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Thumb Motor Performance Varies by Movement Orientation, Direction, and Device Size During Single-Handed Mobile Phone Use

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Objective: The aim of this study was to determine if thumb motor performance metrics varied by movement orientation, direction, and device size during single-handed use of a mobile phone device.

Background: With the increased use of mobile phones, understanding how design factors affect and improve performance can provide better design guidelines.

Method: A repeated measures laboratory experiment of 20 right-handed participants measured the thumb tip's 3-D position relative to a phone during reciprocal tapping tasks across four phone designs and four thumb tip movement orientations. Each movement orientation included two movement directions: an "outward" direction consisting in CMC (carpometacarpal) joint flexion or abduction movements and an "inward" direction consisting in CMC joint extension or adduction movements. Calculated metrics of the thumb's motor performance were Fitts' effective width and index of performance.

Results: Index of performance varied significantly across phones, with performance being generally better for the smaller devices. Performance was also significantly higher for adduction–abduction movement orientations compared to flexion–extension, and for "outward" compared to "inward" movement directions.

Conclusion: For single-handed device use, adduction–abduction-type movements on smaller phones lead to better thumb performance.

Application: The results from this study can be used to design new mobile phone devices and keypad interfaces that optimize specific thumb motions to improve the user-interface experience during single-handed use.

Keywords: biomechanics, Fitts' law, motor control, texting, keypad interface

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INTRODUCTION

According to the head of the United Nations International Telecommunications Union, the number of cellular phone subscribers in the world was estimated at 4 billion in 2008 (UN News Service, 2008). Despite the recent increase in cell phone users, design guidelines to optimize thumb motor performance when using these devices is limited in the human factors literature. Gustafsson, Johnson, and Hagberg (2010) did describe thumb motor behavioral differences using a two-axis goniometer spanning the base of the thumb at the wrist. They explored how posture and angular velocity of the thumb varied across tasks (holding and texting), gender, and symptomatic and asymptomatic users. However, they did not explore how these motor behavior parameters varied across phone design or how movement direction may affect motor behavior.

In single-handed mobile phone use, movement of the thumb is limited because the hand has to successfully complete the prehensile task of securing the phone, which defines the base for the thumb to complete the tapping tasks. The distribution of muscles acting at the thumb makes it most suited for grasping activities (Bourbonnais, Forget, Carrier, & Lepage, 1993), and thumb–cell phone interaction introduces new movement and exertion requirements. The prehensile requirements change based on the size and shape of the device being gripped (e.g., Edgren, Radwin, & Irwin, 2004). Park and Han (2010) investigated the effects of touch key sizes and touch key locations on the usability of a mobile phone and used transition time and task completion time as performance metrics; however, they did not examine different device sizes and specific thumb movements. Thumb tip 3-D

