# TOWARD PRACTICAL AUDIO-GUIDED TACTILE GRAPHICS: EVALUATION OF TACTILE EXPLORATION SPEED AND FINGERTIP DETECTION ERROR

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**Abstract:**

**Audio-assisted tactile graphics systems have been developed to support visually impaired people. However, previous studies evaluated finger recognition methods only in a static state. In this study, to put the system into practical use, we quantitatively evaluated the tactile exploration speed and finger tracking error in a dynamic state. The experiment revealed that the maximum tactile speed of a visually impaired expert reached approximately 330 mm/s, indicating the need for a frame rate higher than 30 fps or coordinate interpolation. Furthermore, the finger tracking error varied depending on the line width, direction, and shape. Based on the statistical analysis, we proposed flexible margin settings for the audio guidance area: ±5.5 mm for vertical lines, ±7.5 mm for horizontal and curved lines, and ±10.0 mm for corners. These findings contribute to realizing a more practical system.**

**Keywords:**

**Tactile graphics; Audio guidance; Tactile exploration speed; Fingertip detection error**

## 1. Introduction

People with visual impairments widely use tactile graphics, in which figures are physically represented by raised dots and lines, as a means of acquiring visual information such as shapes. Tactile exploration refers to the process by which a user explores a tactile graphic with their fingertips to understand its shape. However, there are limitations to acquiring information through touch. Whereas vision can process a wide range of information instantaneously, touch requires information obtained at the fingertips to be integrated sequentially, which demands considerable time and cognitive effort to grasp the overall structure. Furthermore, Braille used to convey textual information within tactile graphics requires a certain amount of space, thereby limiting the area available for drawing figures. In addition, according to a survey by the Ministry of Health, Labour and Welfare [1], the Braille literacy rate among people with visual impairments is said to be only about 10%; for those who have not learned Braille, tactile graphics with Braille annotations are difficult to understand. For these reasons, fine graphical details and textual information are often omitted.

Against this background, research and development have been advancing on audio-guided tactile graphic systems, which support understanding by adding audio information to the raised information of tactile graphics.

In this study, with the aim of putting such a system into practical use, experiments will be conducted with participants including people with visual impairments. Based on users' tactile exploration speed, the system's responsiveness will be evaluated, and the fingertip tracking error during line-tracing motions will also be quantitatively assessed.

The objective is thereby to derive system requirements and guidelines for defining audio guidance regions in order to realize more appropriate audio guidance in real-world usage environments.

## 2. Related Work

Several systems that add audio guidance have been researched and developed to address problems such as the limited amount of information that tactile graphics can convey. For example, Wang et al. [2] developed a system using a dedicated touch pad, while Zeinullin et al. [3] developed a system that combines alignment markers placed on tactile graphics with fingertip detection technology. However, these approaches require either dedicated devices or space for placing markers, and therefore have the drawback that existing tactile graphics cannot be used as they are.

In contrast, Hashimoto et al. [4] proposed a low-cost and highly portable system that uses a standard smartphone and a blue marker attached to the fingertip, allowing arbitrary existing tactile graphics to be used without modification.

In actual use of tactile graphics, users mainly perform exploratory movements in which they move their fingers quickly, and such dynamic motions can produce sources of error that do not appear when the finger is still. Therefore, for the practical implementation of the system, it is essential to evaluate its tracking capability and recognition accuracy under dynamic conditions in which the finger is moving, and to clarify its characteristics.

## 3. System Overview

The audio-guided tactile graphic system targeted in this study operates by photographing a tactile graphic in advance and preparing and loading a text file that describes the audio guidance regions and their corresponding contents. During use, the system detects the tactile graphic from the iPhone camera image through contour extraction and line approximation, and assigns audio guidance to the designated regions. It then obtains the coordinates of the fingertip by detecting the region of a blue marker attached to the fingertip. When the coordinates fall within an audio guidance region, the corresponding audio guide is output from the iPhone. The series of processes in this system is executed at 30 fps (approximately every 33 ms).

## 4. Tactile Exploration Speed Measurement Experiment

In previous studies, fingertip recognition methods were evaluated only under stationary conditions, and the system's ability to track dynamic tactile exploration movements has not yet been clarified. Therefore, in order to verify the adequacy of the current system's frame rate (30 fps), an experiment was conducted to measure users' tactile exploration speed.

