A Nonlinear Mapping-Based Virtual Touchpad for One-Handed Smartphone Operation

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Abstract. Smartphones with 6-inch or larger screens have become popular. However, such large-screen smartphones are difficult to operate with one hand. Widely used techniques for assisting the user in one-handed operation, such as iPhone's Reachability and Android's one-handed mode, reduce the display areas of screens, which degrades the benefits of large-screen smartphones. In this paper, we propose a virtual touchpad for a large-screen smartphone that uses nonlinear mapping to enable the user to manipulate distant areas as well as to accurately manipulate close areas. We conducted a preliminary experiment to compare eight instances of the proposed virtual touchpad with different mappings and conditions in a target selection task. In addition, we performed experiments to compare the three best instances of the virtual touchpad with conventional normal touchscreen operation and also to evaluate it in web browsing. The results show that the proposed virtual touchpad could reduce the target selection time and largely reduce the strain on the thumb.

Keywords: Smartphone · One-handed operation · Virtual touchpad.

1 Introduction

Smartphones with 6-inch or larger screens have become popular. For example, in series of smartphones such as iPhone, Galaxy, and Xperia, models with 6-inch or larger screens are mainstream. Although such large-screen smartphones have the advantage of being able to display a large amount of information, they also have the disadvantage of being difficult to operate with one hand. Therefore, it is hard to comfortably operate a smartphone in situations where one-handed operation is required, such as when carrying a bag with one hand or holding a strap in a train. Widely used techniques for assisting the user in one-handed operation, such as iPhone's Reachability and Android's one-handed mode, reduce the display areas of screens, which degrades the benefits of large-screen smartphones.

In this paper, we propose a virtual touchpad for a large-screen smartphone that uses nonlinear mapping to enable the user to manipulate distant areas as well as to accurately manipulate close areas. The virtual touchpad is displayed in a semi-transparent manner on the dominant-hand side at the bottom of the screen. The user moves a cursor on the screen by sliding the thumb on the

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virtual touchpad and determines the cursor position by releasing the thumb. We conducted a preliminary experiment to compare eight instances of the proposed virtual touchpad with different mappings and conditions in a target selection task. In addition, we performed experiments to compare the three best instances of the virtual touchpad with conventional normal touchscreen operation and also to evaluate it in web browsing. The results show that the proposed virtual touchpad could reduce the target selection time and largely reduce the strain on the thumb.

The rest of this paper is organized as follows. Section 2 describes previous work related to our method. Section 3 proposes our method, and Section 4 gives its implementation. Sections 5, 6, and 7 present the results of the experiments, and Section 8 discusses the results. Finally, Section 9 provides conclusions and future work.

2 Related Work

Chang et al. [1] divided one-handed pointing techniques for touchscreens into three categories, namely, screen transform, proxy region, and cursor. First, screen transform techniques improve the reachability of targets by transforming the screen space. The widely used iPhone's Reachability and Android's one-handed mode fall into this category. AppLens [6] is another screen transform technique that uses tabular fisheye to simultaneously show multiple applications in different levels of details. Next, proxy region techniques introduce a proxy space for the screen. This category includes ThumbSpace [4, 5], which works like an absolute-position touchpad, and TapTap [11], which uses two tapping operations to enable the second tap on a magnified view produced by the first tap. Finally, cursor techniques adopt a pseudo-fingertip like a remote cursor. MagStick [11] uses a cursor that moves in the opposite direction to the thumb movement. Also, researchers have proposed many other techniques in this category including Extensible Cursor [7], BezelSpace and CornerSpace [12], TiltCursor [1], Extended-Thumb [8], Force Cursor and Event Forward Cursor [2], and the hover-based reachability technique [3].

Lai and Hwang [9] experimentally compared three virtual pointing techniques for thumb-based cursor control on smartphones, namely, a virtual touchpad, a virtual joystick, and a virtual direction key. As a result, the virtual touchpad obtained the shortest mean target selection time and received the highest user satisfaction ratings in three out of four categories. However, its mean error rate was nearly 0.6 % higher than that of the virtual direction key. As a result, it received a lower rating than the virtual direction key in the accuracy category of user satisfaction.