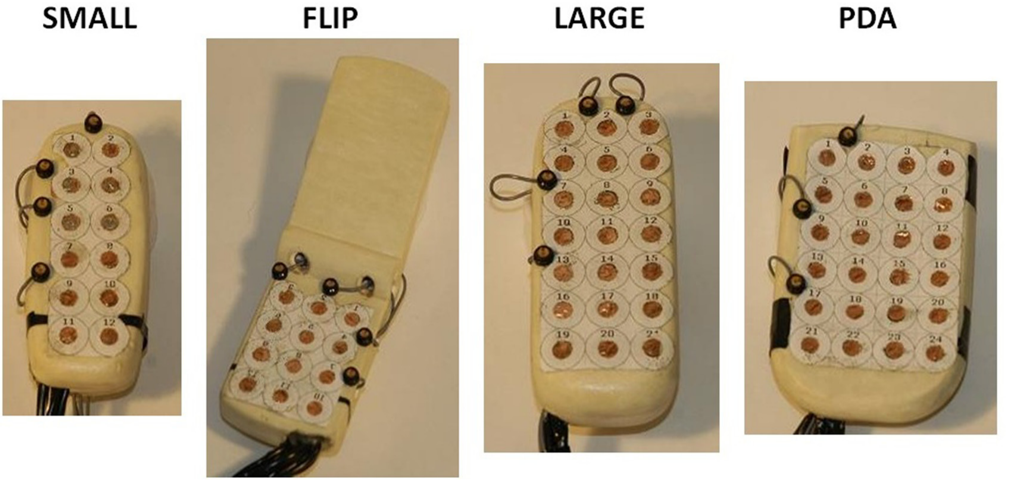

Figure 1. The models of the four emulated mobile phones depicting small, flip, large, and personal digital assistant types of phones.
Source. Modified from Karlson, Bederson, and Contreras-Vidal (2008).

motor control performance in one-handed cell phone tasks has been measured as a function of cell phone profile design by Karlson, Bederson, and Contreras-Vidal (2008). They introduced the concept that performance changes according to the orientation of a movement. However, the only performance metrics they calculated were mean movement time and movement speed limits for similar distance movements. They did not consider more sophisticated and comprehensive measures of motor control performance, such as Fitts' law, which is based on a trade-off between speed and accuracy for a range of movement distances and achieved movement precision (Douglas, Kirkpatrick, & Mackenzie, 1999; Fitts, 1954).

The goal of this study was to analyze the 3-D thumb movements relative to a mobile phone and to use Fitts-like movement performance metrics to differentiate among devices, orientations, and directions. We expected that larger devices would be associated with lower thumb performance because of the different required grips, and we also expected that thumb performance would change with different movement orientations and directions.

MATERIALS AND METHOD

A total of 20 right-handed participants (15 male and 5 female, aged from 18 to 35 years with a median age of 25) were recruited in a repeated measures experiment in which they completed reciprocal thumb tapping tasks in a laboratory setting on four mock-ups of typical mobile phone designs. The phone mock-ups all had different dimensions (Figure 1 and Table 1): The two smaller designs are referred to as Small and Flip, and the two larger designs are referred to as Large and PDA. Circular targets 1.5 cm in diameter were placed on the phones. The larger phones had more targets than did the smaller ones. The grid dimensions were (in columns × rows) Small (2 × 5), Flip (3 × 4), Large (3 × 7), and PDA (4 × 6; Karlson et al., 2008). The distance between targets was their diameter since they were placed side by side (Figure 1). These phones were chosen to resemble the most prevalent single-handed phones at the time of the study protocol development in 2007–2008. All protocols were approved by the University of Maryland Institutional Review Board, and participants provided written consent.

TABLE 1: Phone Mock-Up Dimensions

Device	Reference Model	Dimensions (cm)	Button Configuration (*X* rows × *Y* columns)
Small	Siemens S56 candy bar	10.2 × 4.3 × 1.5	5 × 2
Flip	Samsung SCH-i600	9.0 × 5.4 × 2.3	4 × 3
Large	iMate smartphone	10.2 × 5.1 × 2.3	7 × 3
PDA	HP iPAQ h4155 Pocket PC	11.4 × 7.1 × 1.3	6 × 4

Each trial involved tapping reciprocally on two keys on the phone as quickly as possible for 5 s. A more detailed description of the methods is reported in Karlson et al. (2008).

In addition to the four phone designs, conditions differed with respect to different travel distances and different movement orientations. Different travel distances were achieved by skipping over one or more keys. Different orientations were defined by the location of the two keys specified for each trial and were categorized generally as east–west (EW), northeast–southwest (NESW), northwest–southeast (NWSE), and north–south (NS). In general, the orientations of NESW and NS rely more on abduction–adduction of the CMC (carpometacarpal) joint, whereas the NWSE and EW orientations rely more on flexion–extension of the CMC joint.

Each orientation was further categorized by direction of the thumb movement. "Outward" movements of the thumb were defined as consisting primarily in CMC joint flexion or abduction movements with extension of the IP (interphalangeal) and MCP (metacarpal) joints and include the following directions: S → N, SE → NW, E → W, and NE → SW. "Inward" movements of the thumb were defined as consisting primarily in CMC extension or adduction movements with flexion of the IP and MCP joints and include the following directions: N → S, NW → SE, W → E, and SW → NE.

