Using Psychophysiological Techniques to Evaluate User Experience of Touchscreen Protectors

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Abstract. Since touchscreens were introduced into mobile devices, interaction directly on the touchscreen replaced interaction with the keyboard. In order to protect touchscreens and improve user experience, touchscreen protectors are widely used. This study selected three different designs of touchscreen protectors with three different levels of friction, and a touchscreen without a protector as a control group. The experiment was divided into two tasks, namely the moving task (including horizontal movement and vertical movement) and the circling tasks (including clockwise movement and counter-clockwise movement). User experience was measured through performance, questionnaires and psychophysiological techniques including electromyography (EMG) and electroencephalography (EEG) measurements. Results reflected that a touchscreen without a protector was most suitable for gesture control to improve performance. Among various types of protectors, the protector with the same friction as a touchscreen, was more suitable to improve performance. Results suggested that protectors with excessive or too little friction cannot improve performance.

Keywords: Psychophysiological techniques · User experience · Touchscreen protectors

1 Introduction

With the development of the Internet and mobile technology, mobile devices were rapidly developing, and significantly changed our lives and behavior. For its convenience and flexibility, mobile devices are currently reaching a mass audience. Since touchscreens were introduced into mobile devices, interaction directly on the touchscreen replaced interaction with the keyboard. Although touchscreens clearly enhance the user's experience by offering an even more user-friendly interface than tactile keypads, there is also a need to improve the input performance for the use [1]. Direct touch interaction allows a variety of gesture control, such as clicking, dragging, zooming and rotating [2]. Recently, many mobile applications use gesture control as an input method, especially mobile games, a video game played on mobile devices. Mobile device users can play a great variety of mobile games anytime and anywhere. However, long-term large number of gesture control on touchscreens also causes some harm, such as muscle fatigue, and even muscle pain.

© Springer Nature Switzerland AG 2019
P.-L. P. Rau (Ed.): HCII 2019, LNCS 11576, pp. 323–337, 2019.
https://doi.org/10.1007/978-3-030-22577-3_23

In order to protect touchscreens and improve user experience, touchscreen protectors are widely used. Many people buy a specific screen protector designed for mobile games to improve performance. Retailers of these protectors claim that protectors can reduce the resistance of touchscreens and improve the smoothness of touchscreens. However, there are various kinds of protectors. The materials, surface and manufacturing process of these protectors are different, resulting in difference in physical parameters such as friction, thickness, and hardness. Liu et al. [3] studied the factors affecting the usability of smartphone screen protectors for the elderly. The protectors were classified according to functions such as anti-smudge and anti-glare. But relationships between physical parameters of protectors and user experience are unclear. Among physical parameters of protectors, the coefficient of friction, which influences the smoothness of a protector, has the greatest impact on user experience. To date, there have been few studies on the friction of touchscreens or protectors.

Evaluation of user experience of touchscreens or protectors on previous research is mainly through subjective self-reports such as questionnaires and interviews. In a usability study of touchscreen protectors for the elderly, touchscreen protectors were scored with a usability evaluation questionnaire [3]. Likert Scales were used to evaluate the level of errors, efficiency, learnability, memorability, and satisfaction. Page [4] conducted a usability studied on touchscreen mobile devices for older adults. He used pre-interview to understand participants' current perceptions of touchscreen technologies and post-interview to obtain thoughts and attitudes towards the touchscreen mobile devices. However, since user experience of touchscreens or protectors is greatly affected by the task, subjective self-reports such as questionnaires and interviews cannot separate the feeling of touchscreens or protectors from the feeling of the task. Xiong and Muraki [1] used psychophysiological techniques to investigate relationships between thumb muscle activity and thumb operating tasks on a smartphone touchscreen. Compared with subjective self-reports, psychophysiological techniques can be used to obtain objective physiological data and help understand the state of participants during the task. Electromyography (EMG) measures muscle activity by detecting surface voltages that occur when a muscle is contracted [5]. EMG data can be used to evaluate muscle effort and fatigue of muscles during the experiment.

The current study aims to explore relationships between the coefficient of friction and user experience. This study selected three different designs of touchscreen protectors, and a touchscreen without a protector as a control group. Compared with the touchscreen without a protector, the three protectors selected contained three different levels of friction, which were smaller than the touchscreen, larger than the touchscreen and equal to the touchscreen. User experience in this study was measured through performance, questionnaires and psychophysiological including EMG and electroencephalography (EEG) measurements. This study should provide a better understanding of protectors' friction and its connection to user experience, and offer a knowledge base for the better design of touchscreen protectors.

