map B. In this sort of situation with little information, the ability to carry out a task while switching appropriately between a route map and survey map may be something that is acquired developmentally. This is likely how adaption to way finding occurs in actual scenarios.

5. Conclusion

We created an environment for measuring trajectories and response times as participants explored a VR space. We assigned a navigation task to healthy elementary school students and compared the learning process to that in an earlier study targeting healthy university students. In the future, we hope to link these results to assessments of cognitive map formation and the ability to use cognitive maps, by studying the relationships between navigation responses and various subtests [11]. Our final goal is to extend to evaluation and rehabilitation of children with developmental disorders and results shown in this paper may be referred as control data.

Acknowledgements

This study was supported by research grants from the Hayao Nakayama Foundation for Science and Technology and Culture (a public utility foundation), as well as JSPS KAKENHI Grant Number 15K04105. We thank Miyabi Arai of the Psychology Department at Doshisha University for assistance in the experiment and data analysis.

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