The Pennsylvania State University

The Graduate School

College of Engineering

EFFECTS OF GRIP SPAN IN ONE-HANDED THUMB INTERACTION WITH A SMARTPHONE

A Thesis in

Industrial Engineering

by

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ABSTRACT

The purpose of this study was to investigate whether different grip spans affected the touch performance of one-handed thumb interaction with a smartphone. Tapping time, hit count, and thumb-tip displacement were measured while using three mock-ups of an iPhone 5S, 6, and 6 Plus, respectively. In the tapping task, four positions were tested: top-left, top-right, bottom-left, and bottom-right. The results showed that the hit count ($F_{2,14}=8.596$, $p=.004$) and thumb-tip displacement ($F_{2,14}=11.348$, $p=.001$) significantly decreased as the grip span increased. Thus, I concluded that there existed another problem beyond the limit of thumb length that caused a reachability issue when using a large smartphone. Thus, this should be considered in the user interface design of a large smartphone.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1

Introduction

The big screen has undoubtedly become a megatrend in the smartphone industry as Apple Inc. (Cupertino, CA, USA) finally joined the trend, releasing the iPhone 6 Plus with a 5.5″ screen in 2014. In this era of mobile computing, there is a growing need for large-screen smartphones as people are expecting more from a smartphone than mere phone function. With a large screen, information can more advantageously be displayed and multimedia content watched. On the other hand, as potential problems for a mobile hand-held device, a lack of portability and reachability arise. People more often drop and break their smartphones due to lack of portability, which has resulted in the growth of the smartphone repair industry and the refurbished smartphone industry (Gartner, 2015; Petrillo, 2016). Moreover, many researchers have attempted to solve the reachability issues by addressed it from various angles. However, despite this ongoing discussion, recent research has been limited to focusing only on the thumb length's limitation. Thus, this present research study begins with the question: Assuming one-handed interaction through a normal thumb range of motion, to what extent will performance be affected by increasing the grip span caused by large screens?

Chapter 2

Background

Before the emergence of large-screen smartphones, many studies focused on the diagnosis and measurement of thumb gestures and development of novel gestures. In many studies, the effect of the target size and location was investigated, and an increasing level of touch error was found for smaller targets (Parhi, Karlson, & Bederson, 2006; Park & Han, 2010; Roudaut, Huot, & Lecolinet, 2008; Xiong & Muraki, 2014). Thumb motion while typing on a mobile phone was analyzed using a motion-analysis technique (Ong, 2009; Sakai & Shimawaki, 2010). Possibilities for a new thumb-touch gesture were invented and tested to extend the input method for a smartphone. Hoggan et al. (2013) investigated rotation gestures with the thumb and index finger concerning performance and ergonomics, Bonnet et al. (2013) introduced a thumb-rolling gesture called *ThumbRock*, Ohta and Tanaka (2012) developed a multiple-screen-change interface using a pinch gesture, and Boring et al. (2013)suggested a novel single-touch technique, *Fat Thumb*, that adds a degree of freedom through using the thumb's contact size.

Considering the reachability problem on a large-screen smartphone, a number of studies have been conducted related to touch behavior, usability, range of motion, and alternative touch. Zhang et al. (2015) analyzed the performance of touch behavior on a large-screen smartphone, comparing between gender and target location. Xiong and Muraki, (2016) found that age and thumb length affect the movement coverage on a smartphone touch screen. As an alternative touch method, many attempts were made using back-of-device interaction with the index finger to compensate the untouchable area for the thumb length limit (Buschek, Schoenleben, & Oulasvirta, 2014; Wolf, Müller-Tomfelde, Cheng, & Wechsung, 2012; Yoo, Yoon, & Ji, 2015). Bergstrom-Lehtovirta and Oulasvirta (2014) established a predictive model for the functional area of the thumb to suggest a quantitative design guideline for a mobile user interface.

One-handed thumb interaction with a smartphone has been widely researched. However, there is another approach that has not been researched. In this study, we tested the hypothesis that grip span on a smartphone affects the touch performance of one-handed thumb interaction. Unlike past studies, we controlled the target location between small and large smartphones and further emphasized the effect of grip span.

Chapter 3

Methodology

A repeated measures experiment was conducted to investigate the stated premise. Participants accomplished two tasks involving typical touch gestures, tapping, and swiping, using three smartphone mock-ups to evaluate the performance of one-handed thumb interaction.

2.1 Subject

Eight participants were recruited with an age range of 25 to 30 (4 female, 4 male). All participants had sufficient experience in using a touch-screen smartphone and had no musculoskeletal problems. Seven participants were right-handed, and one was left-handed. For the left-handed participant, a separate mock-up (reflecting horizontally to the mock-up for right-handed participants) was prepared. Hand length (tip to wrist crease) and thumb length (digit 1 length) ranged from 163 to 203 mm and from 56.3 to 65.8 mm, respectively (Greiner, 1991). All participants provided verbal informed consent prior to participation in the study and received compensation ($7/hour).

2.2 Apparatus

Smartphone mock-ups (made of particle board) of three different sizes were prepared to test three different grip spans (Figure 1). The height and width dimensions were equal to the iPhone 5S, iPhone 6, and iPhone 6 Plus (Apple Inc., Cupertino, CA, USA) and were labeled as S, M, and L, respectively (Table 1). The thickness of the mock-ups was identical at 6.70 mm.