2 Methodology

2.1 Participants

Fifteen students (11 males, 4 females) at Tsinghua University ages 22 to 27 (M = 23.81, SD = 1.22) were invited to participate in the experiment. The dominant hands of all the participants were right-handed. None of the participants reported a musculoskeletal disorder or pain, nor any motor disorders or symptoms. All the participants owned touchscreen smartphones for daily use and they all had extensive experience in mobile games. Recruitment priority was given to the participants who took a long time to play mobile games.

2.2 Experimental Sample

This study selected three types of touchscreen protectors with different levels of friction, which were smaller than the touchscreen, larger than the touchscreen and equal to the touchscreen. This study selected two typical materials of touchscreen protectors that were widely used in the market, namely TPU and PET materials. The coefficient of friction of TPU protector was the same as the touchscreen, ranging from 0.15–0.20. Especially, there were two kinds of protectors made of PET material, which were normal PET protector and special PET protector. The coefficient of friction of normal PET protector was the largest among three types of protectors, ranging from 0.20 to 0.25. Special PET protector was manufactured using a special processing technology and had a special composite coating. As a result, its coefficient of friction, ranging from 0.10 to 0.15, was the smallest, even smaller than a touchscreen without a protector. Table 1 shows materials, surface, features, visual characteristics, and physical parameters of three types of protectors and a touchscreen without a protector.

Table 1. Characteristics of three types of protectors and the touchscreen without a protector

Name	TPU protector	Normal PET protector	Special PET protector	Touchscreen without a protector
Material	TPU	PET	PET	Glass
Surface (coating)	AF	AF	AG and AR	AF
Visual characteristics	Glossy	Glossy	Matte	Glossy
Features	Anti-smudge	Anti-smudge	Anti-smudge, anti-glare and anti-reflection	Anti-smudge
Coefficient of friction	0.15–0.20	0.20–0.25	0.10–0.15	0.15–0.20
Thickness	0.15–0.2 mm	0.13–0.16 mm	0.13–0.16 mm	\
Hardness	HB	H	H	\

2.3 Design of Experiment

Two experiments were conducted to investigate user experience associated with the line movement and the circle movement. The effects of the type of protectors (TPU protector, normal PET protector, special PET protector, and a touchscreen without a protector) and the type of thumb (left thumb and right thumb) were examined in the experiment (See Table 2). The type of protectors and the type of thumb were both within-subject factors. The participants completed tasks on different types of protectors in a random order in order to balance the impact of the sequence of experiments. Since there were several subtasks in an experiment of a protector, the participants completed subtasks in a fixed order, which was an alternating sequence starting with the left thumb.

Table 2. Design of experiment

		Type of thumb	
		Left thumb	Right thumb
Type of protectors	TPU protector	A	B
	Normal PET protector	C	D
	Special PET protector	E	F
	Touchscreen without a protector	G	H

2.4 Tasks

The experiment was divided into two tasks, namely the moving task and the circling tasks. Each task contained two subtasks, which were horizontal movement and vertical movement in the moving task, and clockwise movement and counter-clockwise movement in the circling task (See Fig. 1). The participants were required to slide along the specified trajectory as accurately as possible, but there was no need to be too slow to pursue accuracy, allowing the participants to maintain normal speed.

The specified trajectory in the moving task was a line with two dots, namely A and B. The diameter of the dots was 60 px and distance between the target dots was 600 px. In the moving task, movement back and forth (A-B-A) was recorded as one time. The participants were required to repeat line movement ten times for each subtask. There was a display of the remaining number of times on the experimental smartphone as a reminder. The specified trajectory in the circling task was a circle with a dot, namely A. The diameter of the dot was 60 px and diameter of the circle trajectory were 600 px. In the circling task, movement along a circle (A-A) was recorded as one time. The participants were required to repeat circling movement ten times for each subtask.