We measured the 3-D position of the tip of the thumb relative to the bottom-left corner of each mobile phone using an active-marker motion capture system (Optotrak—Certus, Northern Digital Inc.) that has a resolution of 0.01 mm. Data were analyzed using Matlab software (The Mathworks, Natick, MA). Based on the thumb tip position data, taps were identified as the minimums of the thumb's vertical position. The marker's small mass of less than 1 gram was constant across all conditions, and therefore no effect was anticipated from this added mass.

For each tap, movement time, movement distance, and index of performance were calculated. The movement time (MT) was defined from the previous tap to the current tap and the movement distance (A) was defined as the distance between the position of the thumb marker for the current tap and the position of the thumb marker for the previous tap on the surface of the device. For each movement orientation and direction, participant mean values for MT and A were calculated. Taps that involved hopping over one or more keys were defined as "far" keys as opposed to "adjacent" keys (Figure 2). A measure of precision was defined as the effective width (W_e) of the target as $W_e = 4.133 * SD$ (Douglas et al., 1999), where *SD* is the standard deviation of the thumb marker 2-D location on the phone's surface about the mean value for all the taps associated with a movement orientation and direction (Karlson et al., 2008).

The effective index of difficulty ($ID_e = \log_2(2A/W_e)$) and index of performance ($IP_e = ID_e/MT$) were calculated for each trial using the movement time (MT), distance (A), and effective width (W_e). The mean speed of the movement (MS = A/MT) was also calculated for each trial. As opposed to the task-specific performance metrics originally proposed by Fitts (1954), the index of performance (IP_e) parameter defined above could be used to assess the performance of what the participants were effectively achieving by accounting for a tradeoff between the participant's speed and precision (Douglas et al., 1999).

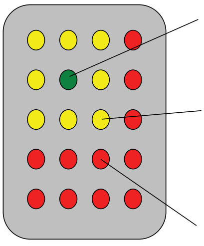

Figure 2. The definition of the levels of the "key proximity" effect.

To test the hypothesis that thumb performance varied across devices and since thumb movement performance metrics were normally distributed, we employed a repeated measures MANOVA for each of the thumb movement performance metrics (movement time, precision, and index of performance) with device (Small, Flip, Large, and PDA) and key proximity (adjacent, far) set as fixed effects and participant as random effect. We also included a device-proximity factor interaction term. To test the hypothesis that thumb performance varied across orientation and direction, we employed a repeated measures MANOVA for each of the thumb movement performance metrics with device, orientation, and direction set as fixed effects and participant as a random effect. The model included the interaction terms between the fixed effect variables. When significance was observed for an effect ($p < .05$), a post hoc Tukey's Honestly Significant Difference test was used to determine if differences in the metrics existed between comparisons. All analyses were run using JMP Software (SAS Institute, Cary, NC).

RESULTS

Performance was generally higher for the two smaller phones (Small and Flip) than for the larger ones (Table 2). Index of performance, movement time, and precision significantly differed across all devices ($p < .0001$), and all but the index of performance differed significantly across the two key proximity categories. Movement time was larger for the far keys condition ($p < .0001$). Precision decreased significantly for the far keys condition ($p < .0001$). Overall, the index of performance remained constant over the two proximities; however, the device-proximity interaction term was only slightly significant ($p = .041$), indicating no substantial differences across devices. These differences within devices were not significant in the post hoc Tukey's analysis.

Thumb performance was found to be significantly higher for the NESW (abduction–adduction; $M = 15.6$, $SE = 0.1$ bits/s) orientation compared to all the other orientations (Table 3). The EW orientation yielded the best precision ($M = 3.6$, $SE = 0.1$ mm), but movement speed was the lowest ($M = 78.9$, $SE = 0.7$ mm/s), which explains why the index of performance was lowest ($M = 13.8$, $SE = 0.1$ bits/s) compared to all the other orientations.