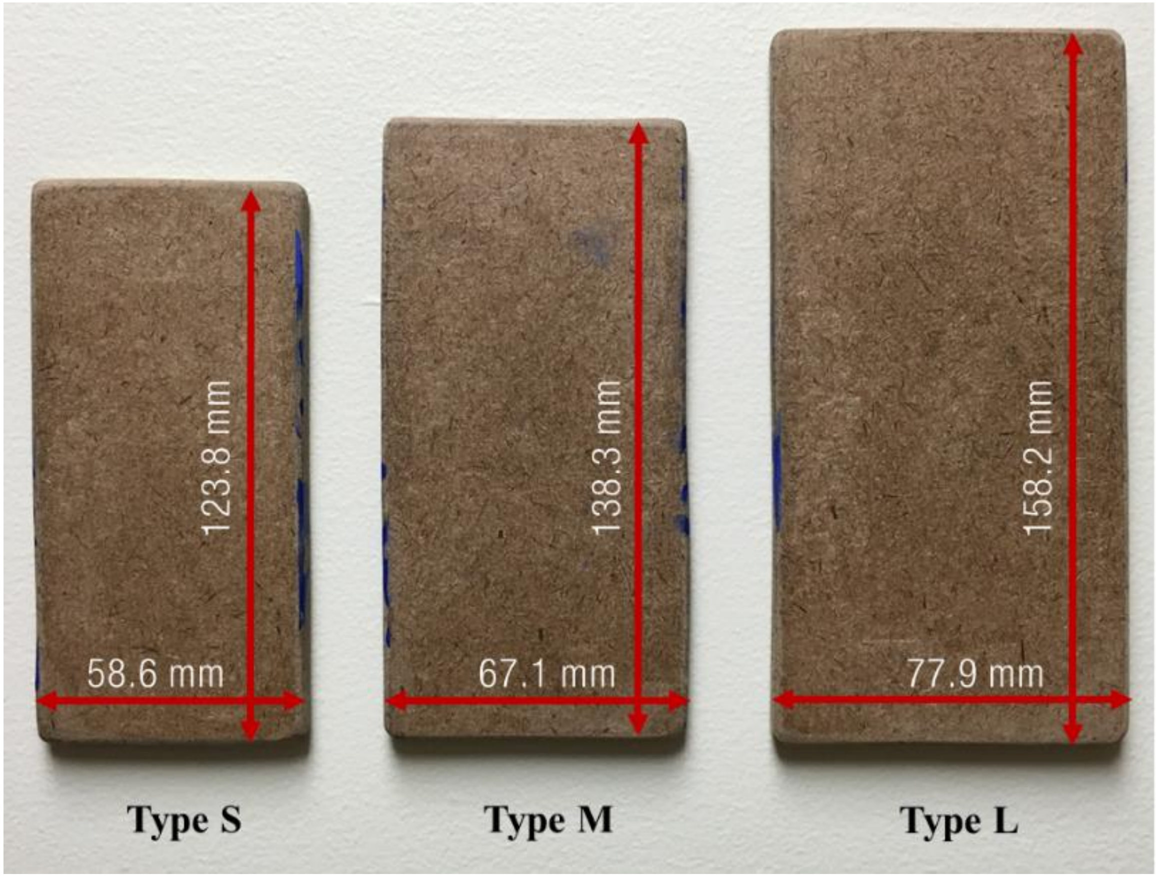


Figure 1. Tested device mock-ups

Table 1. Dimensions of tested devices (*unit: mm*)

Device (Grip span size)	Width	Height
S	58.60	123.80
M	67.10	67.10
L	77.90	77.90

Force Sensing Resistors (FSR) were used to measure tapping time and force (FlexiForce A201™, Tekscan, Inc., Boston, MA, USA), and the data were collected at a rate of 256 samples per second through the FlexComp Infiniti™ data collection system (Thought Technology, Ltd., Canada).

2.3 Experimental Protocol

An overview of the study was provided, and all participants provided verbal informed consent. The hand and thumb lengths of the participants were recorded. Participants were introduced to the two main tasks in this study, tapping and swiping, and practiced for enough time to eliminate any learning effects.

2.3.1 Tapping task

The tapping task aimed to measure the performance of the one-handed thumb-tapping gesture across different grip spans using a within-subjects design with two factors: 1) grip span of three levels and 2) four target positions for tapping (Figure 2). The target positions were located at the edge of the screen in counterclockwise order: top-right (A), top-left (B), bottom-left (C), and bottom-right (D) of the screen. The left-handed mock-up had a clockwise order from top-left (A) to bottom-left (D).

In order to provide an identical tapping position over the three devices, type S was set up as the base model and a screen of the same size was drawn on top of the other two devices with corresponding coordinates. In other words, the target positions on the S, M, and L mock-ups were located at the same distance from the participant's palm (Figure 2). For each participant, the grip posture was controlled to the point where all four target positions were possible to reach.