Poupyrev et al. [10] proposed an interaction technique called Go-Go for manipulating distant objects in a virtual reality space. It is based on the metaphor of being able to freely change the length of a virtual arm, which allows the arm to nonlinearly extend and reach distant objects in the virtual space. If the user operates within a range shorter than a certain distance, the virtual arm moves in the same way as the real arm. However, once a certain distance is exceeded, the virtual arm will extend significantly according to a nonlinear mapping. This makes it possible to seamlessly and directly manipulate objects both near and far.

3 Proposed Method

We propose a virtual touchpad for a large-screen smartphone that uses nonlinear mapping to enable the user to manipulate distant areas as well as to accurately manipulate close areas. Adopting the basic idea behind Go-Go [10], our proposed virtual touchpad uses nonlinear mapping to move a cursor on a smartphone screen. We aim at reducing the error rate compared to the conventional virtual touchpad using linear mapping, which was used in Lai and Hwang's experiment [9]. From the viewpoint of Chang et al.'s categorization [1], our virtual touchpad can be regarded as a cursor technique with emphasis on the use of nonlinear mappings for moving the cursor.

As shown in Fig. 1(a), a semi-transparent virtual touchpad is displayed on the dominant-hand side at the bottom of the screen. The user can move a cursor on the screen by sliding the thumb on the touchpad and determine the cursor position by releasing the thumb, which allows the user to manipulate the entire screen only with the thumb. When the user releases the thumb from the touchpad, a touch event occurs at the cursor position. However, when the user releases the thumb outside the touchpad, no touch event occurs. If the user wants to select an area within the touchpad, normal tapping causes a tap event at the tapped position.

Unlike conventional virtual touchpads, the distance of the cursor movement relative to the distance of the thumb movement follows nonlinear mapping. We consider two specific nonlinear mappings A and B as shown in Fig. 2. Mapping A computes cursor movement distance $f_{\mathrm{A}}(d)$ from a thumb movement distance d with the following formula:

$$f_{\mathrm{A}}(d) = \begin{cases} d & \text{if } d \leq D \\ d + k(d-D)^2 & \text{otherwise,} \end{cases}$$

where D is the distance at which the cursor starts faster movement than the thumb, and k is a certain coefficient between 0 and 1. This is obtained by applying the same formula as Go-Go to our virtual touchpad. Fig. 2(a) shows mapping A. Intuitively, the cursor movement is equal to the thumb movement until it reaches D, but it increasingly becomes larger once it exceeds D.

Mapping B computes cursor movement distance $f_{\mathrm{B}}(d)$ with the following formula:

$$f_{\mathrm{B}}(d) = \begin{cases} d & \text{if } d \leq D_1 \\ d + k(d-D_1)^2 & \text{if } D_1 < d \leq (D_1+D_2)/2 \\ d - k(d-D_2)^2 + a & \text{if } (D_1+D_2)/2 < d \leq D_2 \\ d + a & \text{otherwise,} \end{cases}$$

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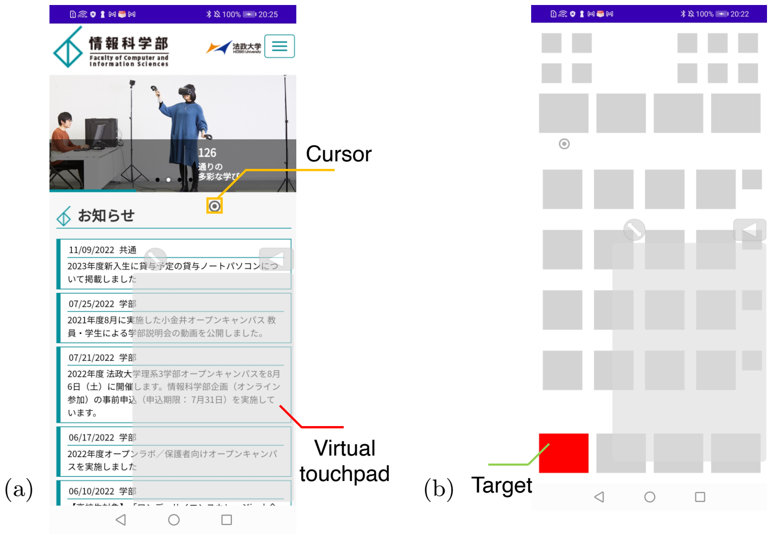

Fig. 1. (a) The proposed virtual touchpad and (b) the application used in the comparative experiment.