### 4.1 Experimental Environment

An iPhone 14 was used as the device, and it was fixed with a stand 40 cm above the tactile graphic so that the camera surface was parallel to the tactile graphic during recording. The tactile graphic was printed on A4-size paper using a PIAF tactile image fuser. Based on Nielsen's study [5], the participants consisted of five sighted individuals and one visually impaired individual; the sighted participants wore blindfolds. As for the software, an improved version of the existing system was used, which allowed the recording of fingertip coordinates $(X, Y)$ obtained from the blue marker, along with timestamps and other data, in CSV format. The experimental setup is shown in Figure 1.

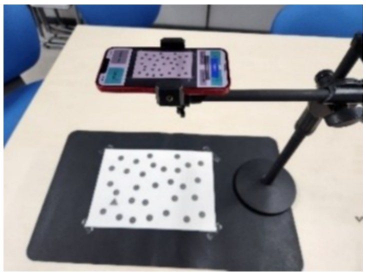


**FIGURE 1.** Experimental Environment

### 4.2 Tactile Exploration Task

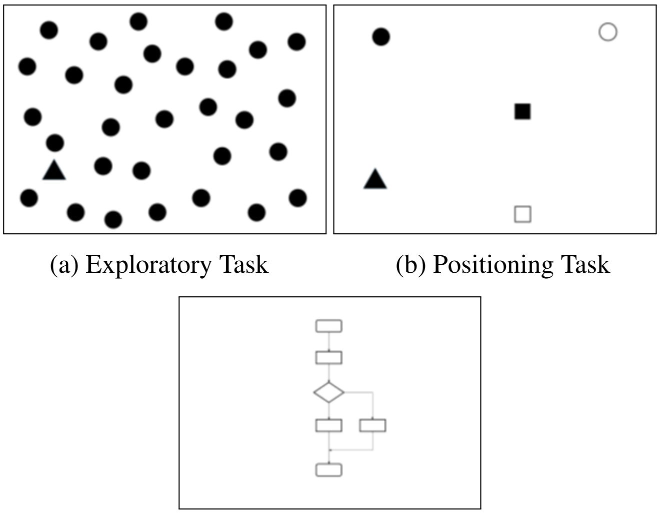
To cover a variety of tactile exploration movements, the following three types of tasks were designed. The tactile graphics used in the tasks are shown in Figures 2 (a)-(c).

1. Search task: A task in which the participant searches for a target figure (an equilateral triangle) among many background figures (circles), signals as soon as it is found, and the time until completion is measured.

2. Position recognition task: A task in which the participant memorizes the positional relationships of five basic figures within a time limit of one minute.

3. Figure memorization task: A task in which the participant memorizes, within a time limit of one minute, the flow and structure of a simple flowchart composed of rectangles, diamonds, and arrows.

Each participant completed a total of seven trials: three search tasks, two position recognition tasks, and two figure memorization tasks. The order in which the figures were presented was randomized. In addition, after the time limit had elapsed in the position recognition and figure memorization tasks, the participants were asked to draw the figures they had memorized on paper. Furthermore, interviews were conducted after the experiment to obtain subjective opinions. The size of each figure in each task was approximately 2.0 $cm^2$. This was determined as a sufficiently perceivable size with reference to the area of 0.4 $cm^2$ reported as easy for visually impaired people to distinguish [6].



(a) Exploratory Task (b) Positioning Task

(c) Pattern Memory Task

**FIGURE 2.** Sample Tactile Graphics

## 4.3 Results

For the collected data, values with an inter-frame movement speed of 0.01 px/ms or less were regarded as stationary and excluded. After that, the coordinates were transformed into real-space coordinates, and the tactile exploration speed was calculated.

Table 1 shows the basic descriptive statistics for each participant.