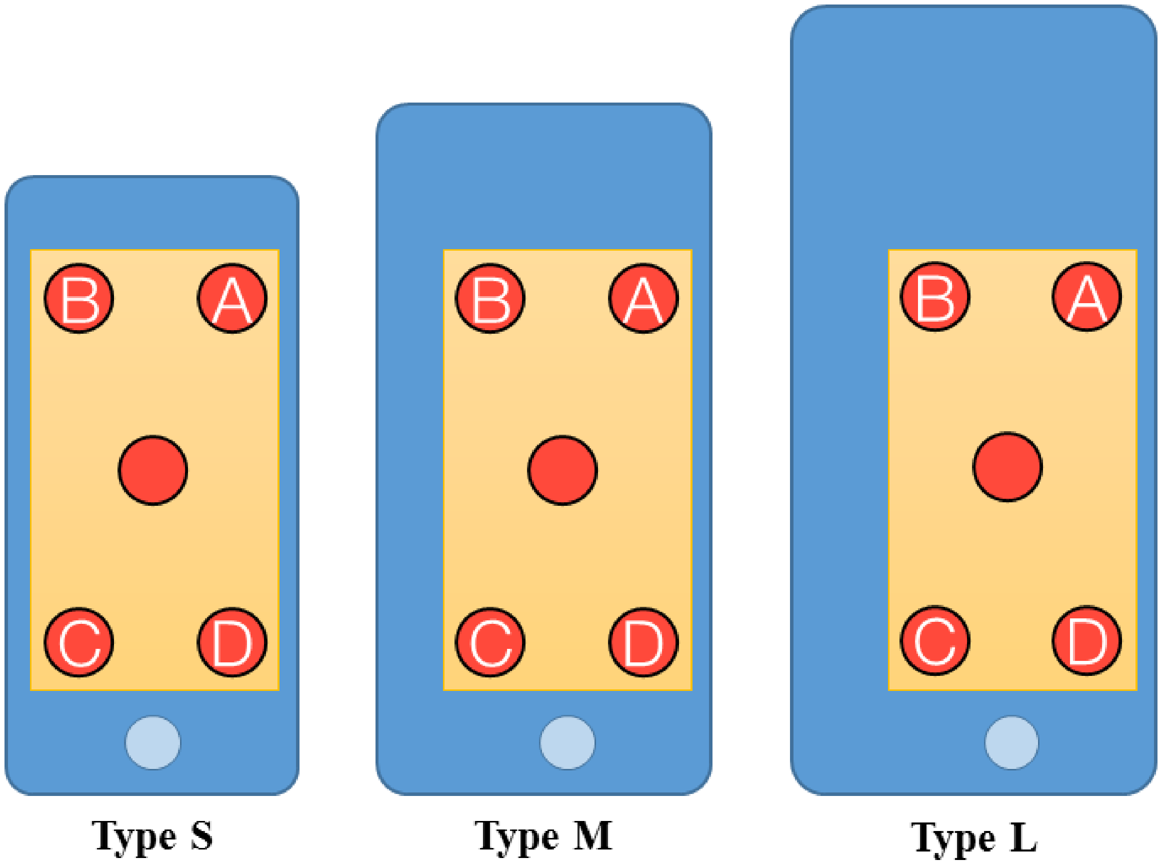


Figure 2. Target locations and position ID on the screens

Each participant performed twelve sessions (3 grip spans × 4 target positions) with three replications (total of 36 trials). For each trial, participants tapped 30 times on the center and the assigned target position (e.g., the A button) in turn as quickly and accurately as they could. The order of the 12 sessions was randomized for each participant. FSRs were placed on the center and each target position to measure tapping time and hit count (dependent variables; Figure 3).

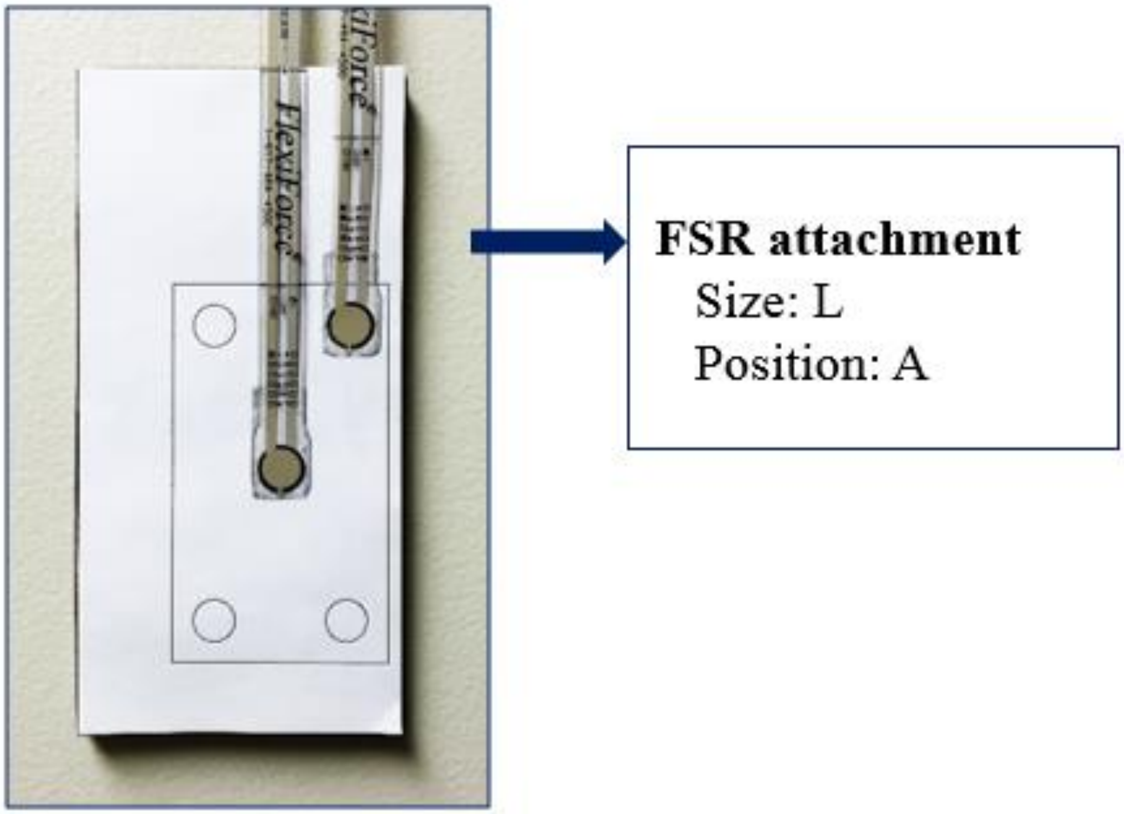


Figure 3. FSR attachment on the position A of a type L device

For each trial, the first and last three taps were eliminated to minimize errors from starting and ending the recording. In other words, 30 taps for each trial were recorded but were trimmed to a total of 24 taps. The tapping time was recorded as the total time for the 24 taps. The hit count was computed based on the assumption that a loss in touch pressure (i.e., inability to fully execute the button on the touch screen) would increase as the input offset error increased. Thus, the magnitude of touch pressure was employed as the scale to measure an input offset. For each participant, the pressure on all target positions (for all sizes) was normalized based on the average pressure on the center of type S to minimize the subject effect. A tap pressure that was measured greater than 70% of the normalized pressure was considered as a hit (where less than

70% was considered as a miss). In each trial, hit was counted out of the 24 taps. Figure 4 illustrates an example of computing the number of hits, through the FSR data-collection screen (BioGraph Infiniti, Ver.5.1.4, Thought Technology, Ltd., Canada).