where D_1 is the distance at which the cursor starts faster movement than the thumb, D_2 is the distance at which the cursor finishes the faster movement, k is a certain coefficient between 0 and 1, and a is a constant. The constant a is determined in such a way that the quadratic function between D_1 and the midpoint of D_1 and D_2 and the quadratic function between D_2 and the midpoint of D_1 and D_2 have a tangent line at the midpoint of D_1 and D_2, which satisfies the following formula:

$$a = k\left(2\left(\frac{D_1 + D_2}{2}\right)^2 - 2D_1\left(\frac{D_1 + D_2}{2}\right) - 2D_2\left(\frac{D_1 + D_2}{2}\right) + D_1^2 + D_2^2\right).$$

Fig. 2(b) shows mapping B. It is similar to mapping A in that, when D_1 is exceeded, the distance of the cursor movement becomes longer than the distance of the thumb movement. However, beyond the midpoint between D_1 and D_2, the distance of the cursor movement gradually approaches the distance of the thumb movement, and once it exceeds D_2, it becomes equal to the distance of the thumb movement again. The coefficient k is larger than that of mapping A, and the rate of increase in the distance of the cursor movement relative to the distance of the thumb movement is larger.

In our experiments on the proposed virtual touchpad, we consider an additional parameter called cursor reset. When the cursor reset is enabled, the cursor is forced to move back to the default position at the time of the thumb's release from the virtual touchpad.

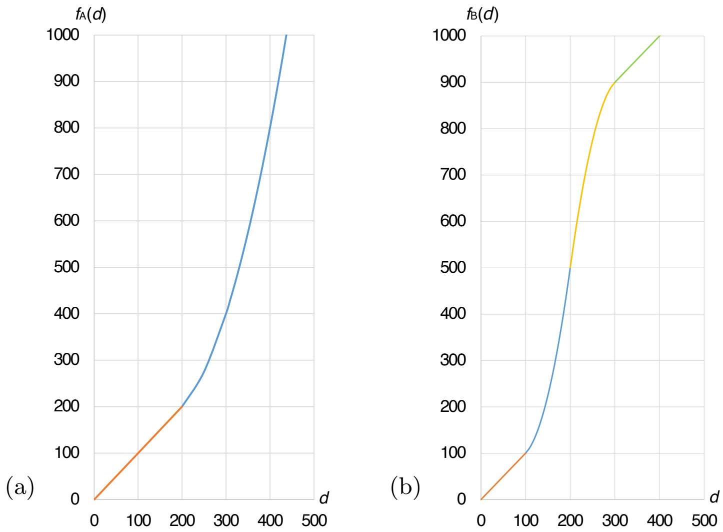

Fig. 2. Nonlinear mappings (a) A and (b) B for the proposed virtual touchpad.

4 Implementation

We implemented the proposed virtual touchpad and the applications used in our experiments in Java on Android Studio. The implemented virtual touchpad operates within these applications. We used Android's WebView to enable the web browsing in these applications. We first developed eight instances of the virtual touchpad and the application for the preliminary experiment that we present in Section 5. In addition, we implemented three instances of the virtual touchpad and the applications for the comparative and the user evaluation experiment that we present in Sections 6 and 7 respectively. We also implemented conventional normal touchscreen operation for comparison. In these applications, the virtual touchpad is displayed at the bottom right of the screen.

5 Preliminary Experiment

We conducted a preliminary experiment to explore appropriate parameters for the distances at which the cursor using one of the two nonlinear mappings starts and finishes faster movement and also to investigate the need to reset the cursor position when the thumb is released. In this experiment, we used eight instances of our virtual touchpad with two patterns of parameters for each of the two nonlinear mappings and with or without the cursor reset as shown in Table 1. To distinguish these instances of the virtual touchpad, we use labels such as A_D200_noR, which indicates that the corresponding instance uses mapping A with $D = 200$ and no cursor reset.

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Table 1. Eight instances of the proposed virtual touchpad used in the preliminary experiment.