Index of performance for "outward" movements of the thumb was significantly higher than "inward" movements ($p < .0001$), with performance for the NE → SW direction being significantly better than all the other directions (Figure 3). The difference in performance between "inward" and "outward" movements was smaller for the movement orientations that rely on more abduction–adduction of the CMC joint (NESW and NS; 5% difference) than on flexion–extension (NWSE and EW; 13% difference). "Outward" movements also yielded significantly lower movement times ($M = 0.28$, $SE = 0.00$ s; $p < .0001$) and higher movement speeds ($M = 102.4$, $SE = 0.6$ mm/s; $p < .0001$) than "inward" movements ($M = 0.30$, $SE = 0.00$ s and $M = 97.4$, $SE = 0.6$ mm/s respectively), and better precision ($M = 3.6$, $SE = 0.00$ mm for "outward" vs. $M = 3.8$, $SE = 0.00$ mm for "inward" movements; $p < .0001$). Interactions between orientation and movement direction showed significant effects ($p < .0081$) for all the dependent variables analyzed: index of performance, precision, mean movement speed, and mean movement time.

DISCUSSION

Our goal was to characterize differences in thumb tip movement performance during single-handed mobile phone use based on several design features—device size, orientation, and direction of thumb movement. The results indicate that thumb movement performance varies

TABLE 2: Least Square Mean (and standard error) Values for Thumb Motor Performance Metrics for Device and Key Proximity

	Performance Metrics							
	Movement Distance A (mm)[a]		Movement Time (ms)[a]		Precision W_e (mm)[a]		Index of Performance (bits/s)[a]	
Device	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
Small	30.7	0.5[B]	297	13[B]	3.7	0.2[A,B]	14.7	0.5[A]
Flip	28.5	0.5[A]	303	13[B]	3.6	0.2[B]	14.4	0.5[A,B]
Large	31.3	0.5[A]	307	13[A]	3.8	0.2[A]	14.1	0.5[B,C]
PDA	28.6	0.5[B]	307	13[A]	3.6	0.2[B]	14.1	0.5[C]
Key proximity								
Adjacent	19.6	0.5[B]	271	13[B]	3.6	0.2[B]	14.3	0.5
Far	40.0	0.5[A]	337	13[A]	3.8	0.2[A]	14.3	0.5
	ANOVA *p* Values							
Device	<.0001*		<.0001*		<.0001*		<.0001*	
Proximity	<.0001*		<.0001*		<.0001*		.8271	
Device × Proximity	<.0001*		.0003*		.9575		.0410*	

[a]Results from Tukey's post hoc analysis for the main effects of either device or key proximity. Values in the column with the same superscript letter are statistically similar within either device or key proximity. Values with different letters are ranked such that A > B > C.
*Statistically significant ANOVA results.

TABLE 3: Mean (and standard error) Values of Thumb Motor Performance Metrics for Each Orientation

Movement Orientation[a]	EW *M*	EW *SE*	NESW *M*	NESW *SE*	NWSE *M*	NWSE *SE*	NS *M*	NS *SE*	Interpretation
Movement distance (mm)[b]	**21.4**	**0.2[D]**	**34.3**	**0.3[A]**	**29.9**	**0.3[B]**	**28.4**	**0.2[C]**	Larger value is more difficult[c]
Movement time (s)[b]	**0.28**	**0.00[C]**	**0.29**	**0.00[B]**	**0.31**	**0.00[A]**	**0.29**	**0.00[B]**	Smaller is better
Movement speed (mm/s)[b]	**78.9**	**0.7[D]**	**121.6**	**1.0[A]**	**99.1**	**0.9[C]**	**100.2**	**0.7[B]**	Larger is better
Precision W_e (mm)[b]	3.6	0.1	3.8	0.1	3.7	0.1	3.7	0.0	Smaller is better
Index of performance (bits/s)[b]	**13.8**	**0.1[C]**	**15.6**	**0.1[A]**	**14.0**	**0.1[C]**	**14.6**	**0.1[B]**	Larger is better

[a]Bolded rows indicate a significant ($p < .05$) main effect across movement orientations. All significant findings had *p* values less than .0001.
[b]Results from Tukey's post hoc analysis. Values in the row across orientations with the same superscript letter are statistically similar. Values with different letters are ranked such that A > B > C > D.
[c]According to the formula for the index of performance, larger amplitude movements have larger indices of difficulty.

