Measurement Methods of Spatial Ability using a Virtual Reality System

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***Abstract*—Some people cannot effectively utilize pedestrian navigation systems due to their limited spatial ability. To provide guidance in consideration of an individual's spatial ability, measuring spatial ability is necessary. In this paper, we propose measurement methods for spatial ability using a virtual reality system. We studied spatial ability in terms of movement towards a destination. Then, we considered methods to measure the ability. To carry out experiments for validation of these methods' effectiveness, we developed a virtual reality system that provides virtual walking experiences using a pedestrian navigation system. Using this system, we carried out experiments measuring two abilities: recognizing the subject's location; and recognizing the direction with respect to the destination. Also, we got subjects to answer a questionnaire about the sense of direction with experiments with which our objective data was compared. As a result, the experiment for recognizing the subject's location made clear individual differences and gender differences. Also, from the result of experiment for recognizing direction towards the destination, subjects were divided into three groups: "Good at recognizing direction"; "Weak at recognizing direction"; and "Taking a long time to recognize direction". These results were substantially consistent with their self-assessment.**

I. Introduction

When we do not know the way to a destination, we can use pedestrian navigation systems such as those on mobile devices. However, some people cannot effectively utilize the pedestrian navigation system due to their limited spatial ability. For example, users not having the ability to read a map, cannot understand the guidance of a navigation system which uses a map. The purpose of this study is to provide guidance in consideration of a person's spatial ability. To provide this guidance, measuring the ability becomes necessary.

A person's spatial ability is a complex, consisting of various abilities. For example, whether an individual can recognize their own location on a map is one aspect of spatial ability. Using navigation systems based on maps, we can look at a marker which represents an estimated location. However, these systems make some errors about the estimated location. Thus, people must recognize their own location considering the errors. People who have good spatial recognition can identify their own location by matching their surrounding environment with that of the information on the map. However, people without good spatial recognition have difficulty in identifying their location. Therefore, even if we make use of navigation systems, measuring one's spatial ability is important.

In the psychology field, the spatial recognition for wayfinding has been studied widely [7], [6]. However, they do not measure quantitatively the spatial ability. Currently, we can get the quantitative data of users' activity from navigation systems. Nevertheless, the spatial ability has not yet been measured using this data.

In this paper, we propose spatial ability measurement methods of using a virtual reality system. Firstly, we studied abilities for moving toward the destination and methods for measuring these abilities. Second, to undertake experiments for measuring these abilities objectively and quantitatively at a low cost, we developed a virtual reality system. This system provides a virtual walking experiment using a pedestrian navigation system.

The main contribution is to propose the efficient methods of measuring person's spatial ability. We achieve the contribution by creating a VR system and make it possible to measure the abiliy of anyone in any place at any time conveniently. We confirm that individual differences found in the experiments are consistent with each subject's self-assessment using a questionnaire. The individual differences from our measurement method provide possibilities that might be applied to navigation systems.

II. Related Work

There are a lot of methods and systems for pedestrian navigation. For example, Navitime shows users a route toward their destination and their location on a map [1]. Navigation without using a map is possible through voice/audio prompts [2]. Navigation is also possible with the sense of touch [3] and so on [4], [5]. Each method and system has different advantages. However, it is difficult for users to select the most comfortable and optimum method for themselves. Also, using all these different methods effectively is extremely challenging for a specific individual user. Considering an individual's spatial ability, we provide guidance that is the most effective for users.

Spatial recognition for wayfinding has been studied widely in psychology. In this field, it was found that mental images were good predictors of wayfinding performance [6]. Also, strategies for wayfinding have been researched [7]. However, they do not objectively measure abilities to perform activities accurately and promptly.

Some tasks for measuring people's spatial ability in various environments have also been carried out [8]. For example, Shin Murakoshi et al asked subjects to point to a specific place [9]. By doing this, the angular difference between the correct direction and the answered direction is made evident. However, spatial tasks in psychology have not incorporated maps displaying one's location and the direction the person is facing direction. This information is necessary in order to measure the ability using a navigation system which has some errors about the location and estimated direction.