Instance	Mapping	D or D_1	D_2	Cursor reset
A_D200_noR	A	200	-	No
A_D200_R	A	200	-	Yes
A_D300_noR	A	300	-	No
A_D300_R	A	300	-	Yes
B_D100-300_noR	B	100	300	No
B_D100-300_R	B	100	300	Yes
B_D200-400_noR	B	200	400	No
B_D200-400_R	B	200	400	Yes

5.1 Procedure

We recruited eight participants (six males and two females) who were right-handed and 21.8 years old on average. We used a smartphone HUAWEI P30 lite with a 6.2-inch screen in the experiment. We asked the participants to use the eight instances of the virtual touchpad to select 24 targets displayed evenly on the screen twice each (a total of 48 times) in a specified order. This order was made random and different for each instance of the virtual touchpad to avoid its influence on the selection time. We measured selection times and error rates, and conducted a questionnaire to obtain user evaluations in a five-point Likert scale on four items, i.e., accuracy, simplicity, less strain on the thumb, and overall satisfaction.

5.2 Results

The mean selection times, the mean error rates, and the mean points of the user evaluation are shown in Figs. 3(a), 3(b), and 3(c). The mean selection times were less than 1210 ms for all the instances of our virtual touchpad with cursor reset, and were more than 1300 ms for all the instances with no cursor reset. Similar to the mean selection times, the mean error rates with cursor reset were often lower than those with no cursor reset. In particular, the instances of our virtual touchpad using mapping B and no cursor reset resulted in error rates of over 9 %. In most of the items of the user evaluation, the instances with cursor reset obtained higher points than those with no cursor reset. Also, concerning the distance at which the cursor starts faster movement, the instances using 200 for mapping A and the instances using 100 for mapping B obtained better results on the whole.

6 Comparative Experiment

Next, we conducted a comparative experiment to evaluate our proposed method by comparing it with normal touchscreen operation. In this experiment, we used three instances of our virtual touchpad, A_D200_noR, A_D200_R, and B_D100-300_R, which had showed good results in the preliminary experiment.

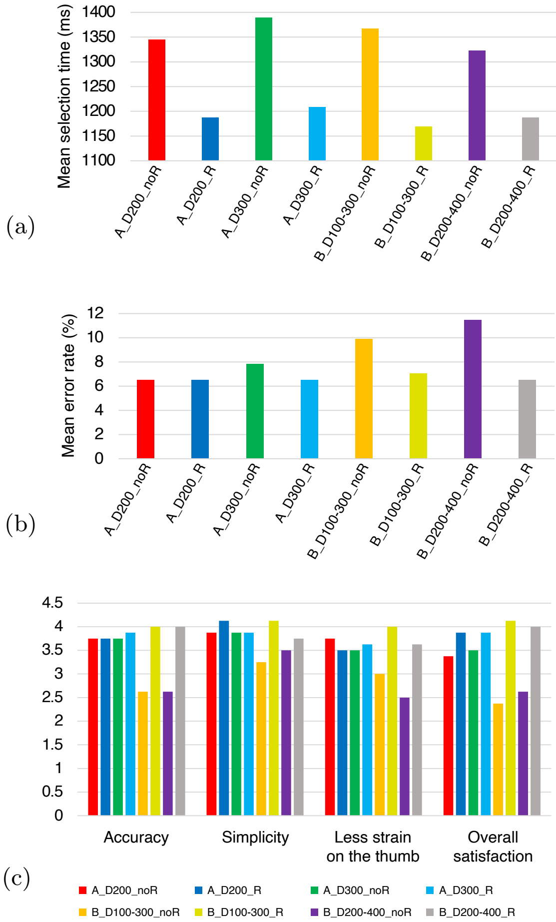

Fig. 3. Results of the preliminary experiment: (a) the mean selection times, (b) the mean error rates, and (c) the mean points of the user evaluation.

6.1 Procedure

For this experiment, we developed an application shown in Fig. 1(b). Although 24 targets were displayed evenly in the preliminary experiment, targets to be selected are not necessarily evenly positioned on the screens of ordinary applications. Many current touch-based user interfaces use areas near the corners and edges of screens [12]. For example, smartphone applications for X (formerly known as Twitter), Instagram, and LINE commonly place multiple small interfaces at the top corners of screens and also put interfaces for screen changes horizontally at the top or bottom of the screens. Also, applications for Instagram and YouTube have a small interface on the right edge of the center of the screens.