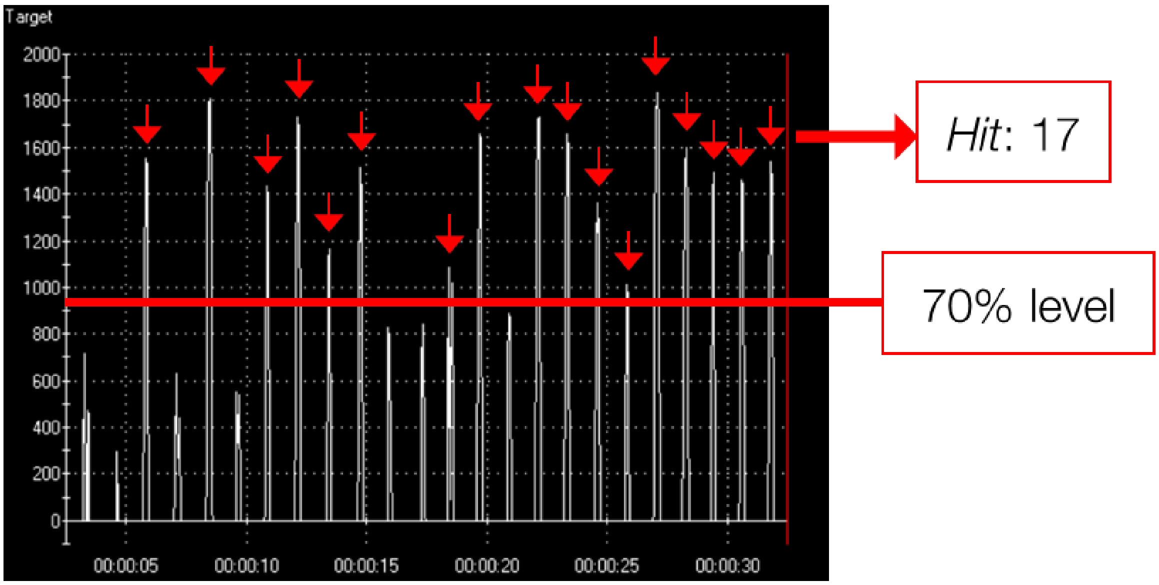
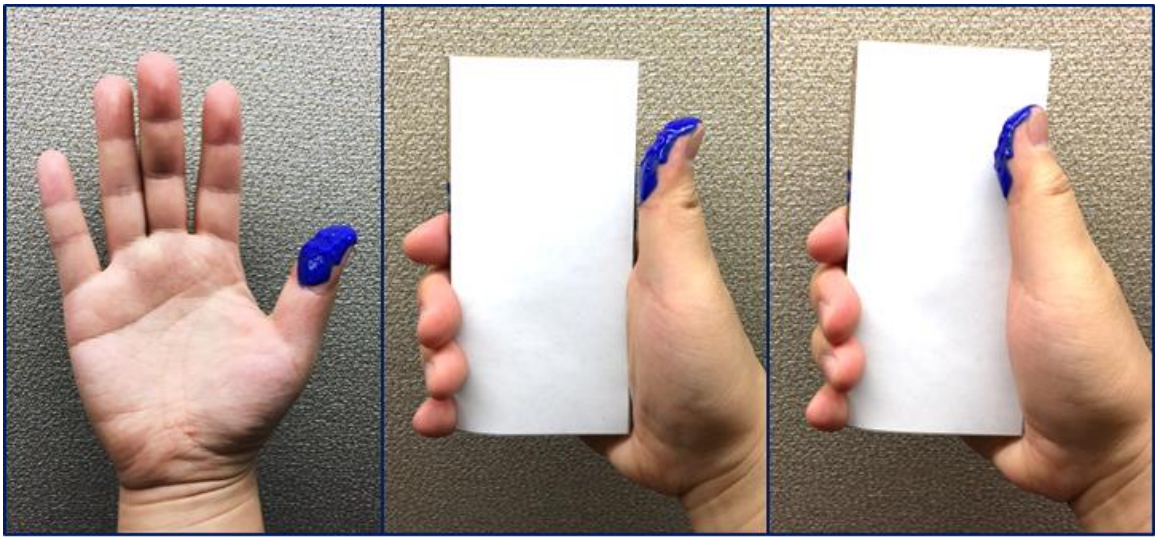


Figure 4. Hit counting procedure example

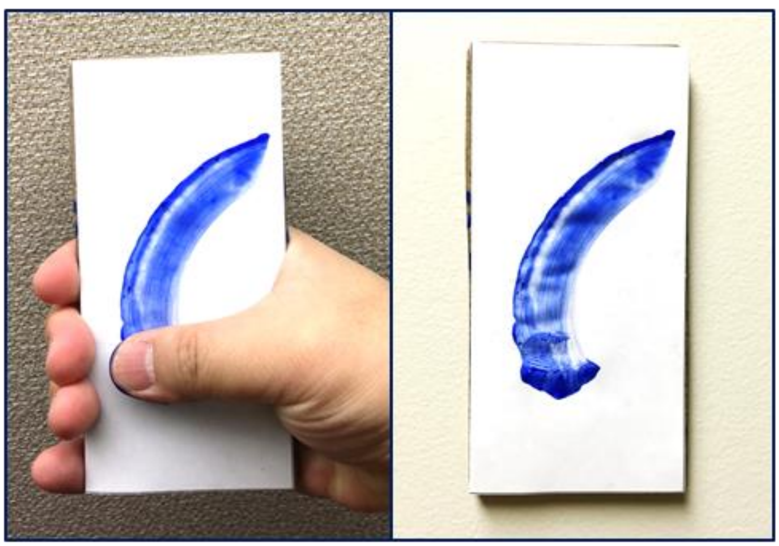
2.3.2 Swiping task

The range of thumb swiping was measured using paper and Washable Fingerpaint™ (Crayola LLC, Easton, PA, USA). A clean white sheet of paper was taped to the three mockups (size S, M, and L), and the thumb of each participant was applied with finger paint. They were instructed to swipe their thumb from top-right to bottom-left (at the maximum abduction limit) on the paper in a counter-clockwise direction, which painted a swiping trajectory. The thumb-tip displacement from top to bottom was measured from the painted area. After completing the experiment, the painted paper was scanned with a 600 dpi resolution and the displacement was measured using Adobe Photoshop™ CS6 (Adobe Systems, Inc., San Jose, CA, USA).

The thumb-swiping gesture was limited to the thumb abduction of metacarpophalangeal and carpometacarpal joints. The interphalangeal joint of the thumb was fixed to make a straight posture between the distal and proximal phalanges. When holding the device, the grip configuration was controlled as a one-handed grip with the little finger positioned at the bottom-left corner. An example of the thumb-painting process is shown in Figure 5.



(i) (ii) (iii)



(iv) (v)

Figure 5. Thumb paint measurement process: (i) apply ink, (ii) grip, (iii) start to swipe, (iv) finish to swipe, (v) result

Chapter 4

Results

There were a total of 288 data sets in the tapping experiment (3 grip spans × 4 positions × 3 replications × 8 participants) and 24 data sets in the swiping experiment (3 grip spans × 8 participants). A repeated measures (within-subject) analysis of variance (ANOVA) was conducted to analyze tapping time, hit count, and thumb-tip displacement with a level of significance of $\alpha=.05$. For all analyses where Mauchly's test of sphericity was violated ($p<.05$), the Greenhouse-Geisser correction was used to correct the degree of freedom (*df*) and *p*-values.