In this paper, we propose a measurement method for spatial ability using a virtual reality system. Using this system, we are able to measure the individual spatial ability objectively and efficiently. Experiments to measure spatial ability while using a map that displays the user's location and direction they are facing were also undertaken.

III. Studying Spatial Abilities and Measurement Method

Spatial ability is made up of various abilities. We need to study what specific abilities are required to move toward their destinations. We asked the experiment subjects what they were thinking and doing while moving toward their destination. As a result, most of the subjects said that they were doing the followings while walking:

- Recognizing their own location on the map
- Recognizing the direction to the destination
- Memorizing the guidance
- Recognizing the north, east, west and south

The abilities involved in moving toward their destination are related to whether the subjects are able to act promptly and accurately. Therefore, we proposed methods to measure these abilities and carried out experiments. In this paper, we will mention the experiments related to the first and second actions, i.e. recognizing their own location and recognizing the direction to the destination. To measuring these abilities, we obtained data about time to demonstrate the difference between the correct (objective) answer and subjects' (subjective) answer. We developed a virtual reality system that provides virtual walking experiences to carry out experiments and obtain the data.

IV. Virtual Reality System for Measuring Abilities

In this section, we will discuss a virtual reality system for measuring the previously mentioned abilities. In the following subsections, we will discuss the development of the virtual reality system and the advantages of using virtual reality.

A. Development of Virtual Reality System

We developed the system with Unity[1], a platform for creating 2D or 3D games. Oculus Rift DK2[2] , a HMD (Head Mount Display), was used for experiencing the virtual environment. The system design and set-up during the experiment are shown in Fig. 1 and Fig. 2. Researchers input the data about the range of errors and the environment in which they want to carry out experiments into the system. Then a 2D map from Open Street Map[3], and a 3D map is imported from the Unity Asset Store[4] is imported into the system. Subjects use a hand-held controller for operation. Examples of operations done using this system are listed below.

- Moving within the virtual environment
- Turning in the direction the subject is facing in the virtual environment
- Expanding and reducing the map
- Changing the display area of the map
- Answering for measurement experiments

A subject's visibility displayed inside the HMD altered to reflect the data inputted from the controller and the HMD in 2D or 3D maps. An example of the 3D virtual environment displayed within the HMD is shown in Fig. 3. The right side of these images is seen by the right eye and the left side of these images by left eye. When looking down, one is able to see the 2D map in the virtual environment. That scene is shown in Fig. 3(b). Some markers can be seen in the map that is shown in Fig. 4. The circular blue marker represents the subject's location. The rectangular blue marker represents the direction in the virtual environment that the user is facing. The researchers factor in a margin of errors for the markers. The translucent light blue marker represents the range of error in estimating the location. Integrating all the input data, the system outputs the experiment data. About the raw data and the analysis data, we will describe the raw data and the data analysis in section IV-B.

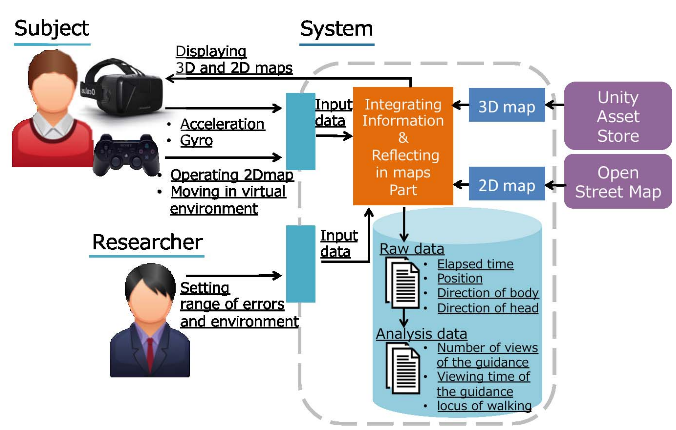


Fig. 1. Ability Measurement System Overview

[1]Unity. http://japan.unity3d.com/
[2]Oculus Rift. https://www.oculus.com/
[3]Open Street Map. http://www.openstreetmap.org/
[4]Asset Store -Unity. https://www.assetstore.unity3d.com/

