Evaluation of Virtual Tactile Dots on Touchscreens in Map Reading: Perception of Distance and Direction

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In order to assist blind people in using a flat touchscreen, "virtual" tactile dots which feedback either of or both speech and vibration when touched have been proposed. In this paper, we investigated their effectiveness in map reading application. We conducted two experiments with eight blind participants in which participants perceived the distance and direction between two virtual tactile dots. Their results show that the perception of distance and direction by virtual tactile dots was accurate enough. However, the search time for these dots was significantly longer than that for real tactile dots. This search time issue made us conclude that the reading and vibrating tactile map is not practical.

Keywords: blind people, vibrotactile, touchscreen, tactile distance perception, tactile direction perception

1. INTRODUCTION

The development of online maps and the prevalence of mobile devices powered by a high-resolution screen and high-speed internet connections have made reading maps online with these devices part of daily life for many people. In fact, a survey showed that reading maps ranks third after calling and taking pictures in reasons for smartphone usage [1]. However, this obviously does not apply to totally blind people who cannot see the maps on the screen. Although there do exist several navigation apps for blind people (such as BlindSquare by MIPsoft, Ariadne GPS by Giovanni Ciaffoni, etc.) that can be used with a screen reader, their functions are limited to providing local, point information such as the address of the present location, searching for shops around the present or designated location, and navigating at intersections. These apps do not provide geographical information including the whole route. For blind people to obtain such area information, two-dimensional tactile maps are necessary.

For online map apps to display dynamic map information, static tactile maps made with conventional thermoform, capsule paper, and embossed paper are insufficient and refreshable tactile displays are necessary. The development of refreshable tactile displays dates back to the mid of 1990s when the mainstream operating system of personal computers adopted a graphical user interface (GUI) [2]. At present, tactile display products are on the market in Japan (DV-1 and 2 by KGS Corporation). Moreover, a touch-sensitive tactile display [3] and an online tactile map system using a tactile display have been developed [4]. However, refreshable tactile displays are generally too big and heavy to carry around and too expensive to purchase personally. As a result, few people use tactile graphics display products [5]. Mainstream touchscreen devices are more practical to use than devices specially developed for people with disabilities, since mainstream devices are reasonably priced and small enough to carry around. In this case, their speech output and vibrating functions are to be utilized as the substitute of tactile information.

Many researchers have proposed using vibrotactile and speech feedback as a means of assisting blind people in using a flat touchscreen [6]. The basic function of vibrotactile feedback is to vibrate when the predesignated areas are touched on the screen. What is on that place is announced by the voice simultaneously. In this paper, we call these areas "virtual tactile dots." The feedback of tactile and auditory senses is intended to assist blind users in selecting menu items [7], pressing the numeric keypad [8], and pressing six keys mimicking the six Braille dots [9]. To increase the kinds of information conveyed, the strength and pattern of vibration were varied [10] and multiple vibration motors were used [11]. As for the assistance for using online maps, a tactile map app, DocumentTalkerTouchMap, has already been developed for Android OS, which gives feedback of speech and vibration when buildings, shops, major roads, railways, and rivers are touched on the screen [12]. The effectiveness of this vibrating and reading map can be evaluated with the accuracy and efficiency of distance and direction perception by the vibration and audio on the flat touchscreen.

Tactile perception of distance or length has been explored in the field of education for the blind [13] and man-machine-interface. Duran and Tufenkjian had congenitally blind children compare two different-length cylinders and observed four kinds of tactile kinesthetic methods for measuring length: (1) body part as a measuring instrument, (2) kinesthesis, (3) time duration, and (4) physical principles [14]. Thereafter, the accuracy of length perception by each method above was investigated. Perception of the length of voluntary

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movements was investigated by using metal rods [15]. For accurate measurement, special apparatuses were developed to explore the characteristics of length perception by sliding fingers across the object [16] and by multiple-finger grasping [17]. Abovementioned experiments allowed the subjects to actively touch objects. In passive touch experiments, on the other hand, two rods' tips [18] or multiple vibrating pins [19] were placed on the subject's body, and the subject judged the distance between the two stimuli. As is seen, the stimuli used in these studies are real, tangible objects. No study has been found in which virtual tactile dots were used as stimuli.