3.1 Tapping Time

Since Mauchly's test for sphericity was significant for grip span ($p<.011$) and position ($p<.004$), the *df* was corrected. However, grip span ($F_{1.125,7.874}=2.463$, $p=.121$), position ($F_{1.259,8.812}=4.012$, $p=.071$), and interaction between grip span and position ($F_{6,42}=7.968$, $p=.133$) did not significantly affect the tapping time.

3.2 Hit Count

Hit count was generally lower for the larger grip span than for the smaller grip span, regardless of the target position (See Table 2). A repeated measures (within-subject) ANOVA of the hit count showed that there were significant main effects for grip span ($F_{2,14}=8.596$, $p=.004$), no significant main effects for position ($F_{3,21}=2.705$, $p=.071$), and an interaction between them ($F_{6,42}=31.242$, $p=.573$). Pairwise comparisons were performed on significant effects, and the results showed that grip spans M and L recorded a worse hit count than grip span S

(p<.017;p<.016). Figure 6 and Figure 7 show a tendency of the hit count to decrease according to the size of the grip span.

Table 2. Mean and standard error values of the hit count for each size and position

Size	Position	Hit Count	
		Mean	Std. Error
S		19.865	1.908
	A	21.542	1.678
	B	20.375	2.303
	C	16.958	2.612
	D	20.583	1.677
M		16.552	1.970
	A	19.667	2.141
	B	15.750	2.916
	C	15.875	2.321
	D	14.917	1.975
L		13.083	2.698
	A	15.333	2.987
	B	13.750	3.735
	C	10.750	3.309
	D	12.500	2.387

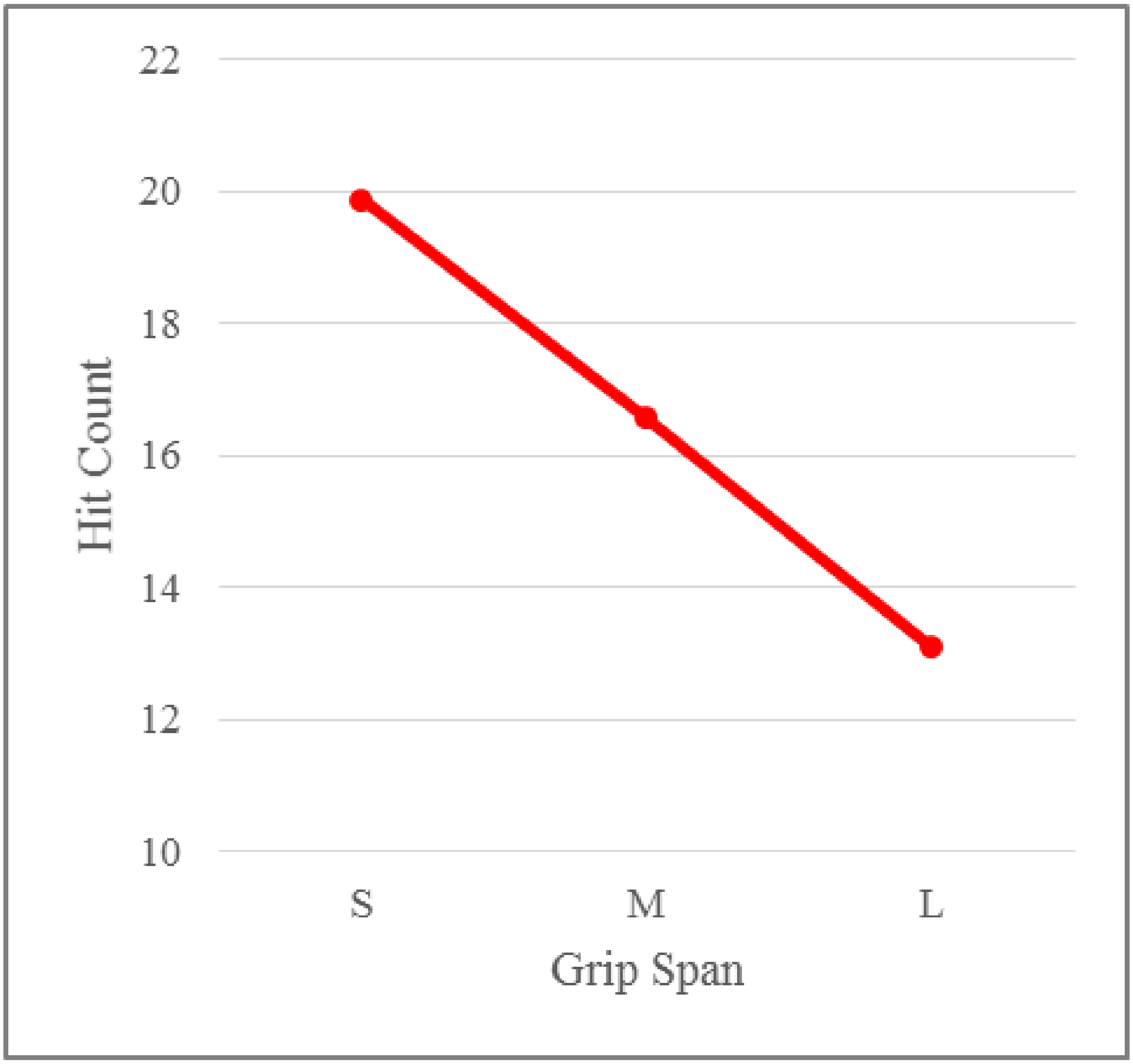


Figure 6. Monotone decreasing trend of hit count (mean and standard error) for size