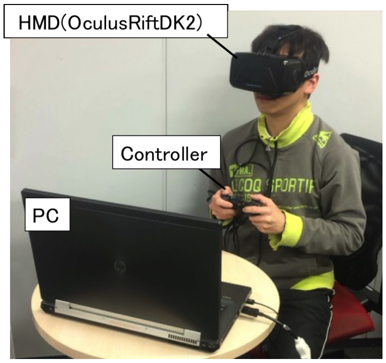
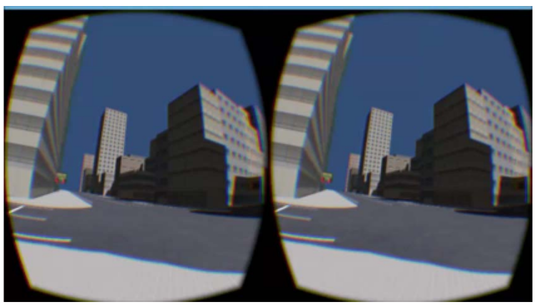
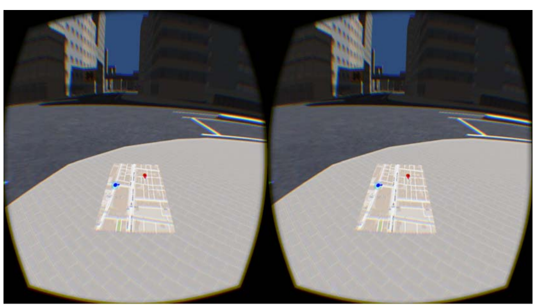


Fig. 2. Experiment Set-Up



(a) Facing Front



(b) Facing Down

Fig. 3. Subject's Visibility through the HMD

In this system, subjects are limited not to move while facing down and looking at a map in the virtual environment. In the real world, moving while looking at a map on a mobile device display is dangerous and not encouraging, because there are many vehicles and people. In the same way as the real situation, subjects are not encouraged to move while facing down in the virtual environment. We designed the system does not permit to move while facing down.

B. Advantages of Using the Virtual Reality

There are three advantages of using virtual reality. First, there is the cost factor carrying out experiments to measure spatial ability in VR environments is very cost effective. If we carry out experiments in the real world, then we have to move toward the actual location to conduct the experiment. If many experiments are required the costs can increase significantly. Besides monetary costs, people taking part in the experiment may spend a great deal of time and exhaust their energy by physically moving so much.

Fig. 4. Location and Directional Markers on the Map

The second advantage is that we, the researchers, can set the configuration freely. For example, we can set the following factors when we try to carry out the experiment in a particular environment:

- The guidance method used in the experiment
- The error value of estimating location and direction
- The environment in which the experiment is conducted

The third advantage is that this system records the experiment data of the subjects. The HMD has some sensors, for example, an acceleration sensor and a gyro sensor. Using the sensors within the HMD along with the subjects' input from their controllers, we can procure the raw data from the experiments. Specifically, we can get the elapsed time, head direction in the virtual environment, body direction in the virtual environment and their location in the virtual environment. An example of this data is shown in Table I.

TABLE I
EXAMPLE RAW DATA FROM THE SYSTEM

Elapsed time	Head Direction		
[s]	x[°]	y[°]	z[°]
28.07	347.80	129.76	357.41
28.10	347.82	131.53	357.37
28.12	347.86	129.42	357.31

Body Direction			Location		
x[°]	y[°]	z[°]	x[m]	y[m]	z[m]
0	110.00	0	9.41	0	1.09
0	110.00	0	9.42	0	1.10
0	120.00	0	9.44	0	1.13

By processing this data, we can get the following data analysis:

- The number of views from the guidance
- Guidance viewing time
- Where the subject looked while using the guidance
- Locus of subject's movement

V. EXPERIMENTS FOR MEASURING SPATIAL ABILITIES

In this section, we will discuss experiments about two methods for measuring the abilities studied in section III using a map displaying a subject's location and the direction they are facing.