Tactile perception of direction has been explored for developing a haptic interface in the field of tele-operating of robots or virtual reality. In such research, a small pad or a tactile dot was placed under the finger pad and the subjects judged the direction of its movements [20-22]. Similar to the distance perception experiments, the direction of vibrating stimuli was judged in a series of passive touch experiments [23]. However, no study has investigated direction perception of virtual tactile dots.

Against this background, we decided to explore if vibrotactile and audio feedback can give the accurate perception of distance and direction that is required in map reading. Their accuracy and time performance was compared with those for "real" tactile dots made on capsule paper. On the basis of these experimental results, we discuss the effectiveness of the vibrating and reading map app in assisting blind users.

2. EXPERIMENT 1: DISTANCE PERCEPTION

2.1. Objective

The objective of Experiment 1 is to determine if the virtual tactile dots provide blind participants accurate distance perception.

2.2. Experimental Design

Two kinds of "virtual" tactile dots (voice only and voice and vibration) were compared with "real" tactile dots that can actually be touched by fingers in terms of the participants' accuracy of and reaction time for distance perception. The reason for preparing the voice only condition as one virtual "tactile" dot condition was a practical one: the user cannot understand what he/she has touched without speech, and some tablet devices do not provide vibration.

The virtual tactile dots were implemented by software originally developed for the experiments. They were two circles vertically arranged in the center on a touchscreen. When the user touches a dot, a synthesized voice alone or a combination of voice and vibration is outputted. The diameter of the virtual dots was 9 mm (158 pixels). First, the diameter of virtual dots was set to 3 mm, equivalent to the real tactile dots' size. However, a few trials showed that this size was so small that they were often not touched. Thus, we chose 9 mm on the basis of work by Ishibashi et al. that showed that the tactile dot symbols with a diameter of 9 mm were detected faster than smaller dots in tactile maps [24]. A guide to tactile graphics states that circles up to 8 mm in diameter are considered to be point symbols rather than area symbols [25]. To distinguish the two dots, each dot is identified as either "Station" or "Goal" by the voice. The dots are designated as goal or station at random. If the user keeps on touching a dot, a voice or a combination of voice and vibration is also outputted continuously. Even if the user touches another dot while he/she is touching the other dot, the preceding voice continues.

The touch interface device used in the experiments was a Google Nexus 5 tablet with the Android 5.0.1 OS. This device was chosen because it can produce vibration (Nexus 7 cannot). Its touchscreen is 110 by 62 mm (1920 by 1080 pixels). The vibration of the tablet was measured using a digital vibration meter (Model 1332B, Showa Sokki) while it was held by a small vice at both sides to imitate handholding. The sensor of the meter was fixed at the center of the touch screen with double-sided adhesive tape. The frequency of vibration was 156 Hz and peak acceleration 0.42 m/s^2.

The real tactile dots are two tactile circles arranged in the same way as the virtual tactile dots on a sheet of capsule paper that is the same size as the touchscreen of Nexus 5, 110 by 62 mm. The diameter of the real dots is 3 mm. This was the size shown in the same guidebook as a small point symbol [25]. Capsule paper is one technique for creating tactile graphics. It is coated with microcapsules that swell when heated. It is the most popular tactile map production method [26]. Also, precise tactile images can be produced on it by using drawing software. These are the reasons we used microcapsule paper. The original stimulus images were produced on a Windows computer with CAD software (Canvas, ACD Systems) and printed onto swell paper (ZY-TEX2, Zychem) by using a laser printer (Satera MF4380d, Canon). Then, the paper was heated with a heater (PIAF, Quantum Technology) to raise the dots to about 0.5 mm high [27].