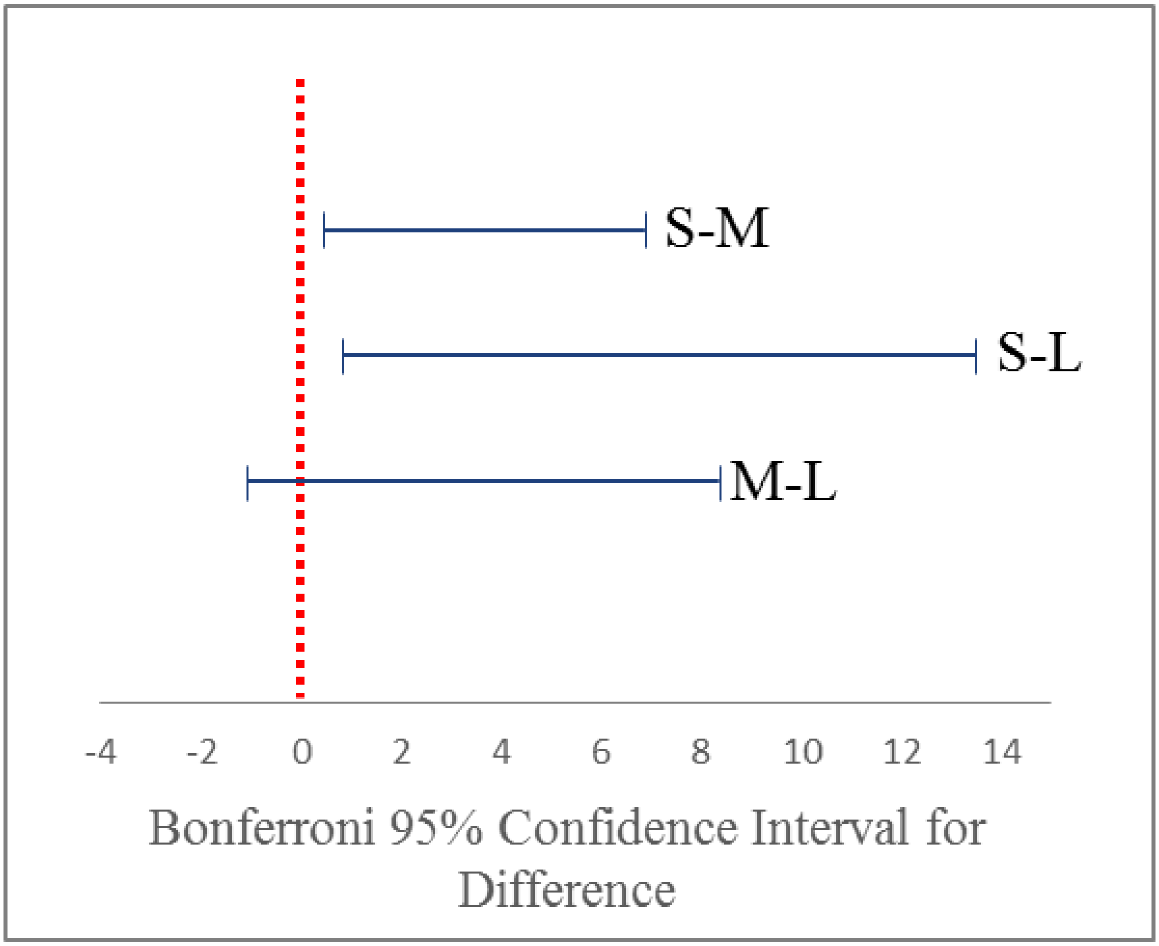


Figure 7. Pairwise comparison result of hit count by Bonferroni confidence interval

3.3 Thumb-tip Displacement

Grip span significantly affected thumb-tip displacement as a main effect ($F_{2,14}$=11.348, p=.001). Figure 8 illustrates the negative effect of grip span for thumb-tip displacement. As size increased, thumb-tip displacement shrank. Based on the pairwise comparison, the thump-tip displacement on grip span L was significantly reduced by 11.375 mm on grip span S (p<.003) and 6.175 mm less than on grip span M (p<.032) (Figure 9). Table 3 summarizes the mean and standard error values for the size. One sample image of the finger paint measurement shows a clear difference of thumb-tip displacement among the three tested devices (Figure 10).