A. Experiment Configuration

We set the common configurations to carry out both of the experiments we mentioned in the previous section. When the subjects wearing HMDs looked down, they could see the mobile device showing the map including markers of their location and the direction they were facing in the virtual environment. These location and directional markers had some errors. Table II shows the type of errors and the error range. For the location markers, the margin of error is within a radius of 25m. For the directional markers the margin of error is less than 30 degrees on both sides of the person with respect to the direction they are facing.

TABLE II
TYPE AND RANGE OF ERROR WE SET IN ALL EXPERIMENTS

Type of estimation error	Range of error
location	within a radius of 25m
direction	less than 30 degrees on both sides

We used 3D models of real cities and urban areas that were unfamiliar to subjects. An example of a 3D model of a real city is shown in Fig. 5. The 3D models used were of Akihabara, Sapporo and Tenjin. All places are located in Japan. The data are provided by ZENRIN[5] and anyone can download them for free at the Unity Asset Store.

Subjects were permitted to move in the virtual environment during the experiment before they provided their final answers regarding location and direction. We assumed that there might be some people who wanted to move around to get familiar with the surrounding environment.

These experiments were carried out in nine trials per subject. The place for each of the trials was different. Also, in order to reduce the subjects' experience, we tried not to carry out two experiments in the same city in succession.

We had to consider the differences among the people taking part in the experiments regarding their experience and familiarity with using a controller. Before we carried out the experiments, we asked the subjects to practice operating this system.

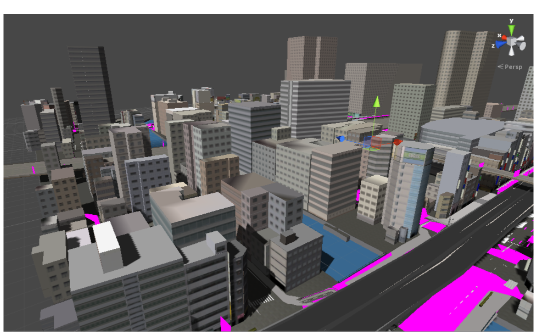


Fig. 5. Example of 3D models

[5]ZENRIN. http://www.zenrin.co.jp/

B. Recognizing Location

A person wearing a HMD can see the map displaying a marker that represents their location. However, the marker has a margin error that is within a radius of 25m. In this experiment, we measure whether the subjects can recognize their own location in the map accurately and promptly while factoring in the error. Subjects identified their own location. They can see the cursor that is used on the map. This cursor can be moved by the controller. They move the cursor to where they believe they are in the map. Then, they press the answer button on the controller. Before we carried out experiment, we asked the subjects to answer as soon as possible. The subjects consisted of nineteen males and fifteen females, all in their twenties.

In this experiment, we considered the following values for measuring abilities for recognizing a person's location:

- time to answer
- the distance between the answered location and the true location

The description of the distance between the answered location and the true location are shown in Fig. 6. The black point represents the subject's answered location and the human represents the subject's true location. The red line represents the distance between the answered location and the true location.

Fig. 6. Description of the Distance Between the Answered Location and the True Location

C. Recognizing the Direction to the Destination

Subjects can see the map displaying their directional marker. The directional marker has a margin of error of less than 30 degrees on both sides of their actual direction. In this experiment, we measure whether the direction can be identified to the specified point accurately and promptly considering the margin error. Subjects' answers about the direction to the specified point were as follows. The point is shown in the map and can be seen on the mobile device in the virtual environment. Subjects press the answer button on the controller while facing the point that they suppose it is correct. Before beginning the experiment, we asked the people taking part to answer as soon as possible. Eighteen males and seventeen females – all in their twenties made of the subjects.

In this experiment, we considered the following values when measuring abilities for recognizing the direction to a specified point:

- time to answer
- the angular difference between the answered direction and the true direction

The description of the angular difference between the answered direction and the true direction is shown in Fig. 7. The human figure represents the subject's true location and red marker represents the destination. The red line represents the angular difference between the answered direction and the true direction.