In all conditions, the two dots were spaced four different distances apart (20 mm, 40 mm, 60 mm, and 80 mm). The longest distance was determined by the long side of the Nexus 5's touchscreen (110 mm). Because swiping down from the top or up from the bottom of the screen activates notifications, these areas were excluded. Within this range, the number of stimuli which was thought not to be easily anticipated by the participant was chosen.

Fig. 1 shows examples of the virtual tactile dots on the touchscreen and real tactile dots on capsule paper both used in the experiment.

2.3. Participants

Eight totally blind people participated in the two experiments. Their ages ranged from 21 to 45 years, six in their twenties, one in his thirties, and one in his forties.

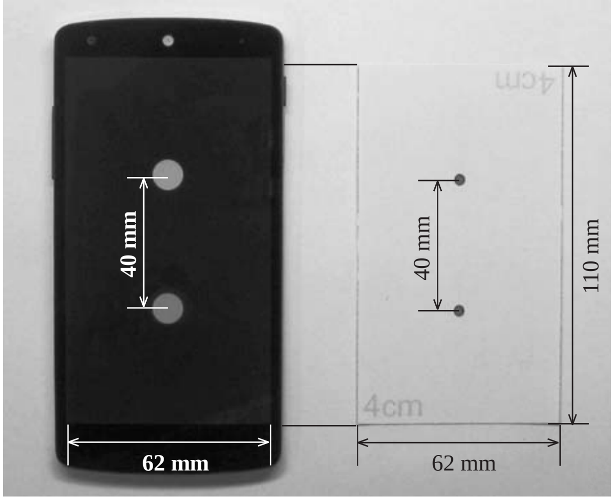

Fig. 1 Virtual (left) and real (right) tactile dots for distance perception. In both stimuli, the two dots are 40 mm apart.

Six were males and two were females. Seven had started using Braille when they were six and the other when he was 15. Seven had been using touchscreen devices, mostly iPhones, for nine month to three years and two months and the other had never used one. They were paid for their participation.

2.4. Procedure

The experiment was conducted in a quiet room. The participant sat at a desk, and the stimuli were presented on the desk.

There were six permutations of the three conditions. Thus, the first six participants were allocated to these six arrangements to avoid order effects. The arrangements of the seventh and eighth participants were the same as the first and second, respectively.

The participant joined three sessions for each condition. In each session the participant first practiced the procedure about five times using the same stimuli as used in the experiment. Hand movements while measuring the distance were not instructed by the experimenter and left for the participants to choose. After the practice, the participant performed the actual experimental procedure in five trials with each of the four types of stimuli (20 mm, 40 mm, 60 mm, 80 mm (Fig. 1)), for a total of 20 trials. The stimuli were presented in random orders. In each trial, the participant was asked to judge the distance between the dots in units of centimeters and respond orally. The time from the start to completion of perceiving was measured with a stopwatch and recorded as the reaction time. The real tactile dot stimuli were handed to the participant by the experimenter one sheet at a time. For the virtual tactile dot stimuli, the Nexus 5 tablet was handed to the participant and he/she was instructed to press the volume control button to begin the task and then to press it again after answering the question to move on to the next trial. The participant was given a break after each of the 20 trials.

During the experiment, the actions of each reader's hands were videoed. The video was used later to confirm and rectify the record written during the experiment and analyze the participants' hand movements.

Table. 1 Tactile kinesthetic methods used in distance perception. The eight participants are named A to H in the order of participation. The three sessions of participant A and the voice and vibration condition session of D were not videoed. F, SP, and SL denote Finger, Span, and Sliding method, respectively.