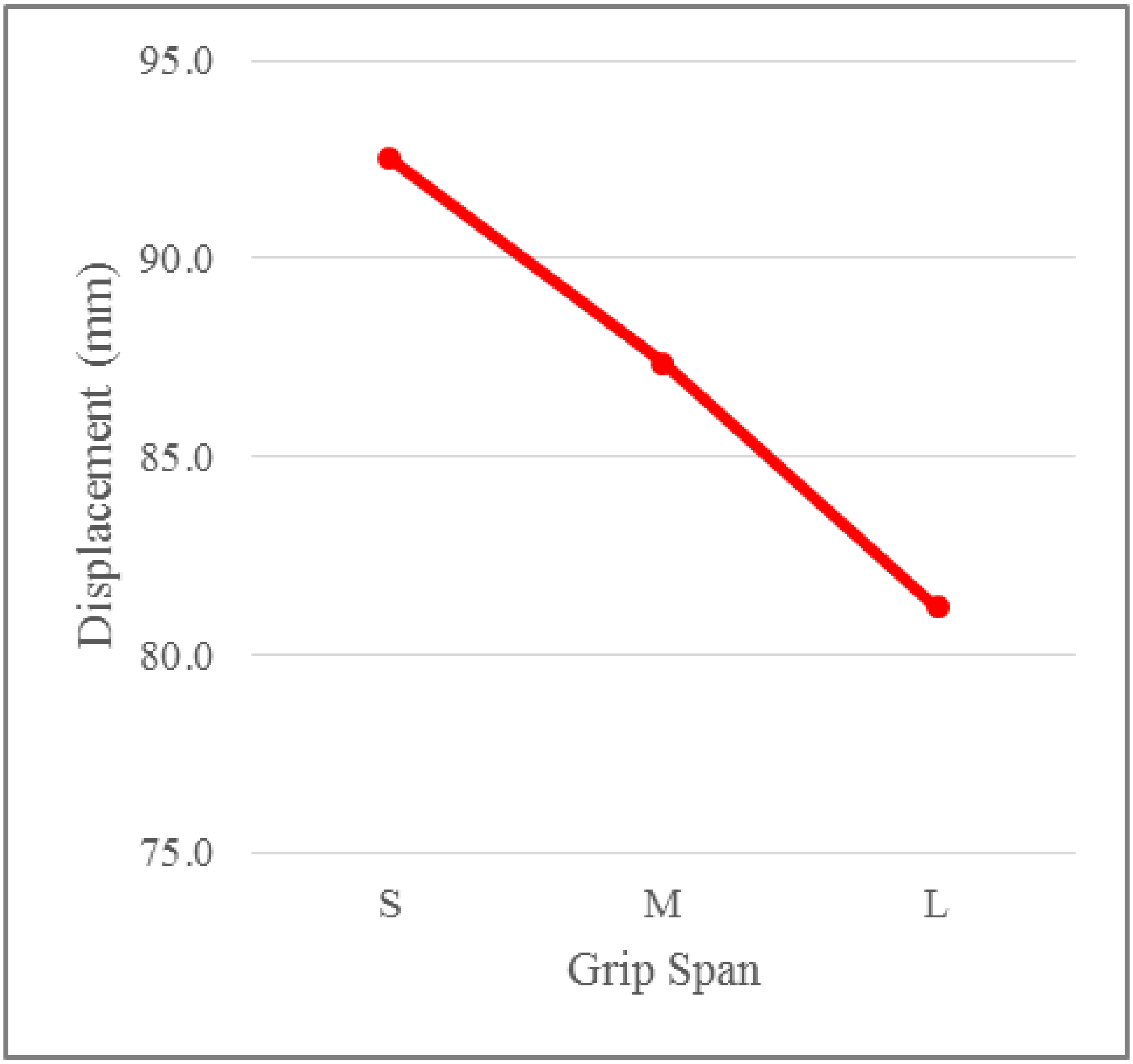


Figure 8. Monotone decreasing trend of thumb-tip displacement (mean and standard error) for size

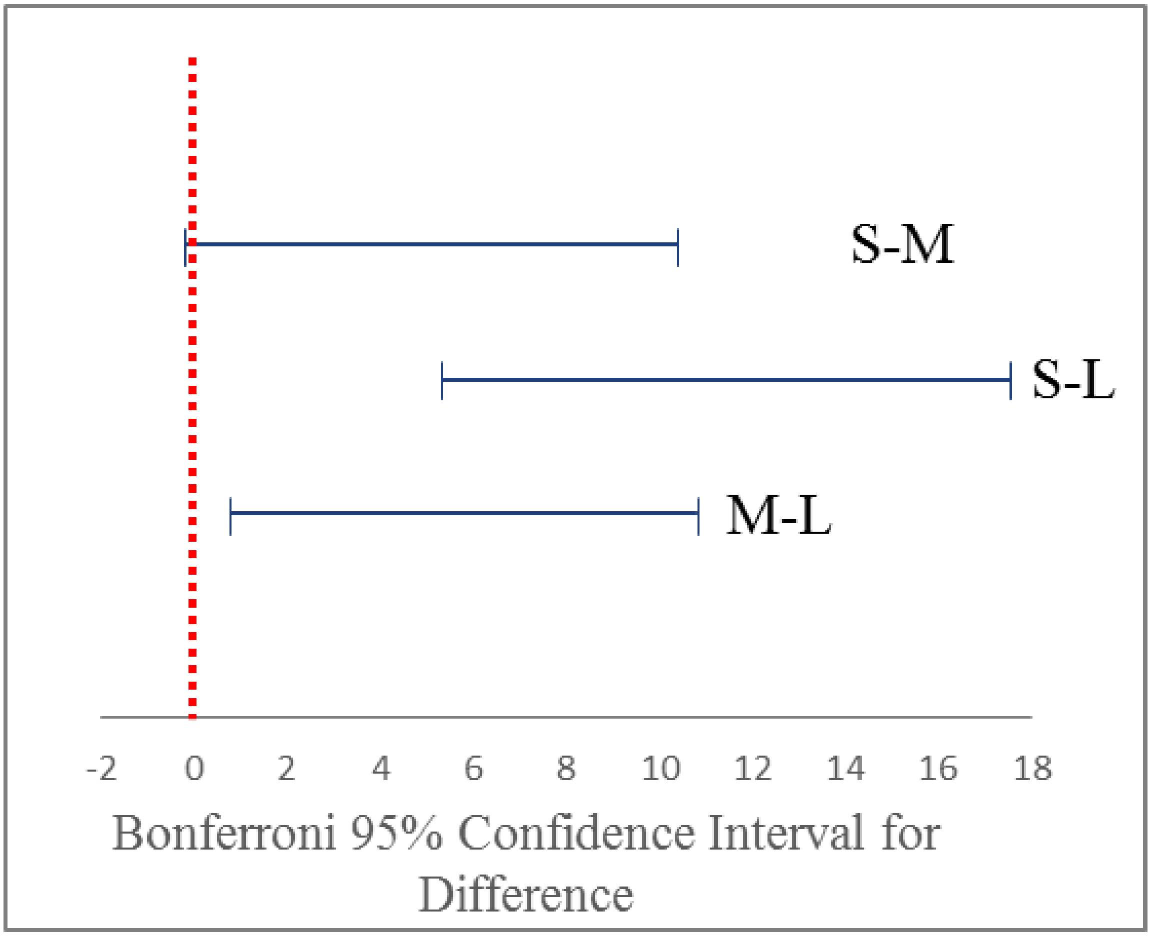


Figure 9. Pairwise comparison result of thumb-tip displacement by Bonferroni confidence interval

Table 3. Summary of thumb-tip displacement results

Size	Thumb-tip Displacement		Pairwise Comparisons			
	Mean	Std. Error	Size	Mean Difference	Std. Error	*p*
S	92.563	5.023	M	5.200	2.253	.054
			L	11.375	2.599	.003
M	87.363	5.344	S	-5.200	2.253	.054
			L	6.175	2.305	.032
L	81.188	5.418	S	-11.375	2.599	.003
			M	-6.175	2.305	.032