We recruited eight participants (six males and two females) who were all right-handed and 22.0 years old in average. We used the same smartphone, HUAWEI P30 lite with a 6.2-inch screen, as in the preliminary experiment. In Fig. 1(b), targets are shown as rectangles, and the participants were asked to select the red target that randomly moved in different areas of the screen. The order of target selection was the same as in the preliminary experiment. We measured the selection times and computed the error rates. In addition, to examine the strengths and weaknesses of each instance of the virtual touchpad, we calculated the mean selection time and the mean error rate for each target.

6.2 Results

Fig. 4 shows the results. The two instances of our virtual touchpad with cursor reset obtained the shortest mean times of about 1090 ms while the normal operation had the lowest error rate of about 6 %. Concerning the mean selection times for different areas of the screen, all the instances of our virtual touchpad resulted in shorter times than the normal operation in the top left, the right central, and the bottom area. Regarding the mean error rates for different areas of the screen, the instance of our virtual touchpad using mapping B and cursor reset resulted in lower mean error rates than the normal operation in the top left and the top right area, the instance using mapping A and no cursor reset resulted in a lower mean error rate at the upper central area, and all the instances of our virtual touchpad resulted in lower mean error rates at the right central area.

7 User Evaluation Experiment

We conducted an additional experiment to evaluate the effectiveness of our virtual touchpad for operations in web browsing, which people actually perform in daily life. We compared the same three instances of the virtual touchpad with normal touchscreen operation as in the comparative experiment.

7.1 Procedure

We used Android's WebView to display websites inside the application for this experiment. The participants and the used smartphone were the same as in the comparative experiment. The actual screen is shown in Fig. 1(a). We asked the participants to surf the Internet by using the three instances of the virtual touchpad as well as the normal operation. After five minutes of using each technique, we asked them to evaluate it in a five-point Likert scale on the four items, accuracy, simplicity, less strain on the thumb, and overall satisfaction.

7.2 Results

Fig. 5 shows the results of the user evaluation. Concerning accuracy, the normal operation, which was familiar to the participants, obtained the highest point of

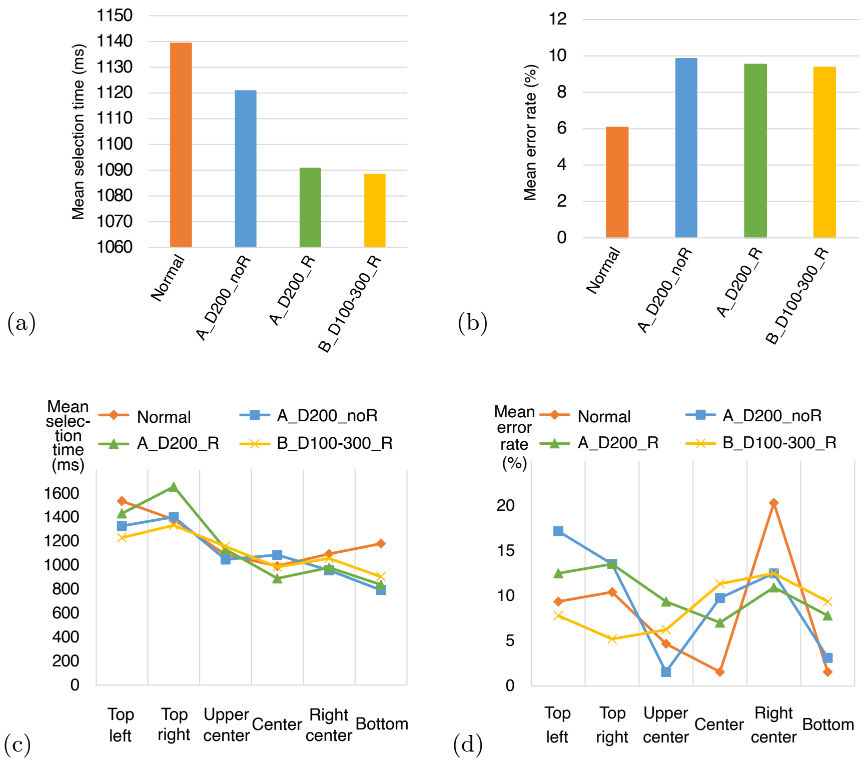

Fig. 4. Results of the comparative experiment: (a) the mean selection times and (b) the mean error rates for the entire areas, and (c) the mean selection times and (d) the mean error rates for different areas.

over 4.5. However, all the instances of our virtual touchpad resulted in 4 or higher points in terms of less strain on the thumb, which was higher than the normal operation. Regarding overall satisfaction, the instance of our virtual touchpad using mapping B and cursor reset obtained the highest point of 4.2.