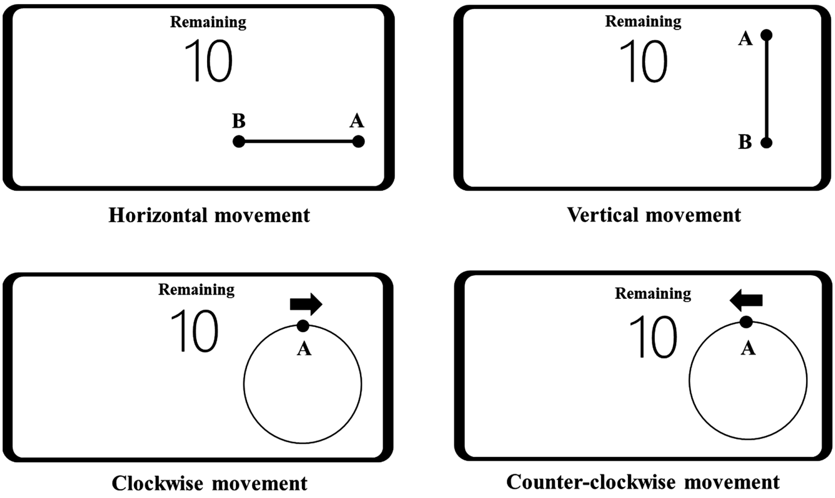

Fig. 1. The specified trajectory (taking the right hand as an example)

2.5 Measurements

Task Performance. Performance was measured by accuracy and time to complete the task. Accuracy refers to the proximity between the actual trajectory of the movement and the specified trajectory. The software records the coordinates of the track during the experiment and distance between the actual trajectory and the specified trajectory can be obtained. This study used the standard deviation of the distance of all ten times movement as the measurement of performance accuracy. Time to complete the task can reflect the speed of movement. This study used the duration of all ten times movement as the measurement of time to complete the task.

Thumb Muscle Activity. Abductor pollicis brevis (APB) in right and left thumb were targeted in this study. In APB, the electrodes were placed over the muscle belly between the metacarpophalangeal (MCP I) and carpometacarpal (CMC I) joints [6]. EMG data were used to evaluate muscle effort on a touchscreen protector, as well as fatigue of thumb movement. This study used the root mean square (RMS) amplitude at APB in right and left thumb as the measurement of muscle effort. When muscles are fatigued, the spectrum shifts from high frequency to low frequency and the median frequency (MF) value also decreases. The greater difference in decline reveals higher levels of muscle fatigue. In this study, the difference between the median frequency (MF) of APB in the first 20% of the time period and the median frequency (MF) of APB in the last 20% of the time was used as the measurement of muscle fatigue.

Subjective Usability Evaluation. To measure usability evaluation, protectors were scored with a questionnaire completed immediately after tasks of each protector. Three items were related to thumb muscle activity, including perceived effort of thumb muscles, perceived fatigue of thumb muscles and perceived comfort of thumb muscles. Three items were related to touchscreens or protectors, including user satisfaction, frustration, and perceived response speed. One item was related to the task, which was difficulty of the task. Each subjective variable was measured with a single item with 7-point Likert scale.

Emotion. Two-dimensional Arousal-Valence model advocated by Russell [7] was used in this study. EEG data was used to measure emotion during the task. The asymmetrical frontal EEG activity may reflect the valence level of emotion experienced [8]. The positive valence was measured by the difference in alpha spectrum between right hemispheres of the frontal lobe and left hemispheres of the frontal lobe as follows.

$$\text{Positive valence} = \alpha\,\text{PSD}_{\text{right}} - \alpha\,\text{PSD}_{\text{left}} \tag{1}$$

where "right" and "left" denote the symmetric pairs of electrodes on the left/right hemisphere, i.e. AF4 and AF3, F4 and F3, F8 and F7, and FC6 and FC5 in this study.

The degree of arousal was measured by beta spectrum on the frontal lobe. Besides, this study also measured emotion during the task through Self-Assessment Manikin (SAM) instrument [9]. The Self-Assessment Manikin (SAM) is a non-verbal pictorial assessment technique that directly measures the pleasure and arousal associated with a person's affective reaction to a wide variety of stimuli [10]. Self-Assessment Manikin (SAM) instrument was added to subjective usability evaluation questionnaire completed immediately after tasks of each protector.

2.6 Apparatus and System

A testing system was developed to present the tasks and collect performance data during the task execution (See Fig. 2). All the participants used the same five-inch screen Android smartphone to maintain a level of experimental consistency.

Delsys wireless system was used to collect EMG data in this study. Two wireless EMG electrodes were placed on abductor pollicis brevis (APB) muscles in right and left thumb (See Fig. 2). Before mounting the electrodes, the skin was cleansed with alcohol pads to remove skin debris and improve the electrical contact with the electrodes.