Participant	B	C	D	E	F	G	H
Voice Only	F	SL	F	SL	SL, SP	SP	SL
Voice & Vibration	F	SL	-	SL	SL, SP	SP	SL
Real Dots	F	SP	F	SP	SP	SP	SP

2.5. Results

The accuracy of distance perception was analyzed for all eight participants. However, the hand movements and reaction times were analyzed for seven participants because all the sessions for the first participant and the voice and vibration condition session for the fourth participant were not recorded by mistake.

For the perceived distance and reaction time, the mean of five trials of the same condition and presented distance was treated as the individual data in each condition.

2.5.1. Tactile Kinesthetic Methods

Seven participants' tactile kinesthetic methods used in distance perception are broadly classified into three types. The first was the "Finger method," in which the width of the finger was used as a scale. The distance was estimated from how many fingers could be placed between the two dots. The second was the "Span method," in which the angle between the thumb and the index or middle finger was used as a scale. The distance was estimated from how large this angle was. The third was the "Sliding method," in which a finger slid on the stimuli between two dots. The distance was estimated from the time period during sliding. These methods correspond to three of those observed by Duran and Tufenkjian in congenitally blind children: body part as a measuring instrument, kinesthesis, and time duration, respectively [14].

The methods used by individual participants are shown in Table 1. Four out of five participants who used the Span method for real tactile dots changed to the Slide method for virtual tactile dots. The reason for this change is thought to be that the two virtual dots cannot be touched simultaneously (even if they are, only the preceding voice is outputted) and this restriction hindered them from using the Span method in which two fingers touch the objects at the same time. Meanwhile, two participants who used the Finger method did not change methods between the real and virtual conditions. The reason for this is thought to be that the Finger method does not necessarily require simultaneous touch of two or more fingers.

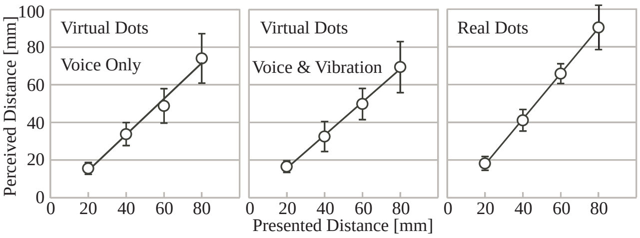

Fig. 2 Relationship between presented and perceived distance.

Table. 2 Coefficients of linear function fitting.

	Slope	Intercept [mm]	Coefficient of Determination
Voice Only	0.95	-4.6	0.988
Voice & Vibration	0.88	-6.5	0.998
Real Dots	1.21	-6.5	1.000

2.5.2. Accuracy of Distance Perception

The means of the distances reported by the eight participants are presented in Fig. 2. These graphs show that the perceived distance is directly proportional to the presented distance in all the tactile dot conditions. Linear functions are fitted to these data and their slopes, intercepts, and coefficients of determination are summarized in Table 2. Slopes for two virtual tactile dot conditions were approximately 1, and the absolutes of their intercepts are less than 10 mm. These results suggest that the distance can be perceived accurately in virtual tactile dot conditions.

In two virtual tactile dot conditions, perceived distances were slightly shorter than the presented distances. In contrast, in the real tactile dot condition, perceived distances were longer than the presented distances of 60 and 80 mm. A one-way analysis of variance of tactile dot conditions for each distance revealed significant differences for presented distances of 40 mm, 60 mm, and 80 mm (F [2, 14] = 4.90, 16.91, 19.29, $p < 0.01$). Tukey's multiple comparison test revealed a significant difference between the voice and vibration condition and real dot condition for 40 mm distance and between the two virtual dot conditions and real dot condition for 60 mm and 80 mm distances.

2.5.3. Reaction Time

The mean reaction times for seven participants are presented in Fig. 3. The reaction times in the real tactile dot condition were around 5 s whereas those in the virtual tactile dot conditions were fairly long, ranging from around 10 s to more than 20 s. These long reaction times stemmed from the search for intangible virtual tactile dots taking a long time. The difficulty in searching for virtual tactile dots was not related to the presented distance. Therefore, Fig. 3 does not show that the longer the presented distance, the longer the reaction time.