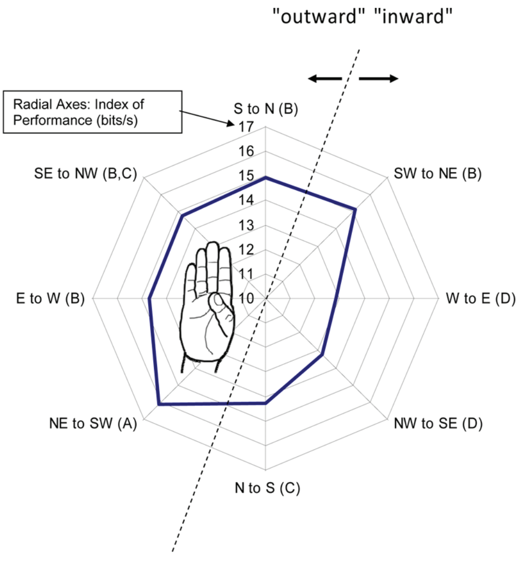

Figure 3. Index of performance (bit/s) for each movement direction for a right-handed user. The letter in brackets reports the results from Tukey's post hoc analysis. Values with the same letter denotes groups without significant differences. Values with different letters are ranked such that A > B > C > D.

by device, movement orientation, and movement direction, with larger devices and inward movements associated with less performance capabilities.

First, performance differed across phone designs. This could possibly be explained by the fact that the larger phones forced the user to have a wider grip on the device, constraining the CMC joint in an extended posture, thus reducing the thumb's range of motion. Therefore, physical obstruction of the phone may have been more prominent when reaching for farther keys. This hypothesis is supported by the result that precision (W_e) was significantly different across the adjacent and far key conditions for both larger phones (Large and PDA) but not for the smaller ones (Small and Flip). Karlson et al. (2008) did not find a significant difference in mean movement time for trials across devices when considering only movement time and movement speed as performance metrics. By using Fitts' motor control performance metrics that account for the distance traveled and the precision of the movement (the speed vs. accuracy trade-off), we observed different effects when expanding the data included in the comparison across different movement distances, allowing for more capabilities in evaluating the device designs.

Thumb performance (IP_e) was found to be significantly higher for the NESW orientation compared to all the other orientations. This could be explained by two hypotheses. First, fewer joint degrees of freedom are involved in performing the abduction–adduction compared to the flexion–extension-type movement orientation. For abduction–adduction movements, the thumb is held in an extended position, and the thumb abductor–adductor muscles are fired to abduct–adduct the CMC joint about a neutral, or comfortable, position of the thumb over the phone. If the first IP and MCP joints are approximated as hinge joints (Cooney & Chao, 1977), these joints can be considered to be static during abduction–adduction movements, which can be assumed to involve a minimum of a single degree of freedom about the CMC joint. The flexion–extension movements involve a reciprocal movement of the thumb joints. For example, the NW → SE movement direction involved flexion of the MCP and IP joints along with extension of the CMC joint. This movement can be considered to involve a minimum of three degrees of freedom. This reciprocal movement of the thumb joints is more complex and involves more coordination than the adduction–abduction movements, which might translate into reduced performance. This result is in accordance with results from Tseng, Scholz, Schöner, and Hotchkiss (2003), who suggest that better control is achieved by reducing the number of degrees of freedom utilized in a movement for higher accuracy task requirements.