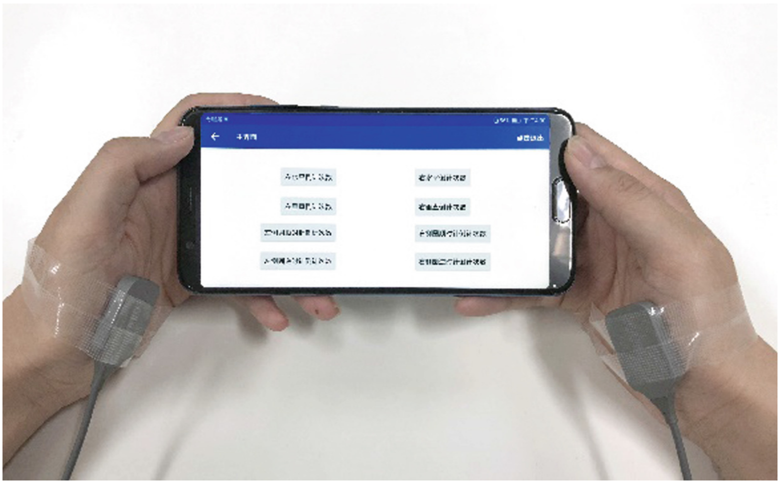

Fig. 2. EMG equipment and Android smartphones used in the experiment

Emotiv was used to collect EEG data in this study. Emotiv device has 14 electrodes locating at AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, AF4. The sampling rate of the Emotiv headset is 128 Hz. The bandwidth of the device is 0.2–45 Hz, and digital notch filters are at 50 Hz and 60 Hz. The A/D converter is with 16 bits resolution.

2.7 Procedure

The participants signed an informed consent agreement at first. The sequence of three types of protectors and a touchscreen was randomized for the participants. Experimental content and process were introduced at the beginning. The participants were allowed to practice before the formal test. Once the participants had sufficient practice, Delsys wireless system and Emotiv wireless system were worn. In each experiment of touchscreen protectors, the participants clicked "Start" to enter the formal test. The moving task with four subtasks (horizontal movement with the left thumb, horizontal movement with the right thumb, vertical movement with the left thumb, and vertical movement with the right thumb) was completed at first. After completing the moving task, the participants were given the subjective evaluation form to complete. Then the circling task with four subtasks (clockwise movement with the left thumb, clockwise movement with the right thumb, counter-clockwise movement with the left thumb, and counter-clockwise movement with the right thumb) was completed, followed by the subjective evaluation form to complete. A rest period (at least five minutes) was provided for the participants when an experiment of a protector was completed. Upon completion of all of the experiments, the participants were interviewed about the difference that they found between protectors and the touchscreen.

3 Results

Two-way ANOVAs were used to determine the main and interaction effects of the type of protectors (TPU protector, normal PET protector, special PET protector, the touchscreen without a protector) and the type of thumb (left thumb, right thumb) on user experience in the moving task and the circling task independently. Statistical significance was accepted at p-values less than 0.05.

3.1 Task Performance

Accuracy. As shown in Fig. 3, in the moving task, the main effect of type of protectors and its interaction with the type of thumb were not significant for performance accuracy. The main effect of the type of thumb was significant for performance accuracy ($P < 0.001$). The performance accuracy of right thumb was significantly better than that of left thumb. As shown in Fig. 4, in the circling task, the main effect of the type of protectors ($P = 0.023$) and the type of thumb ($P < 0.001$) were significant. The interaction effect of them was not significant. The performance accuracy of right thumb was significantly better than that of left thumb. The post hoc tests using BH method showed that the standard deviation of moving distance on the touchscreen without a protector (M = 18.68, SD = 5.58) was significantly less than normal PET protector (M = 20.88, SD = 6.87) and special PET protector (M = 20.31, SD = 7.13), and marginally significantly less than TPU protector (M = 19.61, SD = 5.89). The TPU protector was significantly less than normal PET protector.