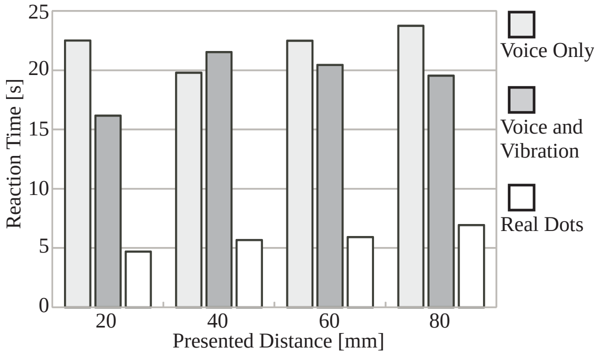

Fig. 3 Reaction time for distance perception.

The reaction times in the virtual tactile dot conditions varied greatly among the participants. The reaction times for five participants were short and mostly the same. When averaged individually for all the four distances, the reaction times for five participants in the voice-only condition ranged from 9.2 s to 19.4 s with a mean of 13.7 s and those in the voice and vibration condition ranged from 11.6 s to 18.7 s with a mean of 14.7 s. In contrast, the other two participants' reactions were two or more times longer: 35.4 s and 26.7 s in the voice-only condition and 51.4 s and 37.7 s in the voice and vibration condition. The reason for their long reaction times was that they frequently repeated the kinesthetic tactile movements before their decision. The kinesthetic tactile methods used by the five fast participants were the Sliding method (three people) and Finger method (two). The methods used by the two slow participants were the Sliding method and Span method. On the basis of these observations and data, it concluded that no specific method produced slow or fast reaction times.

As the distribution of reaction times is right-skewed, we adopted a nonparametric Friedman test instead of using an analysis of variance. The test was done for each presented distance and revealed significant differences in reaction time among conditions (S = 10.57, 6.00, 10.57, 11.14 for each presented distance. $p < 0.01$ for the presented distance of 20 mm, 60 mm, and 80 mm and $p < 0.1$ for 40 mm). Signed rank sum tests as multiple comparisons showed significant differences between the real tactile dot condition and two virtual tactile dot conditions, but no significant difference was seen between the two virtual tactile dot conditions.

There cannot be found any relatoinship between the participants' smartphone usage period and the reaction time in two virtual tactile dot conditions. Neither can a relatoinship between the participants' Braille usage period and the reaction time in the real tactile dot condition.

3. EXPERIMENT 2: DIRECTION PERCEPTION

3.1. Objectives

The objective of Experiment 2 is to determine if the virtual tactile dots provide blind participants accurate direction perception.

3.2. Experimental Design

Two kinds of virtual tactile dot conditions (voice only and voice and vibration) were compared with a real tactile dot condition in terms of the accuracy of and reaction time for direction perception.

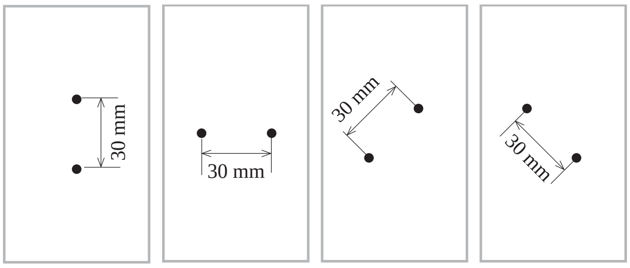

Fig. 4 Four kinds of direction perception stimuli: vertical, horizontal, upwards to the right, and downwards to the right. These are the real tactile dot stimuli made on capsule paper with a dot diameter of 3 mm. The virtual tactile dot size was 9 mm (see Fig. 1).