Another hypothesis as to why performance was found to be better for the NESW orientation than for the NWSE orientation is better visual access to the keys. For the tapping tasks in the NWSE orientation, visual access to the key in the SE corner of the phone might have been interfered with by the thumb itself. This lack of visual feedback information could explain the slower movement times and lower precision observed for the NWSE orientation. This hypothesis is consistent with the results from Park and Han (2010), who found an increase in the error rate for thumb taps on the lower-right part of a touch-screen mobile phone device by right-handed users.

The results support that thumb motor performance changes according to movement direction. For every reciprocal movement task, performance for the “outward” direction was consistently higher than for the “inward” direction (Figure 3). Although thumb joint angles were not measured, we hypothesize that some “inward” movements may have required a large amount of flexion of the thumb’s IP and MCP joints and extension of the CMC joint, which may move the thumb joints closer to the range of motion limit. In turn, passive joint forces may increase at such limits (Keir, Wells, & Ranney, 1996), requiring more effort. The “outward” movements may bring the thumb back to a more comfortable posture, where the motor control is assisted by the conservative nature of passive forces to restore posture back to neutral. The NE to SW (abduction-type movement) direction yielded a significantly better performance than did all the other movement directions. Coincidentally, the endpoint target for this movement was close to the neutral posture of the thumb when in a relaxed state over the phone.

There are limitations relating to the methods and results of this study. First, this study considers only right-handed participants. Results might be different for right-handed participants using their left hand or left-handed participants using the device with their right or left hand. Next, grip posture was not controlled; participants were free to use the most comfortable grip for performing each task. Despite this variability, however, we still observed effects of phone type on performance. This factor, along with hand size, which was not measured, could have been effect modifiers. One consequence of these two limitations is that, since thumb tip position was measured with respect to the phone, the same performance could be achieved by moving the thumb tip over the phone or by moving the device under the thumb. Performance measures might have been different if the targets on the phone mock-ups had been keys that the user needed to depress. However, this limitation was controlled for since the targets were the same for all the phone mock-up designs. The results are also limited by the age and gender distribution (mostly young adults and more men than women). Another limitation to the study is that, because of the rapid evolution of mobile phone technology, the phone mock-ups used may not be representative of the models that are most popular today, such as smart phones with multitouch interfaces. Further limitations that may reduce the applicability to design include the use of dummy phones with nonnormal key-sized contacts, the lack of tactile feedback, and resulting speed and error effects. Finally, the differences in performance were small, and it is unclear if these changes are noticeable to the users.

Applications of this study’s findings include the development of new mobile phone designs and new phone interface designs that increase thumb performance. For example, smaller sized phones and shorter thumb travel distances were found to be associated with better thumb performance, which could be the result of less physical interference of the phone with thumb motion. Therefore, new phone designs could focus on permitting a wider range of motion of the thumb by decreasing potential physical interference at the base where the lateral palm of the hand grips the phone. For example, a widely chamfered edge could promote increased thumb range of motion. Thumb performance was higher for adduction–abduction movements compared to flexion–extension movements, and, therefore, the phone’s keyboard interface could be designed to promote adduction–abduction movements. This could be achieved by tilting the keyboard slightly counterclockwise from the normal orthogonal position. This design would further improve visual access to the whole keyboard while tapping. These design modifications could lead to less awkward postures and therefore lower mechanical loading frequency and amplitude on thumb muscles during texting tasks.

CONCLUSION

Performance was generally better for the smaller devices than for the larger ones. Diagonal movements of the thumb that rely primarily on abduction–adduction of the thumb provide the best overall performance, whereas the “inward” movements that require reciprocal flexion–extension movements with more multiarticulate musculature provided the lowest performance. The results from this study can be used to design new mobile phone devices and keypad interfaces that optimize thumb movement performance, thus improving the user experience with such devices.

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KEY POINTS

- Thumb performance was found to be higher for smaller phones and for the abduction–adduction movement orientations.
- Thumb performance was found to be higher for “outward” directions compared to “inward” directions.
- The results from this study can be used to design new mobile phone devices and keypad interfaces that optimize thumb movement performance, improving the user experience with such devices.

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