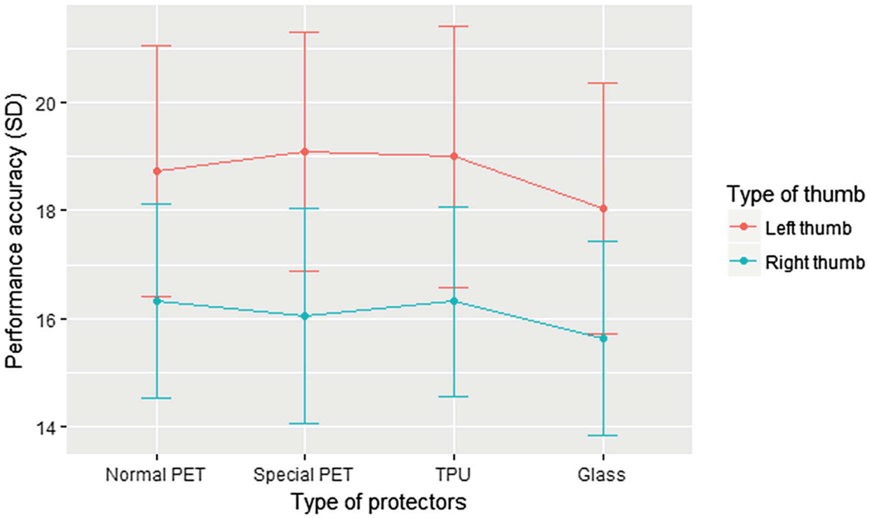

Fig. 3. Accuracy in the moving task

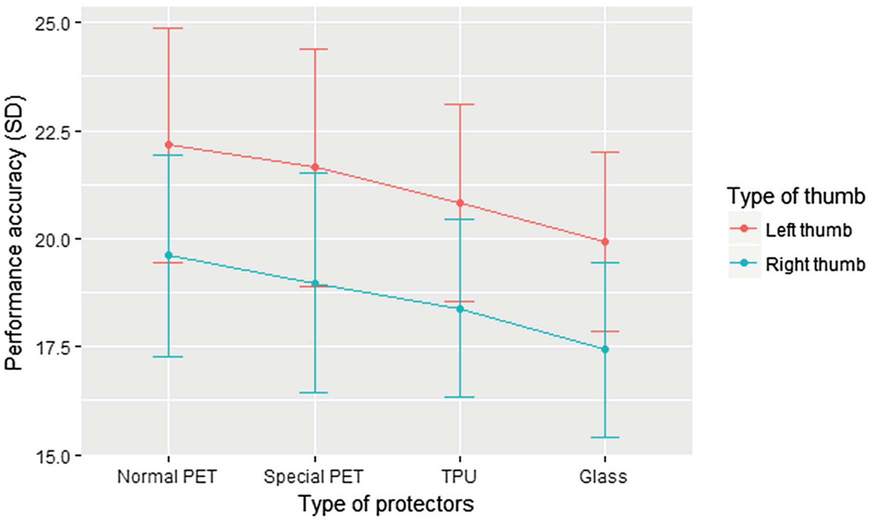

Fig. 4. Accuracy in the circling task

Time to Complete the Task. No significant difference between the type of protectors and its interaction with the type of thumb were obtained in both the moving task and the circling task. The main effect of the type of thumb was significant in time to complete the task in both the moving task (P = 0.012) and the circling task (P = 0.012). Right thumb used significantly less time to complete the task than left thumb.

3.2 Thumb Muscle Activity

Muscle Effort. As shown in Fig. 5, in the moving task, although there seemed to be a difference between types of protectors, the main effect of the type of protectors and its interaction with the type of thumb were not significant for muscle effort of APB. The main effect of the type of thumb was significant for muscle effort of APB ($P < 0.001$). The muscle effort in right thumb was significantly more than effort in left thumb. Paired t-tests were used to further explore the difference between types of protectors. Results showed that muscle effort of special PET protector (M = 124, SD = 105) was significantly less than TPU protector (M = 169, SD = 213), and marginally significantly less than touchscreen without a protector (M = 166, SD = 250). In the circling task, the main effect of the type of protectors and the type of thumb and their interaction were not significant.