Three kinds of tactile dot stimulus were produced in the same way as Experiment 1 except the location of two dots. In all conditions, four different directions between the two dots were prepared (vertical, horizontal, upwards to the right, and downwards to the right). The distances between the two dots were all fixed to 30 mm. Four kinds of direction perception stimuli are shown in Fig. 4 schematically.

3.3. Subjects

The participants in Experiment 2 were the same as those in Experiment 1.

3.4. Procedure

Experiment 2 was conducted consecutively after Experiment 1 with a few minutes' break in between. The room, desk, and procedure were the same as Experiment 1 except the stimuli and the way of reporting. In each trial, the participant was asked to judge the direction and respond orally with one of four choices (vertical, horizontal, upwards to the right, and downwards to the right).

3.5. Results

3.5.1. Tactile Kinesthetic Methods

The Sliding method was used in direction perception by all the eight participants in all the three tactile dot conditions.

3.5.2. Accuracy of Direction Perception

In a session, one direction was presented five times. The accuracy rate for these five trials was treated as individual data. The means of the eight participants' accuracy rates are presented in Fig. 5. Across all the conditions and presented directions, the accuracy rates were high, ranging from 80 % to 100 %. The virtual tactile dot conditions had lower accuracy rates than the real tactile dot condition, and among two virtual tactile dot conditions, the voice only condition had lower accuracy rates than the voice and vibration condition. A Friedman test for each presented direction revealed no significant difference among the three conditions (*S* = 0.44, 0.81, 0.56, 0.81, for vertical, horizontal, upwards to the right, and downwards to the right directions, respectively). This is because six out of the eight participants produced 100 % accuracy rates in all or almost all the conditions and directions.

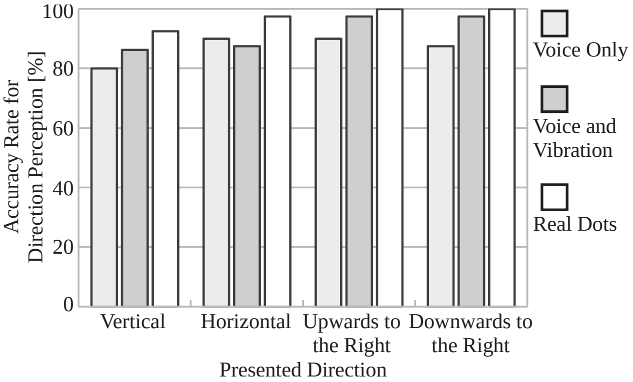

Fig. 5 Correct rate for direction perception.

Table. 3 Tendency of direction perception errors.

Rotation	45° CL	45° CN	90°
Voice Only	10	9	1
Voice & Vibration	2	9	1
Real Dots	3	1	0

Fig. 5 shows that the vertical direction produced more errors than other directions. However, a Friedman test for each tactile dot condition revealed no significant difference among the four directions (*S* = 0.64, 1.16, 1.01, for the voice only, voice and vibration and real dot conditions, respectively).

To explore the trend of errors, they are classified into three groups on the basis of the rotation angle of the perceived direction from the presented direction. For example, when the vertical direction is presented, the answer of upwards to the right means 45° clockwise (abbreviated as CL in Table 3). Similarly, the answer of downwards to the right means 45° counterclockwise (CN) and horizontal means 90°. Table 3 shows that 94 % of the errors were 45° either clockwise or counterclockwise. The tendency of the rotation did not coincide across the three conditions.

3.5.3 Reaction Time

The mean reaction times for seven participants are presented in Fig. 6. The reaction times in the real tactile dot condition were around 3 s whereas those in the virtual tactile dot conditions were fairly long, ranging from around 10 s to more than 30 s. These long reaction times stemmed from the search for intangible virtual tactile dots taking a long time as was observed in Experiment 1. Because the reaction times in the virtual tactile dot conditions varied greatly among the participants, a nonparametric Friedman test was performed for each presented direction. It revealed significant differences in reaction time among conditions (S = 12.00, 12.00, 12.25, 12.00 for each presented direction. $p < 0.01$ for all the directions). Signed rank sum tests as multiple comparison showed significant differences between the real tactile dot condition and two virtual tactile dot conditions but no significant differences between the two virtual tactile dot conditions.