**TABLE 1.** Basic Statistics for Each Participant

| Pt. | Group | (A) | (B) | (C) | (D) |
|---|---|---|---|---|---|
| P1 | S | 50.12 | 56.76 | 30.86 | 167.80 |
| P3 | S | 72.33 | 80.57 | 45.31 | 243.41 |
| P4 | S | 67.43 | 80.04 | 42.34 | 231.79 |
| P5 | S | 50.70 | 53.15 | 32.76 | 158.15 |
| P6 | S | 58.73 | 66.50 | 34.79 | 199.58 |
| Total | S | 59.85 | 68.89 | 36.79 | – |
| P2 | B | 95.84 | 112.19 | 55.66 | 329.95 |

(A) Mean [mm/s]; (B) Standard deviation [mm/s]; (C) Median [mm/s]; (D) 99th paercentile value [mm/s]; S Sighted; B Blind

To examine differences in speed among the tasks for the sighted participants, a statistical analysis was conducted using the median values. A Friedman test was performed at a significance level of 5%, and a significant difference was found among the tasks ($p = 0.0067$). Subsequently, multiple comparisons were conducted at a significance level of 5% using the Wilcoxon signed-rank test with Bonferroni correction. Although the results did not reach the significance level because of the small sample size ($p = 0.0625$), the effect size, expressed as the rank-biserial correlation coefficient, was very large in all pairwise comparisons ($r = 1.0$). The median speeds for the tasks were 65.21 mm/s for the search task, 44.88 mm/s for the position recognition task, and 23.95 mm/s for the figure memorization task, showing a tendency for the search task to yield the highest speed.

On the other hand, for the visually impaired participant, because the data consisted of only one person, statistical tests between groups could not be applied. Therefore, comparison was made using Z-scores based on the distribution of representative values from the sighted group. In the search task and the figure memorization task, the Z-scores for the visually impaired participant were $+2.42$ and $+3.50$, respectively, exceeding the 95% interval for the sighted participants ($|Z| < 1.96$). By contrast, in the position recognition task, the Z-score was $+0.77$, which remained within the distribution range of the sighted participants. In addition, when the 95th percentile value for each participant (the effective maximum value) was calculated, the visually impaired participant showed the highest speed, reaching approximately 330 mm/s.

## 4.4 Discussion

The comparison of Z-scores showed that the visually impaired participant (an experienced user) performed tactile exploration more efficiently and at a higher speed than the inexperienced participants in the search task and the figure memorization task. On the other hand, the fact that the speed decreased only in the position recognition task and remained within the distribution of the sighted participants is thought to be because this task imposed a high spatial cognitive load, requiring the participant to accurately memorize the positional relationships among the figures, and therefore necessitated careful confirmatory movements to reinforce memory.

From the viewpoint of system requirements, the effective maximum speed obtained in the experiment, approximately 330 mm/s, was confirmed from the trajectory data to occur not only during the linear scanning movements used to grasp the overall layout in the early stage of tactile exploration, but also during back-and-forth confirmatory movements for understanding the positional relationships among figures in the latter half of the time-limited task, as shown in Figure 3. Therefore, the system is considered to need to track this speed.

At this speed (approximately 330 mm/s), when the current system operates at 30 fps (approximately 33 ms intervals), the finger moves about 11 mm between frames. This value approaches the figure size used in the experiment, approximately 14 mm, suggesting a high likelihood that the system may fail to detect the finger even when it passes over a figure, and consequently may not provide appropriate audio guidance. Therefore, to achieve comfortable audio guidance, it is necessary to consider implementations such as increasing the frame rate and interpolating coordinates.

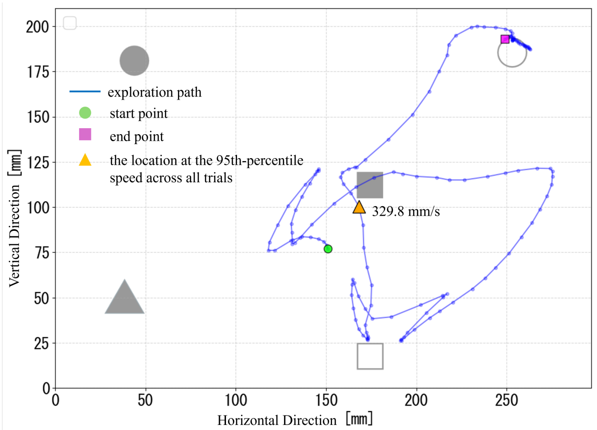



**FIGURE 3.** Tracectories around the P95 value (approx. 330 mm/s)

## 5. Evaluation of Fingertip Detectoin Error under Dynamic Conditions

To verify the accuracy of the system under real-world usage conditions, including the high-speed movements revealed in the tactile exploration speed measurement experiment as well as delay and jitter, the error between the fingertip coordinates during figure tracing and the ground truth (the center of the figure's contour line obtained by skeletonization) was measured.