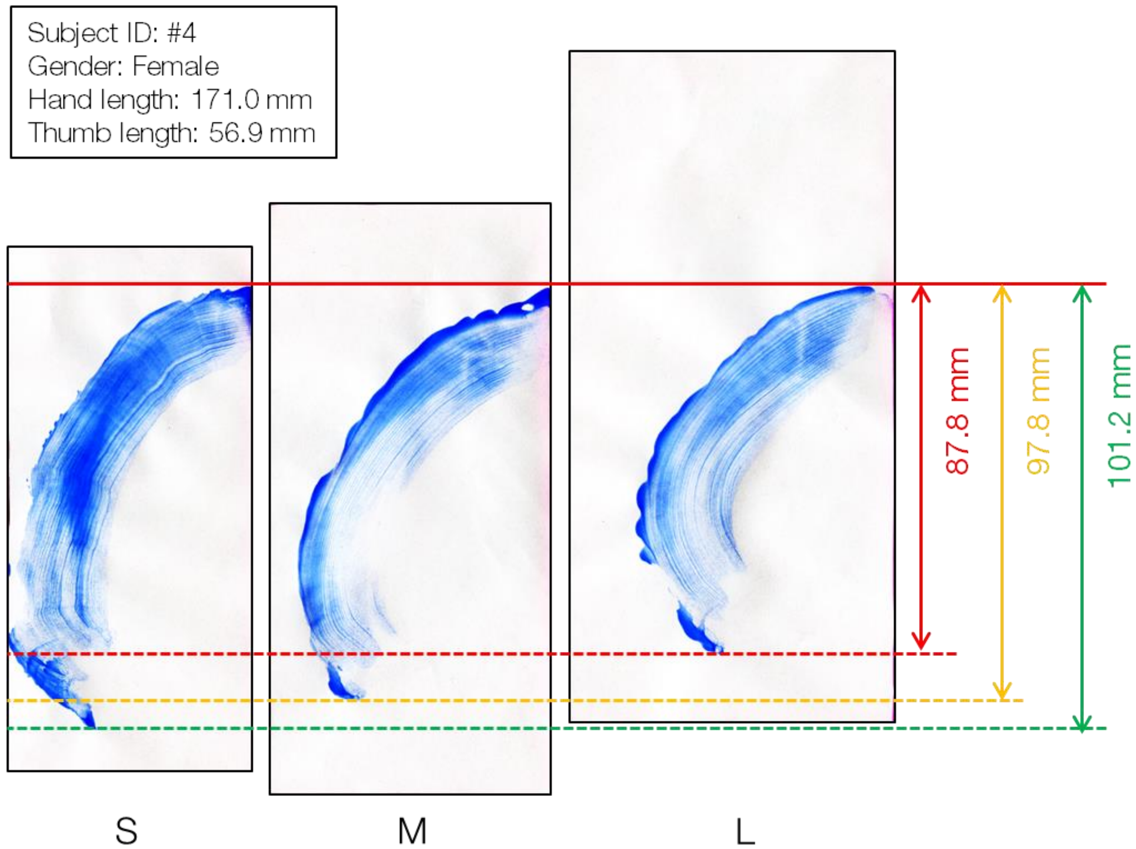


Figure 10. Sample image of finger paint measurement result

Chapter 5

Conclusions and Future Research

The results from this study support the hypothesis that grip span affects the thumb touch performance in one-handed mobile phone interaction. Three criteria—tapping time, touch accuracy, and thumb range of motion—were selected to represent the performance of one-handed thumb interaction, and tapping time, hit count, and thumb-tip displacement were measured to compare performance. Based on the results, we concluded that grip span influences thumb touch accuracy and thumb range of motion in one-handed mobile phone interaction.

In this experiment, thumb-touch accuracy was estimated based on touch pressure. This method was only able to discern “hit” and “miss”, and it was unable to measure the offset error of the thumb touch, quantitatively. Nonetheless, because we set up the target on an identical coordination over different device sizes, this result should still provide valid and meaningful information.

The decrease of the thumb range of motion by grip span was also observed in the vertical direction. As the width of the tested devices increased, the vertical displacement of thumb swiping tended to decrease. The reason the thumb range of motion was measured only in the vertical direction is that many of the participants had sufficient thumb length to fully cover the type S device.

In conclusion, we attested that there existed another problem beyond the limit of thumb length that caused the reachability issue when using a large smartphone. The reachability issue could be caused by an increase in the untouchable area beyond the limit of the thumb length. However, the reduction of the thumb range of motion itself could be another reason. Thus, both enlarging the screen size to exceed the thumb length and shrinking the thumb range of motion would aggravate the reachability issue as a negative synergy effect, and this should be considered in the user interface design of a large smartphone.

4.1 Limitations and Future Work

There were limitations to the methods of this study. First, the tapping task was not strictly controlled, and, as a result, the test for tapping time failed. We requested the participants to tap as quickly and accurately as possible. However, a clear guideline should have been established because there existed quite a different balance between speed and accuracy by the participants. Consequently, some participants who put more emphasis on speed tapped at their maximum speed, ignoring accuracy, and vice versa.

Second, the target location for the tapping task needs to be rearranged considering the participant’s hand size. As the thumb range of motion decreased on larger devices, some participants who have small hands had trouble touching the target, and this caused a zero hit count. It also caused the participants to make unintentional grip changes to make an effort to touch the far targets.

Third, hit count should be calculated based on area, rather than pressure, to measure the touch offset error more accurately. It would not only help make a more precise decision but would also remove the subject effect for tapping pressure.

Reflecting on the results and limitations of this study, we will conduct an in-depth study to investigate the effect of grip span on a large smartphone in the near future. To improve this study, it is first required to consider the relationship between hand anthropometry and thumb-gesture performance. Second, electromyography (EMG) will be measured to investigate muscle activity and physical discomfort on the thumb.

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Appendix

Institutional Review Board (IRB) Application

Table 4. Summary of IRB application

Study ID	Principal Investigator	Title of Study	Approval Date
STUDY 00004185	Kiseok Sung	Effects of mobile phone size in one-handed thumb interaction	01/25/2016

PENNSTATE

IRB Program
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EXEMPTION DETERMINATION

Date: January 25, 2016

From: Julie James, IRB Analyst

To: Kiseok Sung

Type of Submission:	Initial Study
Title of Study:	Effects of mobile phone size in one-handed thumb interaction
Principal Investigator:	Kiseok Sung
Study ID:	STUDY00004185
Submission ID:	STUDY00004185
Funding:	Not Applicable
Documents Approved:	• Questions.docx (0.01), Category: Other • Survey form.docx (0.01), Category: Data Collection Instrument • HRP-591 - Protocol for Human Subject Research.pdf (1.3), Category: IRB Protocol • Tasks.pptx (0.01), Category: Data Collection Instrument

The Office for Research Protections determined that the proposed activity, as described in the above-referenced submission, does not require formal IRB review because the research met the criteria for exempt research according to the policies of this institution and the provisions of applicable federal regulations.

Continuing Progress Reports are **not** required for exempt research. Record of this research determined to be exempt will be maintained for five years from the date of this notification. If your research will continue beyond five years, please contact the Office for Research Protections closer to the determination end date.

Changes to exempt research only need to be submitted to the Office for Research Protections in limited circumstances described in the below-referenced Investigator Manual. If changes are being considered and there are questions about whether IRB review is needed, please contact the Office for Research Protections.

Penn State researchers are required to follow the requirements listed in the Investigator Manual (HRP-103), which can be found by navigating to the IRB Library within CATS IRB (http://irb.psu.edu).

This correspondence should be maintained with your records.