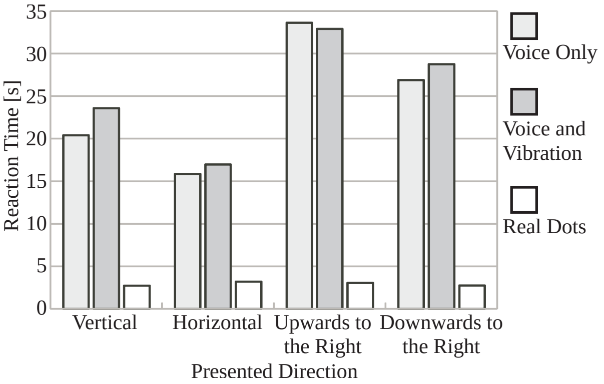

Fig. 6 Reaction time for direction perception.

There cannot be found any relatoinship between the participants' smartphone usage period and the reaction time in two virtual tactile dot conditions. Neither can a relatoinship between the participants' Braille usage period and the reaction time in the real tactile dot condition.

4. DISCUSSION

The results of Experiment 1 made clear that the presented distances between two virtual tactile dots were perceived accurately. It can be even said that the perception of distances was more accurate between two virtual tactile dots than real tactile dots. However, the perceived distances tended to be shorter than the presented distances. In the present study, the diameter of the virtual tactile dots was as big as 9 mm to decrease the number of missed targets. Therefore, the distance between the nearest edges of the virtual tactile dot was 9 mm shorter than the distance between the dot centers when the participant explored by touch in a straight line between the two dots. This can be considered as one reason for the shorter distance perception.

The results of Experiment 2 also revealed six out of eight participants produced accuracy rates as high as 90 %. These rates were as high as those for real tactile dots. Thus, we can conclude that the virtual tactile dots realized with voice only and voice and vibration can provide accurate perception of distance and direction between two tactile dots. Their accuracy is at the same level as real tactile dots.

However, we also found a problem: the search for intangible virtual tactile dots was difficult and took a long time. Seven out of the eight participants had been using touchscreen devices and searching icons and buttons on their devices in everyday life. Then why does searching for virtual tactile dots take so long? The arrangement of app icons on the home screen of these devices is regular and can be remembered easily. Even though buttons in various apps may not be arranged regularly, their arrangements can be remembered through everyday use. In the present experiments, in contrast, the arrangements of the dots were not told to the participants. As for map reading, people often read maps of unknown places. Thus, the situation is similar to the present experiments in that the user has to search for the objects without knowing their locations. Therefore, the same problem is thought to occur in reading the speech and vibrating map. If it takes more than 10 s or 20 s to find an object, the speech and vibrating map cannot be said to be useful.

Then how can we shorten this searching time? The problem of the current tablet deivices is that they can convey the "presense" of vibration but its "location." Multiple vibrating motors may inform the user of the location of vibration and facilitate the search [11]. Still, as long as the touchscreen is flat, the device does not allow the user to use the whole palm to find tactile dots. Thus, the search time will not be shortened enough. For fast search for tactile dots, dots must be really tangible. For map app use, the dots do not necessarily have to be as high as Braille dots (0.5 mm) because their role is just to let the user know where they are. An innovative, small, tactile display device that realize such dots must be developed.

5. CONCLUSION

Eight blind participants took part in two experiments in which virtual tactile dots are compared with real tactile dots. The perception of distance and direction by virtual tactile dots was accurate enough. However, the search time for these dots was significantly longer than that for real tactile dots. This search time issue made us conclude that the reading and vibrating tactile map is not practical.

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