### 5.1 Experimental Method

The participants consisted of a total of 6 people: five sighted individuals and one visually impaired individual. The task figures comprised six types: line segments (vertical and horizontal), basic figures (circle, equilateral triangle, and square), and an irregular simple closed curve, as shown in Figure 4. As for line width, 1 mm was adopted as the minimum width that could be stably raised using the tactile image fuser, and 3 mm was adopted as a thick line width that could be clearly distinguished. In addition, for each figure, a black dot indicating the starting point (and ending point) was placed, with a diameter of 5 mm under the 1 mm line-width condition and 7 mm under the 3 mm line-width condition.

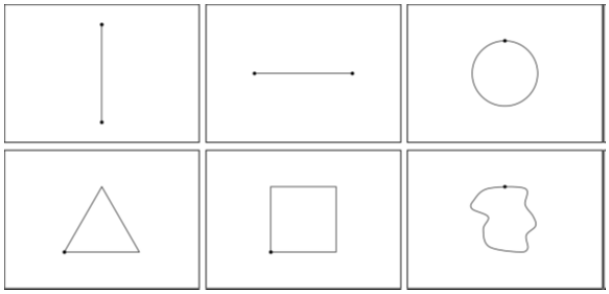


**FIGURE 4.** Six Kinds of Figures

In the experiment, participants were instructed to trace each figure from the starting point (black dot) to the ending point as accurately as possible without lifting their finger, and three consecutive trials were performed for each figure. Interviews were also conducted after the experiment to obtain subjective opinions. Fingertip coordinates were detected using the blue-marker method, which is highly stable. Moreover, to improve marker detection accuracy, a dedicated application was developed, and calibration was performed when attaching the marker to the fingertip so that the center of the screen and the detected point of the marker coincided within one pixel. The device, software, and other experimental conditions were the same as those used in the tactile exploration speed measurement experiment.

### 5.2 Results

The Euclidean distance between the collected trajectory data and the ground truth was calculated, and comparisons were made at a significance level of 5% using the Wilcoxon signed-rank test. As a result, for the horizontal line, the 1 mm width showed significantly smaller error than the 3 mm width ($p = 0.03$), and for other figures containing straight-line segments as well, the 3 mm width tended to show lower accuracy.

The visually impaired participant also tended to show smaller recorded errors for curved trajectories. In particular, for the 3 mm closed curve, which was especially difficult, the error was approximately 1.87 mm compared with the sighted participants' mean of approximately 2.92 mm. Similarly, for the 3 mm circle, the error was approximately 1.68 mm compared with the sighted participants' mean of approximately 2.72 mm.

Focusing on the shapes of the figures, the error for the vertical line was the smallest, remaining stable at an average of about 2.1-2.3 mm, whereas for the horizontal line and curved figures such as the circle and the closed curve, the trajectories fluctuated and the error increased. In particular, for figures containing horizontal line segments, multiple cases were observed in which the traced trajectory formed an arc-shaped path relative to the line segment, as shown in Figure 5 (a). Furthermore, near the vertices (corners) of polygons, overshooting occurred in which the trajectory deviated greatly from the figure's line, as shown in Figure 5 (b), and for figures containing corners, the 99th percentile of the error reached approximately 10 mm.

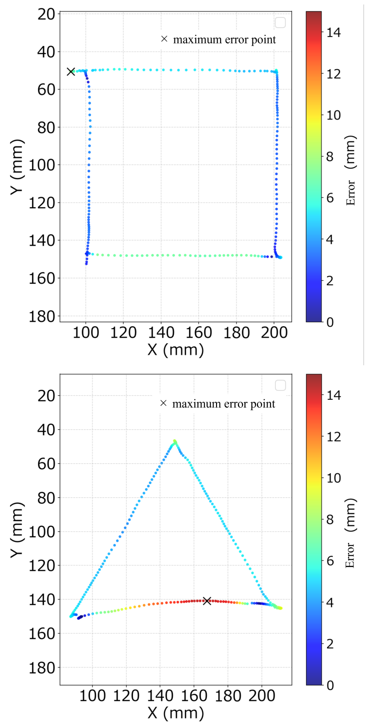



**FIGURE 5.** Fingertip Detection Error under Dynamic Conditions

Based on the error distributions for each figure, the figures were classified into three groups: stable (vertical line), unstable (horizontal line, circle, closed curve, and equilateral triangle), and corner-containing (square and equilateral triangle). For the trajectory data of the vertical line, which belonged to the stable group, recalculation was performed using only the middle 80% of the trajectory in order to exclude localized errors associated with repositioning the finger near the starting and ending points. Table 2 presents the mean, the 95th percentile value (P95) and its 95% confidence interval (CI), and the 99th percentile value after this exclusion procedure.