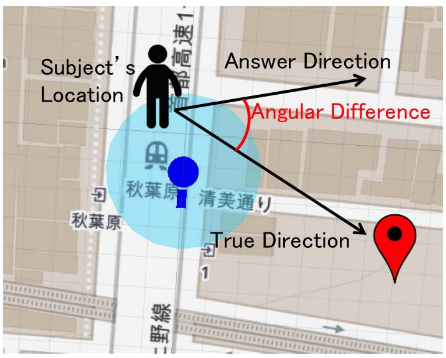


Fig. 7. Description of the Angular Difference Between the Answered Direction and the True Direction

VI. Results and Discussion

In this section, we will discuss the results and considerations of the experiments explained in previous section. As we mentioned previously, these experiments were carried out in nine trials for each subject. Therefore, We calculated the average from the value in order to measure the abilities of these experiments.

A. Recognizing the Subject's Location

We calculated the average of the time to answer and the distance between the answered location and the true location. The scatter plot of the averages is shown in Fig. 8. Blue dots represent the male result and red dots represent female result. Regarding the time to answer, the range of the male result was from 27.4 to 117.1 seconds while the range of the female result was from 48.3 to 136.7 seconds. Regarding the distance between the answered location and the true location, the range of the male result was from 5.8 to 13.3 meters while the range of the female result was from 8.8 to 34.7 meters. Through this experiment, we found that there were individual differences among subjects, especially in the distance between the answered location and the true location. Furthermore the individual differences among the females tended to be greater than those among males. Our system and results based on methods clarify the spatial ability based on gender difference. In the field of psychology, the gender differences in spatial ability have been known [10]. Therefore, the results from our system and methods validate the psychological findings.

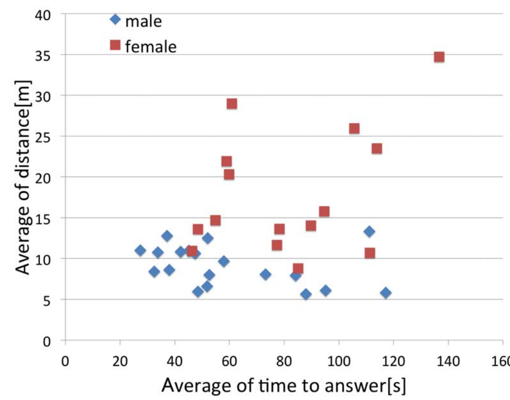


Fig. 8. Result of Recognizing the Subject's Location

B. Recognizing the Direction to the Destination

We calculated the average of the time to answer and the angular difference between the answered direction and the true direction. The scatter plot of the averages is shown in Fig. 9. Regarding the time to answer, the range of all the people was from 11.5 to 115.9 seconds. Regarding the angular difference between the answered direction and the true direction, the range for everyone was from 8.4 to 79.2 degrees. Through this experiment, we could divide the subjects into three groups. Group A represents those that are good at recognizing direction. Group B illustrates those that are weak at recognizing direction. Group C is a cluster of subjects that take long time to recognize the direction. As can be seen from Fig. 9, most of the people who took part in the experiment were able to answer the correct direction promptly. However, some in Group B could not answer the correct direction and some in Group C did not answer promptly. Our system and method can classify the people into three groups based on differences in recognizing the direction to the destination.