8 Discussion

This section discusses the results of the comparative and the user evaluation experiment.

8.1 On the Comparative Experiment

As a result of the comparative experiment, all the instances of our virtual touchpad obtained shorter mean selection times than normal touchscreen operation. In particular, the instances using cursor reset resulted in about 50 ms shorter

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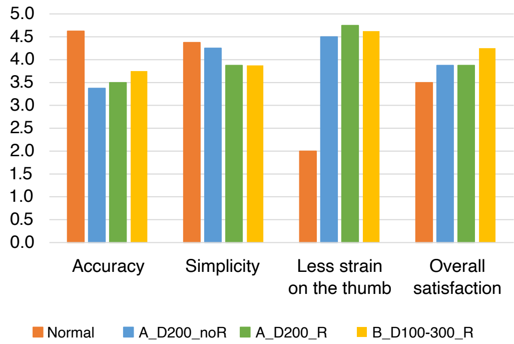

Fig. 5. Results of the user evaluation experiment.

times than the normal operation. We consider that the selection times became shorter since the virtual touchpad removed the need to change the grip of the smartphone in order for the thumb to reach distant areas. We also consider that the cursor reset function enabled the participants to easily perceive the distance of the cursor movement relative to the distance of the thumb movement, which shortened the target selection times. In terms of the mean selection times for different target positions, all the instances of our virtual touchpad resulted in shorter times than the normal operation in the top left, the right central, and the bottom area of the screen. The normal operation requires changing the grip of the smartphone in the case of selecting areas that the thumb cannot reach. Therefore, we consider that the normal operation resulted in longer times than the virtual touchpad in the case of selecting the edges of the screen.

Concerning the mean error rates, all the virtual touchpad resulted in 9 to 10 % while the normal operation achieved about 6 %. This is because the normal operation of directly touching the screen made it less likely that the participants would select wrong targets. However, since the instance of our virtual touchpad using mapping B and cursor reset made the cursor behave in the same way as the thumb, it obtained lower mean error rates than the normal operation which often required changing the grip of the smartphone. In addition, since the instance of the virtual touchpad using mapping A and no cursor reset often placed the cursor in the upper area of the screen, it achieved lower error rates than the normal operation in the upper central area of the screen. We consider that the reason why the normal operation resulted in the highest mean error rate in the right central area of the screen was that changing the grip of the smartphone made the target positions hidden by the hand.

8.2 On the User Evaluation Experiment

As a result of the user evaluation experiment, many participants thought that the normal operation was superior in accuracy. However, in terms of less strain on the thumb, the normal operation, which required changing the grip of the

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smartphone resulted in a low point of 2 while all the instances of the virtual touchpad achieved high points of over 4. In terms of overall satisfaction, the instance of the virtual touchpad using mapping B and cursor reset obtained the highest point of over 4. Many participants found it easy to use because the cursor behaved in the same way as the thumb when they moved it to around the corners of the screen where small targets were placed. Therefore, we consider that it was more highly evaluated than the other two instances of the virtual touchpad that used mapping A.

9 Conclusions and Future Work

In this paper, we proposed a virtual touchpad that used nonlinear mapping to assist one-handed operation of a large-screen smartphone. The results of the experiment on its comparison with normal touchscreen operation indicated that our virtual touchpad had shortened the mean target selection times. Also, our user evaluation experiment showed that it largely reduced strain on the thumb. However, the normal operation obtained better results than all the instances of our virtual touchpad. Among the three instances of the virtual touchpad used in the comparative and the user evaluation experiment, the instance using mapping B and cursor reset achieved the best results.

Our future work includes reducing the error rates of the virtual touchpad. A promising approach will be to design an intelligent virtual touchpad that detects user-selectable targets to automatically attract the cursor when it becomes close to small targets as was done by BezelSpace and CornerSpace [12]. Another future direction is to conduct an experiment by using a smartphone with a larger screen, which might produce different results than the experiments that we conducted in this paper. Another direction is to consider the sizes of users' hands since the difficulty of one-handed smartphone operation may differ depending on the sizes of the hands, which will more clarify the effectiveness of the virtual touchpad for some group of users.

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