However, because of the uncertainty in estimation arising from the small sample size, the 95% confidence interval for P95 was calculated using the bootstrap method ($B = 10{,}000$).

**TABLE 2.** Statistical Measures by Shape Group

| Group | (A) | (B) | (C) | (D) | (E) |
|---|---|---|---|---|---|
| Stable | 2.01 | 4.80 | 4.44 | 5.49 | 8.63 |
| Unstable | 2.86 | 6.95 | 6.89 | 7.02 | 9.47 |
| Corner | 2.79 | 7.09 | 7.02 | 7. 18 | 10.04 |

(A) Mean Value; (B) P95; (C) Upper bound of the 95% confidence interval; (D) Lower bound of the 95% confidence interval; (E) P99

## 6. Discussion

### 6.1 Tactile Exploration Stategies and Anisotropy of Movement

The experimental results showed that, for sighted participants, thinner lines tended to yield higher accuracy in figures containing straight lines, whereas thicker lines tended to increase error. In contrast, for the visually impaired participant, accuracy was less likely to decline even under the thick-line condition, and particularly high accuracy was recorded for curved figures. This suggests that visually impaired users do not perceive the point of contact with a line merely as a single point, but rather as a surface with width, and that they employ an active exploration strategy in which this information is used as a cue for predicting the direction of movement and guiding exploration.

In addition, differences in accuracy depending on movement direction—that is, anisotropy—were observed in tracing movements. Errors in the vertical direction, where body control is easier, were the smallest and most stable. By contrast, in the horizontal direction and in curved figures, the trajectory tended to become unstable, presumably because moving the arm with the elbow as the center of motion naturally produces an arc-shaped path, making it relatively difficult to maintain a straight line. Furthermore, the tendency for overshoot to occur frequently at corners (vertices) of figures suggests that, under conditions without visual input, it is difficult to respond to sudden changes in movement direction, and fingertip control could not adjust quickly enough.

### 6.2 Guidelines for Setting Margins for Audio Guidance Regions

Based on the experimental results and discussion, we concluded that applying a uniform margin setting is inappropriate.

Therefore, as a conservative guideline, we propose the following margin settings based on values such as the upper bound of the 95% confidence interval of the 95th percentile for each shape category:

1. Stable regions (vertical segments): $\pm 5.5$ mm
2. Unstable regions (horizontal and curved segments): $\pm 7.5$ mm (to allow for trajectory fluctuation)
3. Corners (near vertices): $\pm 10.0$ mm (the maximum 99th percentile value, taking overshoot into account)

These settings are expected to enable the construction of a practical system that takes users' skill levels and movement characteristics into account while avoiding false detections and missed guidance.

## 7. Conclusions

In this study, in order to realize the practical implementation of an audio-guided tactile graphic system, tactile exploration characteristics under dynamic conditions were quantitatively evaluated. In the tactile exploration speed measurement experiment, it was shown that, in order to accommodate the maximum speed of approximately 330 mm/s observed in an experienced user, it is necessary either to secure a frame rate higher than the current 30 fps or to implement interpolation processing for fingertip coordinates. In the experiment evaluating fingertip detection error under dynamic conditions, it was shown that tracing accuracy varies depending on direction and shape, and that a uniform margin setting is therefore inappropriate. Accordingly, based on a statistical analysis of the error distributions, we proposed shape-dependent margin settings for different segment types: vertical segments ($\pm 5.5$ mm), horizontal segments ($\pm 7.5$ mm), and corners ($\pm 10.0$ mm). In future work, it will be necessary to increase the number of participants to improve statistical reliability, as well as to conduct verification using more complex figures and analyze tactile exploration movements using both hands, with the aim of building a more practical system.

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