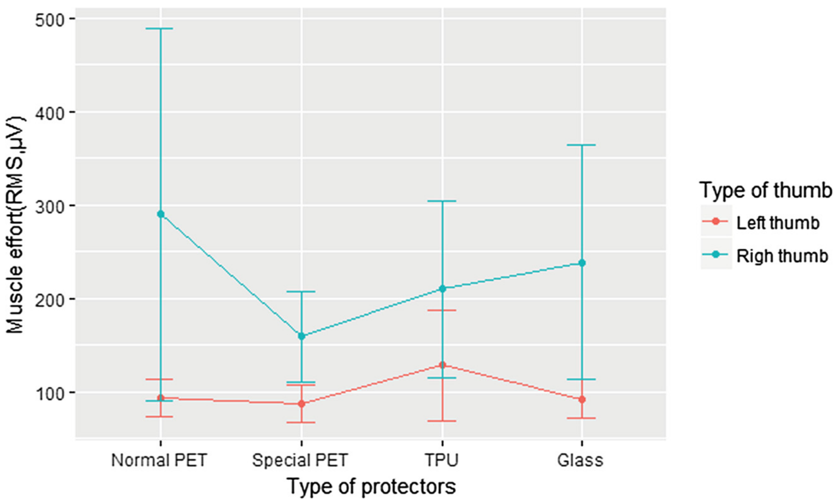

Fig. 5. Muscle effort in the moving task

Muscle Fatigue. In the moving task, the main effect of the type of protectors and its interaction with the type of thumb were not significant for muscle fatigue of APB. The main effect of the type of thumb was significant for muscle fatigue of APB (P = 0.023). The muscle fatigue in right thumb was significantly more than that in left thumb. In the circling task, the main effect of the type of protectors and the type of thumb and their interaction were not significant.

3.3 Subjective Usability Evaluation

Perceived Effort of Thumb Muscles. Perceived effort of thumb muscles was measured by 7-point Likert scale (1 represented too small, 7 represented too large). As shown in Fig. 6, in the moving task, the main effect of the type of protectors was significant (P = 0.015). There was no significant difference between types of thumb in perceived effort of thumb muscles. The post hoc tests using BH method showed that the perceived effort of thumb muscles on special PET protector (M = 3.43, SD = 1.10) was significantly less than normal PET protector (M = 4.23, SD = 0.90), TPU protector (M = 4.00, SD = 0.79), and the touchscreen without a protector (M = 4.30, SD = 0.75). As shown in Fig. 7, in the circling task, the main effect of the type of protectors was significant (P < 0.001). There was no significant difference between types of thumb in perceived effort of thumb muscles. The post hoc tests using BH method showed that the perceived effort of thumb muscles on normal PET protector (M = 4.80, SD = 0.96) was significantly more than special PET protector (M = 3.80, SD = 0.85), TPU protector (M = 4.03, SD = 0.93), and the touchscreen without a protector (M = 4.30, SD = 0.92). Perceived effort of muscles on the touchscreen without a protector was significantly more than special PET protector.

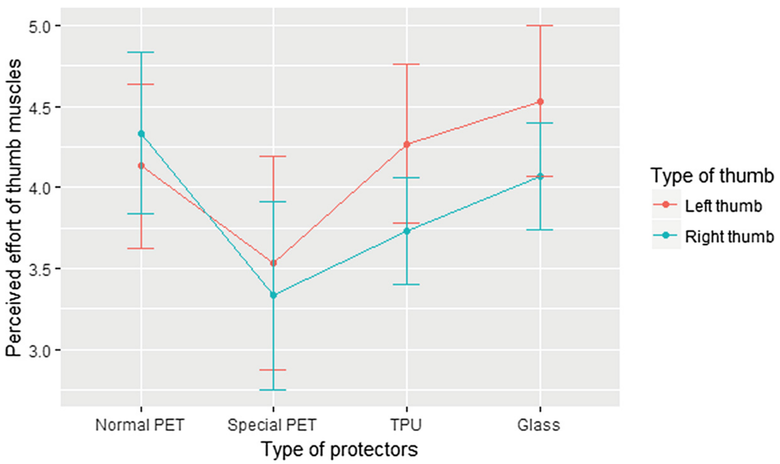

Fig. 6. Perceived effort of thumb muscles in the moving task

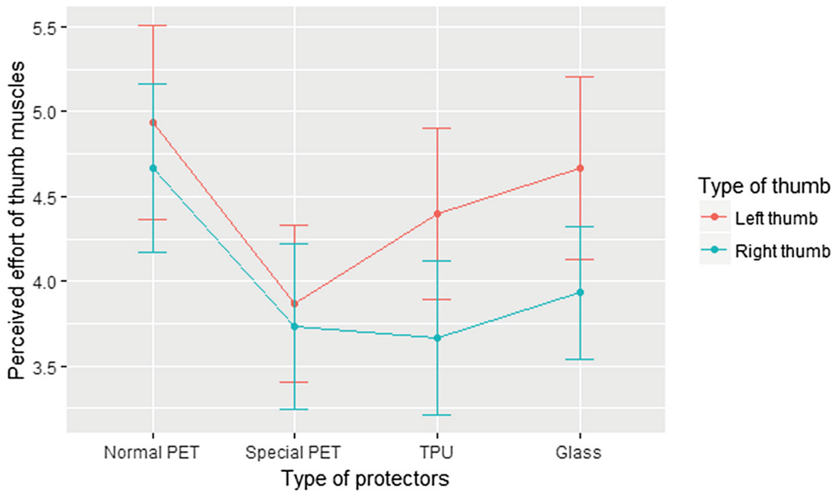

Fig. 7. Perceived effort of thumb muscles in the circling task

Perceived Fatigue of Thumb Muscles. Perceived fatigue of thumb muscles was measured by 7-point Likert scale (1 represented not fatigue at all, 7 represented much fatigue). The main effect of the type of protectors and the type of thumb and their interaction were not significant in both the moving task and the circling task.