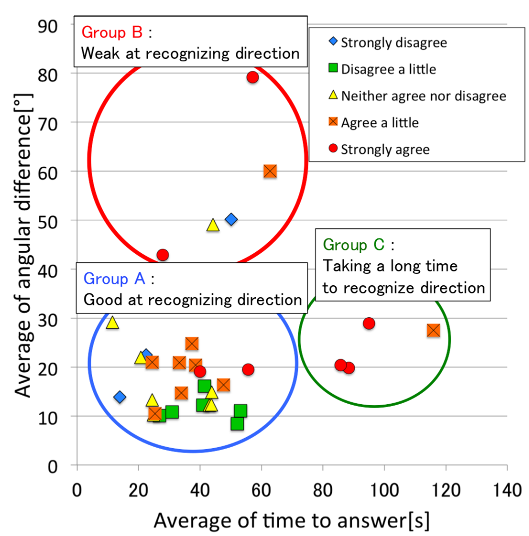


Fig. 9. Result of Recognizing Destination Direction

The scatter plot of nine trials for the subjects of each group is shown in Fig. 10. The results for those belonging to Group A are distributed in a concentrated way close to the vicinity of the origin. The results for people in Group B are distributed in an extended way in the direction of the vertical axis. The results for members of Group C are distributed in an extended way in the direction of the horizontal axis. The reason of these distributions is that subjects who belong to Group B or C can sometimes also give good results. On the other hand, subjects in Group B sometimes answer the wrong direction and those who belong to Group C sometimes take a long time to answer. These results clarify that people do not always go in the wrong direction even if they are not good at recognizing the direction.

After these experiments, we asked subjects to answer the questionnaire about their sense of direction. Specifically, we required subjects to answer the following question: "I cannot determine the road where I should proceed in the intersection" with the following 5 options.

- Strongly disagree
- Disagree a little
- Neither agree or disagree
- Agree a little
- Strongly agree

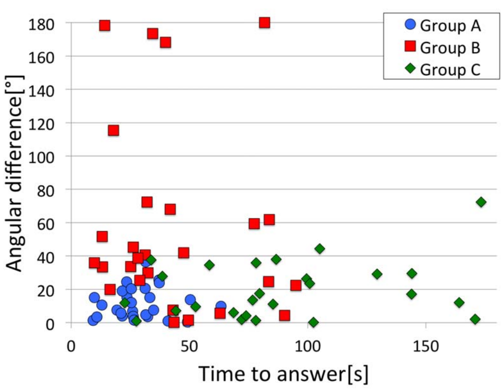


Fig. 10. Result of Subjects in Each Group

The results of the subjects who have bad self-assessment tend to be bad, and results for those with good self- assessment tend to be good (see Fig.9). Most people who answered, "Strongly disagree" or "Disagree a little" belong to Group A. Also, people in Group B or C answered, "Strongly agree" or "Agree a little". While attention is paid to Group A, dots representing subjects who disagree with the questionnaire tend to gather in the vicinity of the origin and dots of those who agree with the questionnaire tend to be away from the origin. However, despite he fact that certain individuals in Group B answered the questionnaire with "Strongly disagree", some of their results were not good. Also, although some in Group A answered "Strongly agree", "Agree a little" and "Neither agree or disagree", their results were not bad. These results demonstrate that there is a difference between the subjects' self-assessment and their real abilities.

To design the measurement methods for the abilities, we obtained and analyzed the data from the experiments. As a result, our analysis evinces the individual differences about abilities. Furthermore these results were substantially consistent with the subjects' self-assessment.

VII. Conclusion and Future Work

In this paper, we proposed spatial ability measurement methods using a virtual reality system. We developed a virtual reality system to carry out the experiments in order to measure two abilities: recognizing one's location; and recognizing the direction to the destination. To measure these abilities, we obtained the data about the time to answer and the differences between the correct answers and subjects' answers. Also, we asked people who took part in the experiment to complete a questionnaire about their sense of direction to compare with our objective data. As a result, differences between individuals and gender differences were made clear. Experiment subjects were divided into three groups: "Good at recognizing direction", "Weak at recognizing direction" and "Taking a long time to recognize direction". These results were substantially consistent with the subjects' self-assessment.

We measured the abilities for "Recognizing the one's own location" and "Recognizing the direction to the destination". To measure spatial ability in detail, we think that we should also measure abilities such as "Memorizing the guidance" and "Recognizing the north, east, west and south". We are going to add subjects to increase the accuracy of the results. Also, in this paper, we undertook nine trials per person. We should investigate the least number trials in order to deliver accurate results.

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