Perceived Comfort of Thumb Muscles. Perceived comfort of thumb muscles was measured by 7-point Likert scale (1 represented not comfortable at all, 7 represented very comfortable). In the moving task, the main effect of the type of protectors (P = 0.026) and the type of thumb (P = 0.049) were significant. The perceived comfort of thumb muscles of right thumb was significantly better than that of left thumb. The post hoc tests using BH method showed that perceived comfort of thumb muscles on normal PET protector (M = 4.20, SD = 1.32) was significantly more than special PET protector (M = 5.20, SD = 1.45), TPU protector (M = 5.27, SD = 1.34), and the touchscreen without a protector (M = 5.10, SD = 1.21). In the circling task, no significant difference was found in main and interaction effect of the type of protectors and the type of thumb.

User Satisfaction. User satisfaction was measured by 7-point Likert scale (1 represented not satisfied at all, 7 represented very satisfied). There was no significant difference between types of protectors in user satisfaction in both the moving task and the circling task.

Frustration. Frustration was measured by 7-point Likert scale (1 represented not frustrated at all, 7 represented very frustrated). There was no significant difference between types of protectors in frustration in both the moving task and the circling task.

Difficulty of the Task. Difficulty of the task was measured by 7-point Likert scale (1 represented very easy, 7 represented very difficult). In the moving task, the main effect of the type of protectors and its interaction with the type of thumb were not significant.

The main effect of the type of thumb was significant (P = 0.039) in difficulty of the task. The task of left thumb was significantly more difficult than that of right thumb. In the circling task, no significant difference was found in main and interaction effect of the type of protectors and the type of thumb.

Perceived Response Speed. Perceived response speed was measured by 7-point Likert scale (1 represented slow response, 7 represented timely response). There was no significant difference between types of protectors in perceived response speed in both the moving task and the circling task.

3.4 Emotion

Valence. None of the EEG indexes showed any statistically suggestive results in valence in both the moving task and the circling task. As shown in Fig. 8, valence was measured by SAM instrument (1 represented the highest level of positive valence, 9 represented the lowest level of positive valence). In the moving task, no significant difference was found between types of protectors. In the circling task, a significant difference was found between types of protectors (P = 0.001). The post hoc tests using BH method showed that the valence of the touchscreen without a protector (M = 2.33, SD = 0.98) was significantly more positive than special PET protector (M = 3.13, SD = 1.19) and normal PET protector (M = 3.67, SD = 1.23). The valence of TPU protector (M = 2.53, SD = 0.83) was significantly more positive than normal PET protector (M = 3.67, SD = 1.23).

Arousal. None of the EEG indexes showed any statistically suggestive results in arousal in both the moving task and the circling task. Arousal was measured by SAM instrument (1 represented the highest level of arousal, 9 represented the lowest level of arousal). No significant difference was found between types of protectors in both the moving task and the circling task.

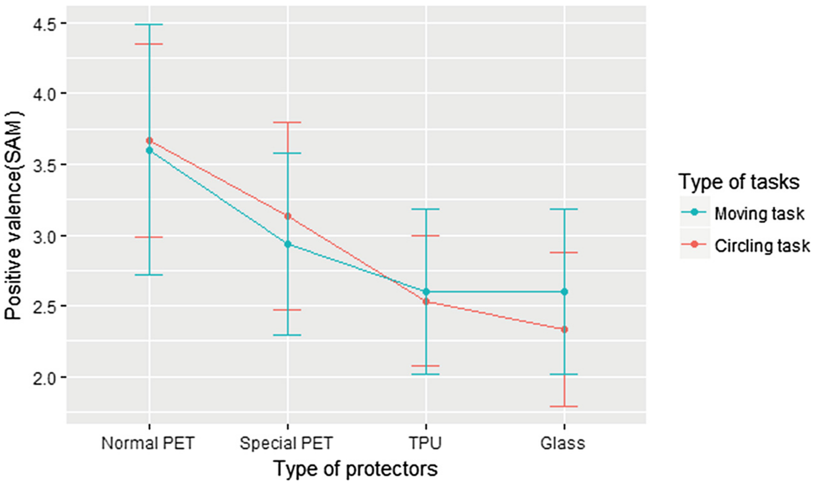

Fig. 8. Valence measurement using SAM instrument

4 General Discussion

Results of task performance revealed that the circling movement was more susceptible to the type of protectors than the line movement. In the moving task, no significant difference in accuracy was found between types of protectors. But there was a significant difference in accuracy in the circling task. Besides, no significant difference between types of protectors was found in time to complete the task. It suggested that difference in accuracy was not due to the speed of movement, but due to the type of protectors itself. Among different types of protectors, special PET protector had the smallest friction and normal PET protector had the largest friction. But performance of them in the circling task was worse than TPU protector and the touchscreen. It reflected that a protector with excessive or too little friction could not improve performance. A protector with the same friction as the touchscreen had the best performance compared with other types of protectors. However, performance of the touchscreen was better than three types of protectors, even better than the protector with the same friction as the touchscreen. Therefore, the touchscreen without a protector was most suitable for gesture control to improve performance. Among various types of protectors, TPU protector, which has the same friction as the touchscreen, was more suitable for gesture control to improve performance.

Thumb muscle activity was measured through EMG at APB in right and left thumb and the item perceived effort of thumb muscles in subjective usability evaluation. The subjective self-reports found a significant difference in perceived effort of thumb muscles between types of protectors in both the moving task and the circling task. In the moving task, perceived effort of thumb muscles on special PET protector was significantly less than other types of protectors and the touchscreen. Compared with results of subjective self-reports, the mean value ordering of EMG measurement in the moving task was consistent with it. Paired t-tests showed that muscle effort on special PET protector was significantly less than TPU protector and the touchscreen. The reason that the results of EMG measurement were not significant may be a too large variance of EMG measurement. In the circling task, perceived effort of thumb muscles on normal PET protector was significantly more than other types of protectors and the touchscreen. It reflected the relationship between friction and muscle effort. Thumb movement on special PET protector with the smallest friction used the least muscle effort. Thumb movement on normal PET protector with the largest friction used the most muscle effort. For muscle fatigue, no significant difference between types of protectors was found in both EMG measurement and subjective self-reports. The reason may be that each subtask lasted less than thirty seconds during the experiment and the short-term thumb movement could not cause obvious muscle fatigue.

Except for the item perceived effort of thumb muscles, there were six items in subjective usability evaluation. However, only one item, perceived comfort of thumb muscles, was significant in the moving task. Perceived comfort of thumb muscles on normal PET protector was significantly more than other types of protectors and the touchscreen.

Emotion during the task was measured through EEG and subjective SAM instrument using two-dimensional Arousal-Valence model. No significant difference between types of protectors was found in EEG indexes in valence and arousal dimensions in both the moving task and the circling task. But using the SAM instrument, a significant difference in valence was found in the circling task. The valence of the touchscreen without a protector was significantly more positive than special PET protector and normal PET protector. The valence of TPU protector was significantly more positive than normal PET protector. Results of subjective valence measurement were in accordance with performance. In the circling task, the best performance on the touchscreen led to the highest level of positive valence, and worst performance on normal PET protector led to the lowest level of positive valence.

Therefore, the touchscreen without a protector had the best performance and the highest level of positive valence, followed by TPU protector with the same friction as the touchscreen. Special PET protector, which had smaller friction than the touchscreen, had the smallest muscle effort. But performance of special PET protector was worse than the touchscreen and the level of the positive valence of special PET protector was also lower than the touchscreen. Normal PET protector had the largest friction and the largest muscle effort among types of protectors. It had the worst performance and the lowest level of positive valence.

In addition, this study also compared right thumb with left thumb. The dominant hands of all the participants were right-handed. Results showed that right thumb performed better and used less time than left thumb in both the moving task and the circling task. EMG measurement showed that right thumb had more muscle effort and a higher level of fatigue during the moving task. Results of subjective usability evaluation showed that participants felt more comfortable and easier in the moving task using right thumb.

The limitation of the current study is that this study only selected three types of protectors. These three types of protectors contained different materials, manufacturing process and different physical parameters such as coefficient of friction, thickness, and hardness. This study mainly compared protectors with three different levels of friction but did not control other physical parameters. Further research could conduct an experimental design with different types of physical parameters to explore relationships between these physical parameters and user experience.

Acknowledgments. This study was supported by Huawei Device Co., Ltd.

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